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Soil organic carbon storage as a key function of soils - A review of drivers and indicators at various scales

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A R T I C L E I N F O

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A B S T R A C T

The capacity of soils to store organic carbon represents a key function of soils that is not only decisive for climate regulation but also affects other soil functions. Recent efforts to assess the impact of land management on soil functionality proposed that an indicator- or proxy-based approach is a promising alternative to quantify soil functions compared to time- and cost-intensive measurements, particularly when larger regions are targeted. The objective of this review is to identify measurable biotic or abiotic properties that control soil organic carbon (SOC) storage at different spatial scales and could serve as indicators for an efficient quantification of SOC. These indicators should enable both an estimation of actual SOC storage as well as a prediction of the SOC storage potential, which is an important aspect in land use and management planning. There are many environmental conditions that affect SOC storage at different spatial scales. We provide a thorough overview of factors from micro-scales (particles to pedons) to the global scale and discuss their suitability as indicators for SOC storage: clay mineralogy, specific surface area, metal oxides, Ca and Mg cations, microorganisms, soil fauna, aggregation, texture, soil type, natural vegetation, land use and management, topography, parent material and climate. As a result, we propose a set of indicators that allow for time- and cost-efficient estimates of actual and potential SOC storage from the local to the regional and subcontinental scale. As a key element, the fine mineral fraction was identified to determine SOC stabilization in most soils. The quantification of SOC can be further refined by including climatic proxies, particularly elevation, as well as information on land use, soil management and vegetation characteristics. To enhance its indicative power towards land management effects, further “functional soil characteristics”, particularly soil structural properties and changes in the soil microbial biomass pool should be included in this indicator system. The proposed system offers the potential to efficiently estimate the SOC storage capacity by means of simplified measures, such as soil fractionation procedures or infrared spectroscopic approaches.

1. Introduction

The multifunctionality of soils is increasingly recognized as a decisive aspect in global land management. After its introduction in the 1990s, the concept of soil functions was further developed to a systemic approach covering all aspects of soil-based environmental, social and economic services (Baveye et al., 2016; Blum, 1993). Although there is no agreed upon definition, the main ecological functions of soils, beyond technical and cultural aspects, are: biomass production, storage and filtration of water, storage and recycling of nutrients, habitat for biological activity and carbon storage. The latter can be regarded as a key function of soils, as it is not only decisive for climate regulation, but strongly affects all other functions as well. In recent years, the rising integration of soil functions in environmental policy making has

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created a need for more detailed and quantitative information on specific soil functions (Baveye et al., 2016; Lehmann and Stahr, 2010; Schulte et al., 2015). This is a prerequisite to assess the impact of land management changes on soil functionality, as it is intended by the “BonaRes” funding initiative in Germany (www.bonares.de). However, a direct quantification of soil functions requires various cost- and labour intensive analyses and, hence, is typically not feasible, especially when large spatial scales are targeted. An alternative approach could be to identify measureable biotic or abiotic properties that contain sufficient information to be used as indicators for the quantification of soil functions (Baveye et al., 2016; Rabot et al., 2017; Schulte et al., 2014; Vogel et al., 2018). Because of the soil's multifunctionality and complexity, an indicator system is needed that integrates the relevant soil processes and their interactions. Such indicators can be derived from “functional characteristics” as recently proposed by Vogel et al. (2018), which have to be measurable in a time- and cost-efficient way and should be reproducible on a relatively low level of expertise.

The main objective of this review is to identify a set of indicators that enables a quantification of soil organic carbon (SOC) storage at different spatial scales. This set of indicators should allow for not only a prediction of current SOC storage from local to regional scales but also for a spatial estimation of the SOC storage potential, which is an important aspect for land management decisions and for reponses to environmental disturbances. A quantification of current and potential SOC storage via a set of suitable indicators could be a promising alternative to precise and accurate determination of SOC storage via (expensive and time-consuming) field work and laboratory analyses. Moreover, for many purposes, an assessment of SOC storage and its role in ecosystem functioning requires less precision. For example, an indicator-based estimation of SOC is probably sufficient to help farmers decide which agricultural measures are appropriate to optimize the SOC level of a specific field. Similarly, landscape planners, administrative bodies or ecologists may wish to identify hotspots which are particularly valuable for conservation, without the need for precise measurements of SOC storage. To this end, the use of indicators of SOC storage is appropriate. Such indicators integrate one or several environmental and soil properties which are known to be related with SOC storage, allowing comparative assessment of soils at different locations with regard to expected SOC storage. The so-called “SCORPAN approach” of McBratney et al. (2003), building up on the factorial equation of Jenny (1941), aims to describe any soil property as a function of climate, organisms, topography, parent material, time, space and soil information itself. This approach provides a framework for an identification of factors controlling SOC storage that could serve as indicators. However, this is impeded by the fact that these factors are scale-dependent, indicating a “hierarchy of controls” (Manning et al., 2015). Important factors at the micro-scale (from particles to pedons), such as metal oxides or specific surface area (SSA), are less relevant at larger spatial scales, where SOC storage can be related to climate, topography, parent material, vegetation, land use and management (Manning et al., 2015; Moni et al., 2010). In this review, we present an overview of the importance of these factors for SOC storage with respect to scale. We further dicuss their suitability as indicators for SOC storage and provide an outlook on an indicator system to estimate actual and potential SOC storage.

