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When bulk density methods matter: Implications for estimating soil organic carbon pools in rocky soils

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ABSTRACT

Resolving uncertainty in the carbon cycle is paramount to refining climate predictions. Soil organic carbon (SOC) is a major component of terrestrial C pools, and accuracy of SOC estimates are only as good as the measurements and assumptions used to obtain them. Dryland soils account for a substantial portion of global SOC, but the pool dynamics are highly uncertain. One crucial component of accurate estimates of SOC on an areal basis is bulk density (ρ_b), the mass of soil per unit volume. Here, we review methods used for calculating ρ_b and assess their prevalence. We show how treatment of coarse fragments (particles >2 mm diameter) influences ρ_b values and discuss the implications for SOC estimates in drylands. In four dryland examples, methods that varied in their treatment of coarse fragments led to substantial (up to 26%) differences in ρ_b. Calculated SOC pools responded proportionally, with SOC differing by up to 518 g C m^{-2}. We suggest a revised method for accounting for coarse fractions in ρ_b calculations. A large portion of the world's soils, particularly in drylands, are fine enough to allow ρ_b determination with cores, but contain coarse fragments that substantially impact SOC mass estimates if not explicitly considered.

1. Introduction

Predictions of future climate and atmospheric chemistry depend, in part, on our understanding of the links between terrestrial and atmospheric carbon (C) pools. These predictions are hampered by uncertainties in inventories of current terrestrial C pools and sinks and how these might change in the future (King et al., 2007). One major component of this uncertainty is the size and dynamics of soil organic carbon (SOC) pools. This uncertainty in SOC pool dynamics is pronounced in dryland systems where low concentrations of SOC are offset by extensive geographic expanses (e.g., Aridisols alone account for approximately 10% of world SOC; Eswaran et al., 1993). Vegetation changes affecting the quantity and quality of organic matter inputs to soils magnify these uncertainties. For example, while woody plant encroachment into grasslands appears to account for a large portion of the terrestrial C sink in North American drylands; SOC responses to shrub and tree proliferation range from negative to neutral to positive, thus precluding robust generalizations (Barger et al., 2011). Better understanding of the SOC pool sizes and their response to changes in land use, land cover, and climate are critical for improving the predictive capability of climate models (Houghton, 2003; Johnston et al., 2004).

Inventories of SOC pools require careful and accurate ground-based measurements of SOC, as current remote sensing technologies cannot penetrate into soil pools (Johnston et al., 2004). One critical component of SOC measurements is bulk density (ρ_b, the oven-dry mass of soil per unit volume), which is necessary for converting measurements of SOC concentration (e.g., mg C g^{-1} soil) to an areal basis using units of area or volume (e.g., g C m^{-2} soil). Careful, spatially-intensive measurements of ρ_b are critical for accurate extrapolations, as ρ_b can be substantially altered by land use and land cover (Davidson and Ackerman, 1993; Don et al., 2011). For example, woody encroachment into drylands can cause strong spatial patterns in ρ_b that may contribute to high uncertainty in SOC responses to encroachment (Throop and Archer, 2008; Liu et al., 2010). In some situations, these changes in ρ_b may necessitate that SOC pool estimates be based on equivalent soil mass calculations (Lee et al., 2009).

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While ρ_b is a simple soil attribute widely assessed by ecologists, engineers, and soil scientists, minor differences in methods can substantially impact estimates of C or nutrient pool sizes. Here, we explore the implications of ρ_b methods on calculated SOC mass and the validity of areal SOC estimates when soils contain coarse (>2 mm) fragments. Although we focus our discussion of this topic on SOC pools, these same concepts are equally applicable for expressing concentrations of soil mineral nutrients or other compounds on an areal basis. The prevalence of coarse fragments in drylands (e.g., Fig. 1) makes this question particularly relevant in these systems.

