Catena 144 (2016) 94–101

Contents lists available at ScienceDirect

Catena

journal homepage: www.elsevier.com/locate/catena

Methods of evaluating soil bulk density: Impact on estimating large scale soil organic carbon storage

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ARTICLE INFO

Article history:
Received 23 June 2015
Received in revised form 28 April 2016
Accepted 2 May 2016
Available online 21 May 2016

Keywords:
Soil organic carbon
Pedo-transfer functions
Mean
Median
Bulk density
Soil type

ABSTRACT

Bulk density (BD) is one of the most important parameters used to calculate soil organic carbon (SOC) storage. Differences in the methods available to substitute missing BD data, including mean, median, and pedo-transfer functions (PTFs), are considered the main reason for the high uncertainty in SOC storage estimations at large scales. In this study, we used the measured BD and SOC contents of 1007 soil profiles to evaluate the accuracy of six BD substitution methods (two mean methods, a median method, and three PTFs). The results showed that PTFs underestimated SOC storage by 8% in the 0–20 cm soil layer, while mean and median methods overestimated SOC storage by 45% and 51%, respectively. Furthermore, the accuracy of PTFs estimates decreased with increasing soil depth. Relative to the measured values, and based on mean errors, root mean square errors, and method efficiency, the PFTs estimates were more accurate than those of the mean and median methods. Estimation bias increased with increasing SOC content for all methods, but differed among different soil types. The results of this study demonstrate that PTFs provide more accurate estimates of SOC storage when the extent of missing BD is substantial. Furthermore, the results provide new insights into establishing optimized PTFs, which contain more soil properties and piecewise functions of SOC content, in order to improve SOC storage estimates at large scales.

1. Introduction

Bulk density (BD) is the ratio of the mass to the bulk or macroscopic volume of soil particles, including soil pores (Blake, 1965). As a basic physical property of soil, BD not only affects the availability of soil moisture and nutrients, but also indirectly reflects soil quality and productivity (Reichert et al., 2009; Sequeira et al., 2014). Furthermore, BD is one of the most important parameters used to calculate soil organic carbon (SOC) storage; and the differences in the selected methods used to substitute for missing BD have been considered one of the main reasons for high uncertainty in SOC storage estimates at a regional scale (Benites et al., 2007; Dawson and Smith, 2007; Wiesmeier et al., 2012; Xu et al., 2015).

It is common for BD to be severely lacking in soil databases, especially at a large scale. Therefore, substitutes for missing BD data have been widely used to estimate SOC storage at regional or global scales. Although field measurements using the classical steel cylinder method are simple to perform for surface soil or at site scale, measurements of BD in 0–100 cm soil profiles across large scales are difficult, time-consuming, and expensive, especially in deeper soil layers and in soils that are rich in roots, stones, and sands (Brahim et al., 2012; Heuscher et al., 2005; Sequeira et al., 2014). To compensate for missing BD data, past studies have developed effective substitution methods, primarily using the mean or median BD values in a database (Batjes, 1996; Ma et al., 2016; Milne et al., 2007; Wang et al., 2001; Wen and He, 2016), or using pedo-transfer functions (PTFs), established based on the relationships between BD and the physical and chemical properties of the soil (Brahim et al., 2012; Heuscher et al., 2005; Kaur et al., 2002). While these substitution methods allow us to estimate SOC storage at regional or global scales, they also introduce uncertainty into the results. For example, using the same data source (Second National Soil Survey in China; SNSSC), the estimated values of SOC storage have ranged from 7.8 to 10.3 kg C m^{-2} in Chinese terrestrial ecosystems under different BD substitution approaches (Wang et al., 2004; Xie et al., 2007; Yang et al., 2007; Yu et al., 2007; Xu et al., 2015).

A number of studies that focused on the influence of BD on SOC storage estimations have emphasized the importance of optimizing PTFs (De Vos et al., 2005; Wiesmeier et al., 2012). However, few studies have focused on the effects of BD substitution methods at large scales, and the accuracy of the different methods (e.g., mean, median, and PTFs) is not clear. In this study, 1007 soil profiles, containing complete information on soil depth, SOC content, and BD from the SNSSC, were

Abbreviations: BD, bulk density; PTFs, pedo-transfer functions; SOC, soil organic carbon; SOM, soil organic matter; SNSSC, second national soil survey in China; MA, method accuracy; ME, mean errors; RMSE, root mean square errors; EF, efficiency.

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http://dx.doi.org/10.1016/j.catena.2016.05.001
0341-8162/

used to quantitatively evaluate the accuracy of SOC storage estimated from different BD substitution methods. Furthermore, we explored how the accuracy of BD substitution methods varied for different soil types, soil depths, and SOC contents.