2. Drivers and indicators of soil organic carbon storage

2.1. Climate

Climatic conditions, namely temperature and precipitation, are key drivers of SOC storage globally as well as at broad (sub-)regional scales, affecting both C input into the soil and SOC decomposition. Precipitation determines net primary productivity (NPP) in many (water-limited) terrestrial environments and thus the input of C into the soil. Furthermore, humid conditions favour the formation of SOC-stabilizing mineral surfaces by intensified weathering of the parent material (Chaplot et al., 2010; Doetterl et al., 2015) and often cause soil acidification leading to reduced decomposition of soil organic matter (SOM) (Meier and Leuschner, 2010). Temperature largely affects the microbial decomposition of SOM as its complex molecular attributes have a high intrinsic temperature sensitivity (Conant et al., 2011; Davidson and Janssens, 2006; von Lützow and Kögel-Knabner, 2009). Although this relationship is governed by multiple constraints, numerous studies have indicated a decrease of SOC with increasing temperatures (e.g., Jobbagy and Jackson, 2000; Koven et al., 2017; Sleutel et al., 2007; Smith et al., 2005;).

As a result of these combined influences, SOC stocks are generally highest under cool humid conditions and decrease under warmer and drier climates both at the global scale (Jobbagy and Jackson, 2000; Post et al., 1982) and at the (sub-)regional scale (Alvarez and Lavado, 1998; Badgery et al., 2013; Baritz et al., 2010; Burke et al., 1989; Callesen et al., 2003; de Brogniez et al., 2014; Gray et al., 2016; Hobley et al., 2015; Martin et al., 2011; Paul et al., 2002; Viscarra-Rossel et al., 2014). However, numerous studies have indicated that the relative importance of climate for SOC storage diminishes with increasing soil depth, where factors controlling the stabilization of SOM (see Section 2.5) become more important (Badgery et al., 2013; Gray et al., 2016; Hobley et al., 2015; Jobbagy and Jackson, 2000). At the regional scale, climate effects may be masked in topsoils by land use/management, particularly in cropland soils, where intensive management (fertilization, irrigation etc.) can counterbalance climate effects (Goidts et al., 2009; Tan et al., 2004; Wiesmeier et al., 2013). Moreover, climate variability at local scales is frequently small, so that climatic control of SOC storage is less relevant in contrast to other factors. In a regional study conducted in the conterminous USA by Homann et al. (2007), mean annual precipitation, evapotranspiration and clay content were positively correlated to SOC in the top 20 cm. The observed differences among regions were attributed to more localized differences in vegetation, clay mineralogy and other processes.

As climate constitutes a major controlling factor for SOC storage at regional to global scales, mean annual air temperature (MAT) has proven to be a suitable indicator that could serve as indicator for SOC storage due to its global availability in free climate databases. Closely related, vapor pressure deficit has also been shown to be closely associated with SOC storage (Allen et al., 2013). Although mean annual precipitation (MAP) has been shown to have a stronger association with SOC and its depth distribution in some studies at regional (Hobley et al., 2015) and global scales (Jobbagy and Jackson, 2000), other studies have reported stronger relationships between SOC with temperature than with precipitation (Allen et al., 2013; Wang et al., 2004). In a review of tropical plantation and successional forests, MAT was a better predictor of SOC than precipitation in a regression tree model, with cooler sites containing greater SOC (Marin-Spiotta and Sharma, 2013). As such, these relationships between climate drivers and SOC storage are not always easy to decipher.

To reconcile these conflicting reports, it has been suggested that the relative importance of either temperature or precipitation on SOC storage depends on the main limiting factors of SOC production and turnover in the study region (Hobley et al., 2015). In arid or semi-arid environments, water availability limits NPP, so that the system, and therefore SOC storage, is input limited (Hobley et al., 2016). In contrast, in regions with sufficient water-availability but colder temperatures, microbial activity is limited to a greater degree than NPP (von Lützow and Kögel-Knabner, 2009), so that the system and SOC storage is output limited. These patterns result in an accumulation of SOC in colder, moister areas, moderate SOC storage in warmer, moist regions and lower SOC storage in drier, hotter regions.

In this context, elevation above sea level may be a better indicator than climatic variables alone, as it integrates the effects of temperature and precipitation on NPP and decomposition and reflects erosional and depositional processes which influence spatial distribution of soil types