1.1. Methods of bulk density determination

Direct measurements of ρ_b are typically performed with the excavation, clod, or core methods (Blake and Hartge, 1986; Elliott et al., 1999; Grossman and Reinsch, 2002). The excavation (or soil pit) and clod methods involve extraction of a sample followed by sample mass determination via weighing. Volume is determined by filling the void left by the extracted sample with a known volume of water, sand, or foam (excavation method) or coating the clod or extracted sample with a water repellent substance (e.g., paraffin wax) and determining the volume via displacement (Blake and Hartge, 1986) or, more recently, three-dimensional laser scanning (Rossi et al., 2008). In contrast, the core method involves weighing a known volume of soil extracted with a corer. As an alternative to direct measurements of ρ_b, pedotransfer functions that estimate ρ_b based on organic matter content are used in some applications (De Vos et al., 2005), and gamma radiation can be used to assess bulk density *in situ* (Blake and Hartge, 1986).

The core method has become the favored ρ_b method for ecologists and is recommended in several of the most widely cited ecological methods books (Robertson et al., 1999; Sala et al., 2000). The core method has numerous advantages: soils collected for ρ_b can be used for chemical analyses, a relatively small area is impacted by sampling, it does not require sophisticated equipment, and the portability and ease of use facilitates collection of a large number of cores. Furthermore, since ρ_b can be spatially variable, collection of a large number of ρ_b samples enables development of predictive equations to quantify spatial patterns within a site (Throop and Archer, 2008). However, there are also drawbacks with the core method. The small volumes typically collected may not be representative of the site due to spatial variability; and accurate measurement of ρ_b must also take into account coarse fragments, which are major components of many soils (Fig. 1). Indeed, soils with coarse fragment contents >34% by volume require a very large soil volume for accurate assessment (Vincent and Chadwick, 1994). Furthermore, insertion of the corer can cause compaction and give misleading estimates of soil volume (Page-Dumroese et al., 1999). The dimensions of the soil corer may also restrict the size of coarse fragments that can be collected, as stones larger than the core diameter may be excluded, thus biasing ρ_b estimates. The presence of rocks or roots may restrict core insertion, even if they are smaller than the core diameter, necessitating that the corer be moved to another location for sampling and thus underestimating rock fragments (Flint and Childs, 1984).

