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Increased uncertainty in soil carbon stock measurement with spatial scale and sampling profile depth in world grasslands: A systematic analysis

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ABSTRACT

There is an important need to better understand how the soil organic carbon (SOC) stocks affect the global atmospheric C balance. Grasslands represent 40% of the earth's land surface but efficiently and effectively quantifying their SOC stocks and their changes is a challenge. Although factors influencing the variability of grassland SOC stocks such as climate, management, or topography have been investigated, very few studies have quantified the uncertainty of SOC stock measurement. Quantifying this uncertainty is critical to determine our ability to detect changes in space or time, and ultimately to develop guidance to help designing appropriate measurement strategies for quantifying carbon stocks and stock changes. SOC stock measurement may be performed at various spatial scales, from local ($\leq$1 km^2) to broader scale ($\geq$100 km^2) applications. In addition, the recommended sampling depth for SOC measurement varies according to project purposes, national circumstances, and land use. To our knowledge, the assessment based on world literature of the effect of spatial scale (i.e. size of the measured area) and sampling depth on the uncertainty of SOC stock measurement in grasslands has never been performed. We quantified the uncertainty of SOC stock measurement from a global analysis of 51 research articles meeting strict requirements of rigour of SOC measurements, totaling 177 grasslands from 19 countries, to assess the effects of the spatial scale and the sampling depth of soil profile on this uncertainty, and to explore the implications for SOC stock change detection involving future sampling.

We observed that spatial scale and soil profile depth combined to explain 44% of the variability of SOC stock uncertainty, as measured by the coefficient of variation (CV). More specifically, the CV increased with the spatial scale and soil profile depth measured. However, the sampling depth effect is less certain due to lack of data at deeper depths. This uncertainty associated with SOC stock measurements has ramifications for SOC stock change detection. For example, at a fixed 0–30 cm soil profile depth, the minimum detectable change (MDC) of SOC stocks between two sampling dates (50 samples) was 14, 20 and 29% at 0.1, 10 and 10 000 km^2, respectively. At a fixed spatial scale of 0.1 km^2, the MDC was 12, 14 and 18% for soil profiles of 0–10, 0–30 and 0–100 cm, respectively. Finally, this study provides global estimates of the uncertainty that will be useful for planning sampling strategies for SOC stock measurement in various projects across the world and to evaluate the feasibility of SOC stock measurement for different investment levels and timescales.

1. Introduction

Soil organic matter is important for soil fertility and productivity through its effects on physical, biological and chemical properties (Stevenson, 1994). In addition, in the context of climate change, there has been an increasing recent interest in estimating soil organic carbon (SOC) as a change of soil carbon stocks affects the rate of accumulation of atmospheric carbon dioxide (CO_2) (Janzen, 2004). As the SOC pool is about two times larger than the atmospheric pool (Falloon et al., 2009), a relatively small increase of SOC could significantly offset the rising of atmospheric CO_2 (Fontaine et al., 2004). Consequently, it becomes essential to precisely measure SOC stocks under various soil and climatic situations in order to detect and account for changes.

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Grasslands represent about 40% of the earth's land surface after excluding areas of permanent ice cover (Wang and Fang, 2009), and their soils include nearly 30% of terrestrial soil carbon stocks (Janzen, 2004). There are generally two main climatic divisions of natural grasslands in the world: tropical and temperate (Coupland, 2009). This article includes also cultural grasslands, defined as grasslands primarily planted and maintained for agricultural reasons (Dixon et al., 2014). The spatial variability of SOC stocks is generally greater in grasslands than arable lands (Goidts et al., 2009a; Soussana et al., 2010). This variability is probably linked to the diversity of soils, plant communities, topography, and management factors (grazing regime, exposure to fire, fertilization, biomass harvest, etc.). These factors result in underlying soil variability, in terms of SOC concentration, soil bulk density, and consequently on SOC stock. In addition, carbon change measured in grasslands usually represents small values, as evidenced by the net carbon balance of $0.15 \pm 0.07\,\mathrm{Mg\,C\,ha^{-1}\,year^{-1}}$ estimated by Chang et al. (2015) for European grasslands or by the carbon sequestration potential of 0.1 to $0.9\,\mathrm{Mg\,C\,ha^{-1}\,yr^{-1}}$ measured for managed grasslands in the United States over a 20-yr period of changing management (Ogle et al., 2004). For all these reasons, efficiently and effectively quantifying SOC stocks and their changes in grasslands is a challenge.

Factors influencing the variability of grassland SOC stocks such as climate, management, or topography have been well studied (Allen et al., 2010). However, very few studies have aimed at actually quantifying the uncertainty of SOC stock measurement. Quantifying this uncertainty is critical to appreciate the confidence of the results (Goidts et al., 2009a), to determine our ability to detect changes in space or time, and ultimately to develop guidance to help designing appropriate measurement strategies for quantifying carbon stocks and stock changes. These appropriate measurement strategies are necessary to adequately measure soil carbon and to properly account for changes in national inventories and carbon trading systems. In addition, the uncertainty of SOC measurement affects the fulfillment of national and international carbon policy, the success of emission trading schemes, and validation of modelled SOC changes (Jones, 2010).

