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Global soil organic carbon assessment

Uta Stockmann [a,*], José Padarian [a], Alex McBratney [a], Budiman Minasny [a], Delphine de Brogniez [b,c], Luca Montanarella [b], Suk Young Hong [d], Barry G. Rawlins [e], Damien J. Field [a]

[a] Soil Security Laboratory, Faculty of Agriculture and Environment, The University of Sydney, Australian Technology Park, Eveleigh, Biomedical Building C81, Suite 401, 1 Central Avenue, NSW 2015, Australia
[b] Joint Research Centre of the European Commission, Institute for Environment and Sustainability, via E. Fermi 2749, 21027 Ispra, VA, Italy
[c] Georges Lemaître Centre for Earth and Climate Research, Earth and Life Institute, Faculty of Sciences, Université Catholique de Louvain, 3 Place Louis Pasteur, 1348 Louvain-la-Neuve, Belgium
[d] National Academy of Agricultural Science (NAAS), Rural Development Administration (RDA), Wanju 55365, Jeonbuk, South Korea
[e] British Geological Survey, Keyworth, Nottingham NG12 5GG, England

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ABSTRACT

Soil carbon is a key component of functional ecosystems and crucial for food, soil, water and energy security. Climate change and altered land-use are having a great impact on soils. The influence of these factors creates a dynamic feedback between soil and the environment. There is a crucial need to evaluate the responses of soil to global environmental change at large spatial scales that occur along natural environmental gradients over decadal timescales. This work provides a suite of new data on global soil change which will uniquely utilize the world's prior investment in soil data infrastructure. Here we attempt a comprehensive global space–time assessment of soil carbon dynamics in different ecoregions of the world accounting for impacts of climate change and other environmental factors.

1. Introduction

By declaring 2015 as the International Year of Soils the United Nations General Assembly (A/RES/68/232) has recognized the major importance of the soil resource for human life and the need to maintain it for future generations. The intention underpinning this proclamation is to increase people's understanding about the important role of soil for food security through agricultural production, and the essential ecosystem functions that soil fulfils. In part, this has focussed the global agenda on understanding the effect land-use change has on soil properties and functions (Bouma and McBratney, 2013) as well as quantifying the relative impacts of climate change, including changes in temperature and rainfall patterns (Lal, 2004; Milly and Shmakin, 2002; Tao et al., 2003). To achieve this the current condition of global soil needs to be assessed (ITPS, 2015).

Understanding the biological, ecological, chemical and physical processes governing soil functions globally is directly related to most of the grand challenges in environmental science which have been outlined by the US National Academies of Sciences in 2010 (NRC, 2010). Because of the inherently long-term nature of soil change, addressing these questions requires empirical soil information collected over decades. In 1997, Trumbore (1997) recommended this course, i.e. to work on the evaluation of the response of soils to global environmental change at large scales that occur along natural environmental gradients over decadal timescales.

While there is a myriad of equally important soil indicators that could be used to gauge any substantial changes to soils, that may indicate greater potential degradation, the selection of such indicators needs 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. The quantity of soil organic carbon (SOC) seems the obvious choice as it 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 carbon itself is known to the global population (Karlen et al., 2001; Koch et al., 2013). More specifically, this choice stems from the known benefits of SOC for improved soil fertility and productivity and its contribution to food security which has been discussed widely within the *Soil Quality* concept (Andrews et al., 2004) and more

* Corresponding author.

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recently within the wider *Soil Security* framework (McBratney et al., 2014a).

Over the past decades, there have been significant efforts to collect soil profile data around the globe to estimate the amount of SOC stocks worldwide. Such assessments have large uncertainties associated with them; for example Stockmann et al. (2013) discussed that global estimates of the size of the organic carbon pool to 1 m depth vary between 1463 and 2011 Gt C. The variation in these estimates could relate to measurements based on differing spatial data-sets, which consist of various sample sizes, but may also reflect data collected at different times. Moreover, these estimates only provide the total SOC stock at a particular time and do not indicate its temporal trend. A better understanding of global SOC estimates which incorporates an analysis of those factors that lead to changes over time is therefore warranted. Although efforts have been made globally to map the current state of soils or baseline levels of soil properties including SOC concentration, these have not reported any temporal trends (e.g. *GlobalSoilMap* project (Arrouays et al., 2014; Sanchez et al., 2009) and its offshoot *SoilGrids*1 *km* (Hengl et al., 2014) or the baseline SOC maps of Australia (Viscarra Rossel et al., 2014), Denmark (Adhikari et al., 2014), France (Meersmans et al., 2012) and the U.S. (Odgers et al., 2012)). Furthermore, any time-series soil carbon data are mostly available for a range of field trials; they are limited, however, as they only cover selected soils with defined management practices (e.g. Guo and Gifford, 2002; Sanderman and Baldock, 2010), or have been investigated at the national level (e.g. Bellamy et al., 2005; Chapman et al., 2013; Fantappiè et al., 2010; Reynolds et al., 2013). Currently, there is no global dataset that covers the whole range of spatio-temporal variation of environmental landscape conditions with different land uses and soil types.