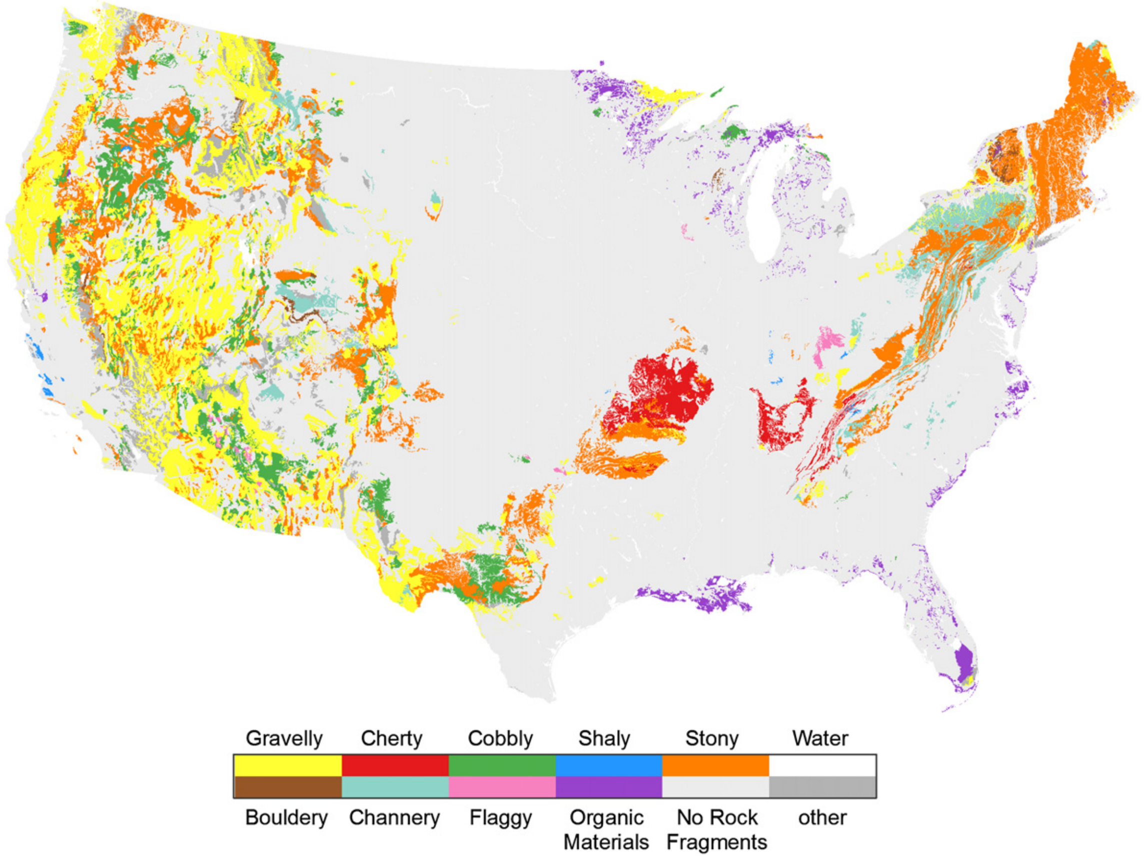

Fig. 1. Map of the conterminous United States showing locations of surface soils containing rock fragments, according to the CONUS-SOIL dataset (Miller and White, 1998, Map accessed at http://www.soilinfo.psu.edu/index.cgi?soil_data&conus&data_cov&rockfrag&image). The rock fragment categories are as defined by the USDA-NRCS Soil Survey Manuel (Soil Survey Staff, 1993, definitions of rock fragment categories available at http://www.soils.usda.gov/technical/manual/contents/chapter3.html#table3-11).

1.2. Variations in core method influence ρ_b calculations

Methods for calculating ρ_b using the core method vary considerably. Robertson and Paul (2000) suggest sieving and excluding coarse fraction (>2 mm) particles and using only the mass and volume of the fine earth fraction (<2 mm particles) in calculations. This method (hereafter "ρ_{FE}") is preferred in many soil survey programs (e.g., US Department of Agriculture, Grossman and Reinsch, 2002). In contrast, other authors do not suggest separating fine earth and coarse fractions and instead calculate ρ_b using the mass of all material in the entire core volume (hereafter "ρ_{core}") (Blake and Hartge, 1986; Elliott et al., 1999).

The measurement technique used may have dramatic implications for calculating carbon mass in soils. With the ρ_{FE} method, removing the mass and volume of coarse fragments replaces any volume of coarse fragments with fine earth in the ρ_b calculations. This method is a logical choice if soils contain no coarse fragments, or when the central question pertains to the inherent properties of the fine earth itself. However, when the focus is on quantifying SOC or nutrient pools, the question goes beyond the inherent properties of the fine earth fraction to include the properties of the coarse fragments within a particular volume of material. In this context, ρ_{core} accounts for the entire core volume, but effectively dilutes the amount of fine earth (<2 mm particle size fraction) present, as fine earth and coarse fragments are neither differentiated nor explicitly accounted for.

An alternative hybrid method is to calculate ρ_b using the mass of the fine earth (<2 mm particle size fraction) component of the sample and the volume of the entire core (hereafter 'ρ_{hybrid}') (e.g., Throop and Archer, 2008). Alternatively, a correction for the volumetric contribution of coarse fragments can be applied to either ρ_{core} or ρ_{FE} during SOC calculations (e.g., Bliss et al., 1995). Including the fine earth mass and excluding the coarse fraction mass is an appropriate choice when measuring properties relevant to the fine earth fraction only (e.g., in the case of a core containing pebbles and rocks, SOC is measured for the fine earth fraction only, as little or no SOC is associated with the coarse fraction). However, using the volume of the entire core rather than that of just the fine earth fraction accounts for displacement of fine earth by coarse fragments.