SOC stock measurement needs vary from local scales ($\leq 1\,\mathrm{km^2}$), such as projects-based C sequestration efforts undertaken by private landowners or cooperatives, to broader scale ($\geq 100\,\mathrm{km^2}$) applications, such as national-level greenhouse gas inventories and design of government policies (Conant and Paustian, 2002). It is generally assumed that the uncertainty increases with the size of the measured area (Boone et al., 1999), due to the increase in spatial variability. However, only few studies have actually quantified the uncertainty of SOC stock measurement at different scales in grasslands, croplands, and forests (Conant and Paustian, 2002; Saby et al., 2008; Goidts et al., 2009a). To our knowledge, the assessment of the effect of the spatial scale (i.e. the size of the measured area) on the uncertainty of SOC stock measurement has never been performed globally. In addition, the sampling depth recommended for SOC measurement varies according to project purposes, institutional preferences, land uses; for example from 0 to 30 to 0–90 cm in pasture soils of New Zealand (Tate et al., 2005; Schipper et al., 2014) and from 0 to 6 to 0–30 cm in some North American regional SOC sequestration rate studies (Olson and Al-Kaisi, 2015). The Intergovernmental Panel on Climate Change (IPCC) recommends sampling to 30-cm (IPCC, 2003). In most soil inventory studies, soils are sampled down to 30 cm, although the SOC content in the upper mineral soil would not be an accurate estimator of the total SOC content as a large part of C could be stored in the subsoil (Jandl et al., 2014). In this context, it is relevant to examine if the uncertainty of SOC measurement is influenced by the soil profile depth. Some studies reported a larger uncertainty of SOC for deeper layers than for surface layers in cultivated soils (Gregorich et al., 1995; Necpalova et al., 2014). However, as far as we know, the uncertainty of SOC stock measurement associated to the sampling depth for grassland soils has never been quantified globally.

The overall objective of our work was to quantify the uncertainty of SOC stock measurement from a large worldwide pool of grasslands, to assess the effects of the spatial scale and the sampling depth of soil profile on this uncertainty and to explore the implications for SOC stock change detection with future sampling.

2. Material and methods

2.1. Literature search and study selection

We searched the literature published up to early November 2014 using two bibliographic databases: CAB Abstract and Scopus. Specific keywords describing heterogeneous land-uses (*grassland*; *prairie*; *savanna*; *shrubland*; *scrubland*; *pasture*; *rangeland*; *dehesa*; *grazing*; *steppe*; *pampa*; *ilano,ilanos*; *cerrados*; *veld*; *meadow*; *alley cropping*; *agroforestry*; *shelterbelt*; *windbreak*; *berry*; *vineyard*; *orchard*; *perennial forage*; *perennial crop*; *toposequence*; *catena*; *soil landscape*; *soil type*; *landform*; *terrain*; *field scale*; *spatial variability*); soil carbon (*soil carbon stock*; *soil carbon concentration*; *soil carbon density*; *soil carbon content*; *soil carbon amount*; *soil carbon estimate*; *soil carbon measurement*; *soil carbon quantity*; *soil carbon pool*; *soil carbon sequestration*; *soil carbon accumulation*; *soil carbon storage*; *soil carbon change*) and measurement type (*measurement type*; *monitoring*; *survey*; *inventorying).* The research was limited to articles in English or French languages. From 2039 articles obtained from these bibliographic databases; we selected those which met the following criteria:

- Grasslands, pastures, rangelands or shrublands were considered in the analysis (and named "grasslands" in this article).
- Experiments included direct soil sampling with determination of SOC stock.
- The SOC stocks ($\mathrm{Mg\,C\,ha^{-1}}$) and their associated measure of variability or error (standard deviation or error) were available for each grassland. The SOC stock was the average of samples collected for SOC measurement. We included studies where the sample was for a single physical soil profile and studies where the sample was the single SOC value for physically mixed subsamples from several physical soil profiles.
- The spatial scale was available or the information sufficient to estimate it properly. This spatial scale corresponded to the grassland area ($\mathrm{km^2}$) from which samples for SOC measurement were collected. We excluded grasslands where SOC stocks represented the mean of replications in randomized experimental designs or paired plots, as the grassland area was not clearly definable for these designs (i.e. uncertain reference area lies between area of experimental unit measured and whole experimental area).

The published studies included in the analysis are presented in Table 1.

2.2. Collected data

Soil C stocks and their associated measures of variability (standard deviation or error) were collected for available soil profiles. There were some cases with more than one soil profile per grassland that corresponded to different depths (for example, 0–5, 0–10 and 0–30 cm etc.) (Table 1). We did not compute stocks and errors for new soil profiles from intermediate available soil layers (for example, 5–10 cm) to prevent biases caused by the recalculation of errors. The DataThief software (Tummers and van der Laan,