2. Methodology

2.1. Data source

The data used in this study were sourced from Second National Soil Survey in China (SNSSC), including geographic locations, soil thicknesses, soil type, and the contents of soil organic matter (SOM) and BD. >50% of the SOC storage distributed in the first meter (Jobbágy and Jackson, 2000), and most past studies have estimated SOC storage to be at a depth of 100 cm; therefore, we chose 1007 soil profiles to evaluate SOC storage in 0–100 cm soil layers (Fig. 1). For soil profiles of <100 cm, we used the observed depth; while for soil profiles ≥100 cm, we extracted data down to 100 cm to estimate SOC storage. For each profile, the measured data on BD and SOC content were available for each soil layer. Based on the national standards of China (GB/T 17296-2009), Chinese soils are divided into twelve types (*ferrallisols*, *alfisols*, *semi-alfisols*, *pedocals*, *aridisols*, *desert* soils, *amorphic* soil, *aqueous* soils, *semi-aqueous* soils, *alkali-saline* soils, *anthrosols*, and *alpine* soils); furthermore, we offered a cross-reference table (Table S1) relating Genetic Soil Classification of China with World Reference Base (Shi et al., 2010; Zhang et al., 2014). *Desert* soils, *aridisols*, and *alpine* soils were not considered in this study due to the limitations of data in SOC content and BD.

2.2. Calculating BD and SOC storages

2.2.1. Method selection for substituting missing BD data

Six methods were selected to estimate BD (M1–M6; Table 1). M1 and M2 used the mean of measured BD at the levels of soil group and order, respectively (Wang et al., 2000; Zhou et al., 2003; Chai and He, 2016). M3 estimated BD using the median of measured BD at the soil order (Chai and He, 2016). M4, M5, and M6 estimated BD by establishing PTFs based on the relationships between BD and soil properties. These equations have previously been used in estimating soil SOC storage in China (Song et al., 2005; Wu et al., 2003; Yang et al., 2007).

2.2.2. Calculating SOC storage

SOC storage (kg C m^{-2}) in the 0–100 cm soil profiles was calculated for each site using Eq. (1):

$$\text{SOC storage} = \sum_{i=1}^{n} SOC_i \times BD_i \times D_i \times (1-C_i) \div 100 \quad (1)$$

where, SOC_i, BD_i, D_i, and C_i represent SOC content (g kg^{-1}), soil bulk density (g cm^{-3}), soil depth (cm), and volume (%) of >2 mm fraction in soil layer *i*, respectively; and *n* is the number of soil layers. The value of SOC content were derived from SOM content using the traditional conversion factor of 1.72 on basis of the assumption that organic matter contain 58% organic carbon (Hollis et al., 2012).

2.2.3. Validation and comparison of SOC storage estimates

We used the actual SOC storage values (calculated using measured BD) to test the accuracy of the different methods. The slopes of fitting straight lines between the predicted and actual values were used to assess the accuracy of each method (Zhang et al., 2010). Theoretically, if the slope of fitting straight line was >1, SOC storage was overestimated, and vice versa. We used the relative accuracy (MA, %) to represent the precision of the different methods:

$$\text{MA} = \frac{L_i}{L_0} \times 100\% \quad (2)$$

where, L_i is the slope of fitting straight lines by the *i*th method ($i = 1, 2, 3, 4, 5, 6$), and L_0 is the slope of $y = x$.

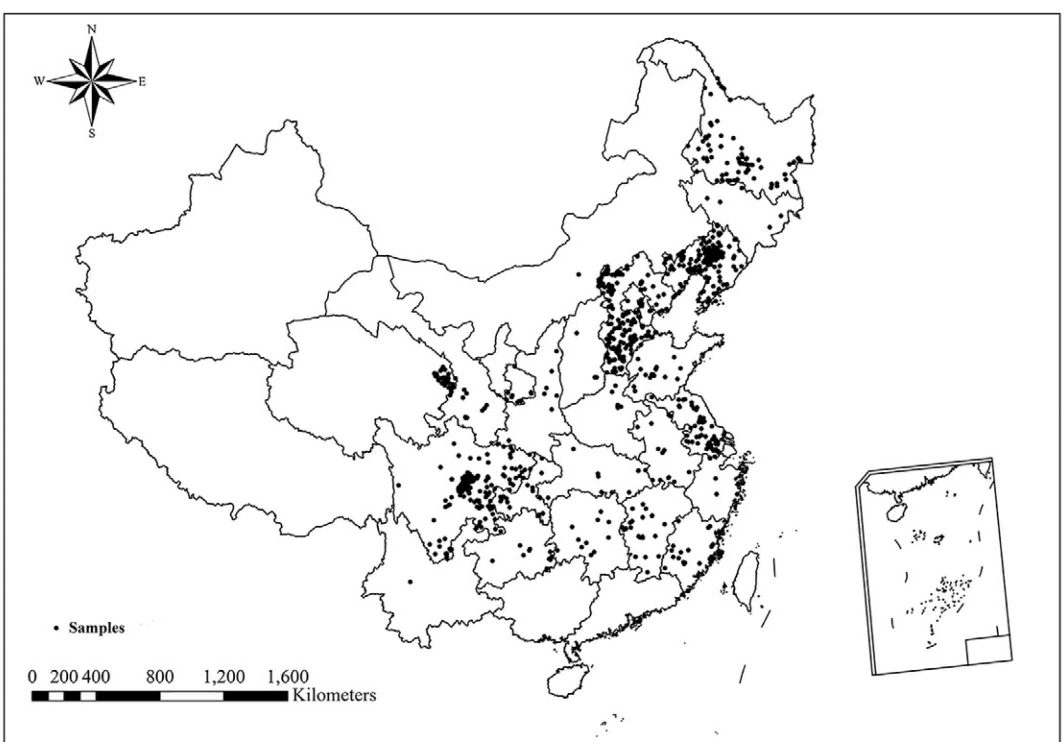

Fig. 1. Spatial distribution of sampling locations (black dots).