To illustrate the potential differences in calculated ρ_b among these three variations on the core method, we present a rather extreme example. Consider a soil in which (a) 50% of a 100 cm^3 core volume is occupied by coarse fragments, and (b) the masses of the fine earth and coarse fractions are 50 and 130 g, respectively. We obtain a ρ_{core} of 1.8 g cm^{-3} if the coarse fraction volume and mass is included. When subtracting coarse fraction volume and mass, ρ_{FE} is reduced by 44% to 1.0 g cm^{-3} ρ_{hybrid}, obtained by excluding coarse fraction mass but including the entire core volume, yields an even lower value of 0.5 g cm^{-3}. Assuming SOC of 15 mg C g^{-1} fine earth and a soil depth of 20 cm, we obtain area-based values of 5400 g C m^{-2} using ρ_{core}, 3000 g C m^{-2} using ρ_{FE}, and 1500 g C m^{-2} using ρ_{hybrid}. The true value in this example is closest to 1500 g C m^{-2}. Calculation of SOC based on ρ_{core} more than triples the amount of SOC calculated on an areal basis, as it does not consider that greater than two thirds of the mass is in the coarse fraction. Calculated SOC doubles with ρ_{FE} relative to ρ_{hybrid}, as it does not account for the volume displaced by coarse fragments.

We explored bulk density methods and their implications for SOC pool calculations by a) conducting a literature survey to determine what methods were most often used for ρ_b determination and b) quantifying the impact of the different core methods on estimates of SOC pools for soils collected from several dryland sites in the southwestern United States.

2. Methods

2.1. Literature survey

A literature survey was conducted to assess the most commonly used methods for ρ_b determination. We searched the ISI Web of Science database (Thomson Reuters, isiknowledge.com) using the search terms "soil organic carbon," "soil carbon," and "SOC" for years 1999–2008. Literature was limited to a subset of ecological and soil science journals (*Biogeochemistry, Biology and Fertility of Soils, Ecological Applications, Ecology, Ecosystems, Geoderma, Global Change Biology, Plant and Soil, Soil Science,* and *Soil Science Society of America Journal*), and total articles in this subset exceeded 1300. Articles in which ρ_b values were obtained from databases or previous studies were discarded, and no more than one article per senior author was used. From the articles meeting our search criteria, we selected 45 articles, covering the range of allowable journals and years, in which ρ_b was determined and used to calculate SOC on an areal basis (see Electronic Appendix A). Among studies using the core method, we noted how the coarse fraction mass and volume were treated. In many cases, authors simply stated that ρ_b was determined using the core method and did not specify if coarse and fine earth fractions were separated. In these instances we assumed the coarse fraction was not excluded and that ρ_b was based on ρ_{core}.

2.2. Field assessments

We explored the impact of the three variations of the core method on ρ_b values and subsequent estimates of SOC pools using well-replicated sampling from four dryland sites in the southwestern United States (Table 1). Core diameter and depth varied at the four sites (see Table 1); but in all cases core diameters were sufficiently larger than coarse fraction diameters so as not to restrict core insertion. For each core, the coarse fraction (primarily stones and pebbles) was separated from the fine earth fraction with a 2 mm sieve. Dry mass of each fraction was determined by drying for at least 48 h at 60 °C. The coarse fraction volume was determined via displacement of water in a graduated cylinder. Bulk density was calculated for each replicate core (n = 35–47 cores per site) using

Table 1
Properties of soils used to compare the effects of ρ_b methods on SOC estimates. Entries in the "Vegetation" column denote the dominant plants in the direct vicinity of core collection sites. Perennial grasses are present at all sites.