In this work we gathered a suite of new soil profile 'time series' data on global soil change which will utilize the world's prior investment in soil data infrastructure assembled over the past half-century and beyond. Ultimately, our aim is to provide a comprehensive global space-time assessment of soil carbon dynamics for different biomes and ecozones of the world accounting for the impacts of climate change and other environmental factors. The analysis of these data could contribute to the design of a global SOC monitoring network, for ongoing measurement and provision of early-warning signals highlighting where the ability of the soil to perform a range of functions may be lost.

2. Global SOC assessment in space and time imperative for food security

Assessing SOC contents globally in space and time is of significance as this soil property is a vital indicator for evaluating soil condition. Over the years research has demonstrated that the maintenance of SOC concentrations is strongly linked to biological activity and agricultural productivity (Stockmann et al., 2013). Maintaining SOC contents above critical limits for specific ecological and climatic zones will help to protect soil resources and maintain crop yields thus contributing to global food security (Bouma and McBratney, 2013).

It has been suggested that where SOC concentrations are reduced below some critical limit, soil nutrient and water holding capacity will be impeded and physical degradation is likely to occur through fragmentation of soil aggregates and increased susceptibility to soil surface crusting and erosion (Amundson et al., 2015).

Various studies have found empirical critical values for SOC concentrations. A study by Aune and Lal (1997) showed that in tropical regions where SOC concentrations fall below 1.1%, crop yields are reduced by 20%. By contrast, Loveland and Webb (2003) reviewed the evidence for a critical value of 2% SOC for soils in temperate regions and reported that the quantitative evidence for such a threshold was slight, although there was evidence for a desirable range of SOC concentrations. Zvomuya et al. (2008) reported that a SOC content of 2% SOC was important for the productivity of soils. Work by Yan et al. (2000) identified a critical limit of SOC of 1.0% below which soil microbial diversity declined linearly. Hassink (1997) suggested that the capacity of soils to preserve SOC is dependent on its association with clay and fine-silt particles. Furthermore, Stockmann et al. (2013) proposed that a critical limit as well as an upper limit of SOC where SOC is saturated is related to the soil's texture (i.e. the amount of clay, silt and sand) in addition to other environmental factors. For example, based on the literature it was posited that a critical concentration of SOC (%) may be of $\sim 1.5k$ for sandy soils and $\sim 0.8k$ for clay rich soils, where k refers to a site or region-specific proportionality constant that depends on a variety of interacting environmental factors including climate and landuse. Such notional critical and saturation levels of SOC could have practical implications by guiding farmers to maintain sufficient organic matter in their soils to ensure optimum productivity is maintained.

Research cited above confirms the necessity for identifying potential SOC deficits worldwide. Once the world soils fall under a certain critical limit, and once this tipping point is crossed, the soil resource has low resilience to recover and accumulate SOC to previous levels. There are a number of events in history that have demonstrated that misuse of the soil can lead to the destruction of the soil's fertility which can impact immensely on society. The 'dust bowl' that occurred in the 1930s in the US and Canadian prairies is such an example which demonstrates that the inappropriate use of agricultural practices can lead to severe agricultural damages and ecosystem failures (Montgomery, 2007a, 2007b). Studying the feedbacks between global and regional climate on the amount of terrestrial SOC including the role of land-use change is therefore of great importance (NRC, 2010).

Recently, Carvalhais et al. (2014) proposed a mean residence time of soil organic carbon of 23 years based on global soil profile data from the Harmonized World Soil Database. The authors took a simplistic approach by calculating the mean turnover time of C(T) through the ratio between carbon stored in vegetation (C_{plant}) and soils (C_{soils}), and the flux into this C storage (GPP):

$$T = \frac{(C_{plant} + C_{soil})}{GPP} \tag{1}$$

3. A global space–time assessment of SOC

Assessing the world's SOC concentrations spatially and temporally comes with a number of challenges, most of which will be addressed in the following.

3.1. Data collation for mapping SOC change

Within this work we focused on the collation and subsequent synthesisation of global historical and recent SOC profile data, sourced from regional, nationwide or global soil (test) databases (Table 1), including the time and depth of sampling, geographical location and analytical methods used.

In addition, where available we acquired additional basic soil property data, most importantly clay content and bulk density as this information is crucial to ultimately assess changes in SOC over time based on an equivalent mass approach (Ellert and Bettany, 1995; Ravindranath and Ostwald, 2008). Although very important,