Site code	Location[a]	Core depth (cm)	Core diameter (cm)	Coarse fraction % of core volume (mean ± SE)	SOC (mg C g^{-1} soil)	Sample size (n)	Soil classification	Vegetation
A	JRN	9	5.70	0.05 ± 0.016	2.7	47	Ustic Haplocambid	Shrub (*Prosopis glandulosa* coppice dunes)
B	SRER	20	4.76	9.6 ± 0.52	4.2	36	Ustic Haplargid	Shrub (Mature *P. velutina)*
C	SRER	5	4.76	12.5 ± 0.59	9.3	36	Ustic Paleargid	Perennial grasses
D	SRER	5	4.76	13.4 ± 0.82	2.6	35	Ustic Haplargid	Perennial grasses

[a] JRN: Jornada Basin LTER, near Las Cruces, New Mexico, USA (32.5 °N, 106.8 °W); SRER: Santa Rita Experimental Range near Green Valley, Arizona, USA (31.8 °N; 110.8 °W).

the three methods reviewed in Section 1.2 (above). We then used the resulting ρ_b values to calculate SOC (g C m^{-2}) to 20 cm depth, based on fine earth fraction SOC (mg C g^{-1} fine earth) values obtained via dry combustion with an elemental analyzer (ECS4010, Costech Analytical Technologies, Valencia, CA).

3. Results

3.1. Literature survey

Our literature survey indicates that coring has clearly been the predominant method used for ρ_b determination since 1999 (43 of 45 papers; Electronic Appendix A). Other methods used were pedotransfer functions based on organic matter content (1 paper) and the compliant cavity method (an excavation technique, 1 paper). Of the 43 papers using the core method, the majority (32 papers) used ρ_{core} and did not appear to separate fine earth and coarse fractions when calculating ρ_b. A smaller group determined ρ_b on the fine earth fraction mass and volume only (ρ_{FE}; 8 papers). The least commonly used method was ρ_{hybrid} (3 papers) in which fine earth fraction mass and the entire core volume were used for calculations. An additional six papers calculated ρ_{core} using the proportion of coarse fragment volume to calculate SOC displacement, thereby effectively obtaining the same results as would be obtained with ρ_{hybrid}. Finally, two papers using ρ_{core} indicated that the coarse fraction was negligible at their sites and thus did not warrant inclusion in ρ_b calculations.

3.2. Field assessments

The extent to which these variations on the core method affected our field estimates of ρ_b and SOC mass varied widely among the four soils. On the sandy dune soil where coarse fraction content was negligible (0.05% of core volume), ρ_{FE}, ρ_{core}, and ρ_{hybrid} approaches yielded virtually identical estimates of ρ_b (Site A in Fig. 2a). On the other three soils, the ρ_{core} approach led to a 17–26% increase in ρ_b relative to ρ_{hybrid}; and use of ρ_{FE} led to a 11–17% increase in ρ_b relative to ρ_{hybrid}. SOC mass estimates were affected proportionately the same as ρ_b, with calculated SOC pools running 0.7–518 g C m^{-2} greater with ρ_{core} compared to ρ_{hybrid}; and running 0.5–284 g C m^{-2} greater with ρ_{FE} compared to ρ_{hybrid} (Fig. 2b). However, because area-based SOC estimates are a function of both ρ_b and SOC concentration, total differences in SOC pools among ρ_b methods will be greater on soils with high SOC concentration than they will be in soils with low SOC. For example, sites C and D were nearly identical in their coarse fragment content (12.5 and 13.4% by volume, respectively), but the higher SOC concentration on site C (9.3 mg C g^{-1} fine earth) propagated a greater range of calculated SOC pools than for the relatively low SOC concentration site D (2.6 mg C g^{-1} fine earth).

4. Discussion

4.1. Implications

Bulk density is a crucial soil property that influences infiltration rates, aeration, root proliferation, and plant growth. From an ecological accounting perspective, ρ_b is required for making mass-to-volume or area conversions and is thus critical for determining the size of SOC and mineral nutrient pools. Our survey of the literature indicates that the core method is, by far, the most widely used technique for estimating this important parameter. However, there are substantive variations on the core method. While the method used for calculating ρ_b from cores is of little consequence for soils with few or no coarse fragments, ρ_b and the resulting SOC mass estimates for soils with substantial coarse fragment content (e.g., many dryland soils, recent volcanic soils, glacial till, alluvial deposits; Fig. 1) can be strongly affected by the method used.

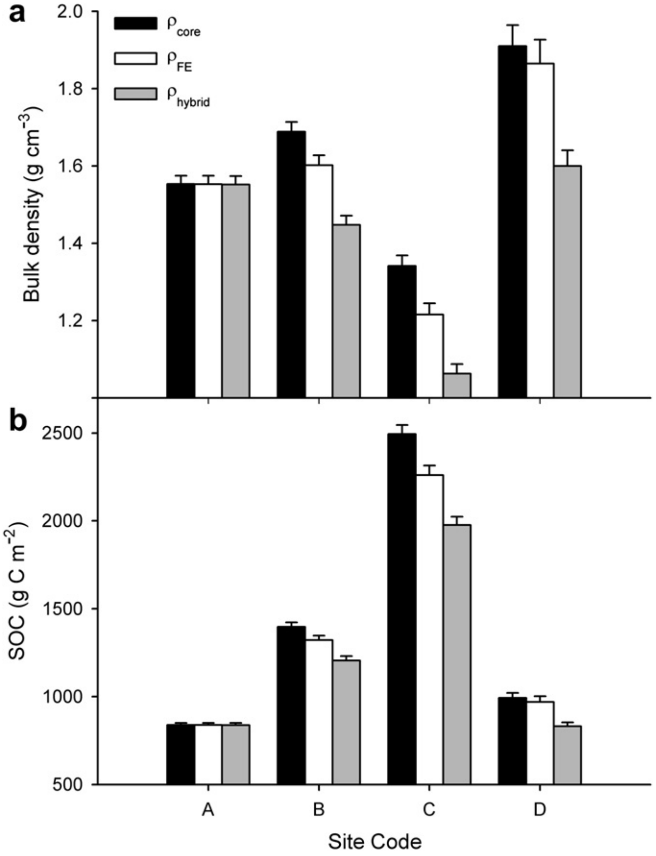

Fig. 2. (a) Calculated bulk density (g cm^{-3}); and (b) calculated SOC mass (g C m^{-2} to 20 cm depth) using bulk density values determined from three different methods [ρ_{core} = mass of entire core divided by entire core volume; ρ_{FE} = fine earth (<2 mm fraction) mass divided by fine earth volume; ρ_{hybrid} = fine earth mass divided by entire core volume]. The soils were collected from four different dryland soils in the southwestern United States (see Table 1 for site codes and details). Soils are arranged in order of increasing proportion of the core volume accounted for by coarse fragments. Values are means ± SE.

Despite the widespread adoption of the core method, it is important to recognize that under many circumstances this method is inappropriate regardless of the variation used, and researchers would do better selecting another method for ρ_b determination. The core method will under-sample coarse fragments when their diameter exceeds that of the corer, making the core method problematic for soils with large fragments (Andraski, 1991). The core method may also yield inaccurate results in soils where significant compaction occurs during corer insertion (Page-Dumroese et al., 1999). Indeed, compaction and disruption of cohesive strata can affect ρ_b even more than high proportions of coarse fragments (Andraski, 1991). Furthermore, of particular relevance to arid soils with a high shrink-swell potential, bulk density measurements can be affected by soil moisture content (McGarry and Malafant, 1987). Despite these limitations to the core method, the benefits of convenience, ease, and large number of samples that can be collected suggest that it will remain widely used.

There is typically a high degree of spatial heterogeneity on landscapes and watersheds where ρ_b calculations would be affected by rock fragments. For example, within the 48 conterminous United States, 33% of the area (primarily the Southwest and East-Central) is classified as having skeletal ($\geq$35% by volume rock content) soils (Fig. 3). In these areas, rock content may be too high for successful

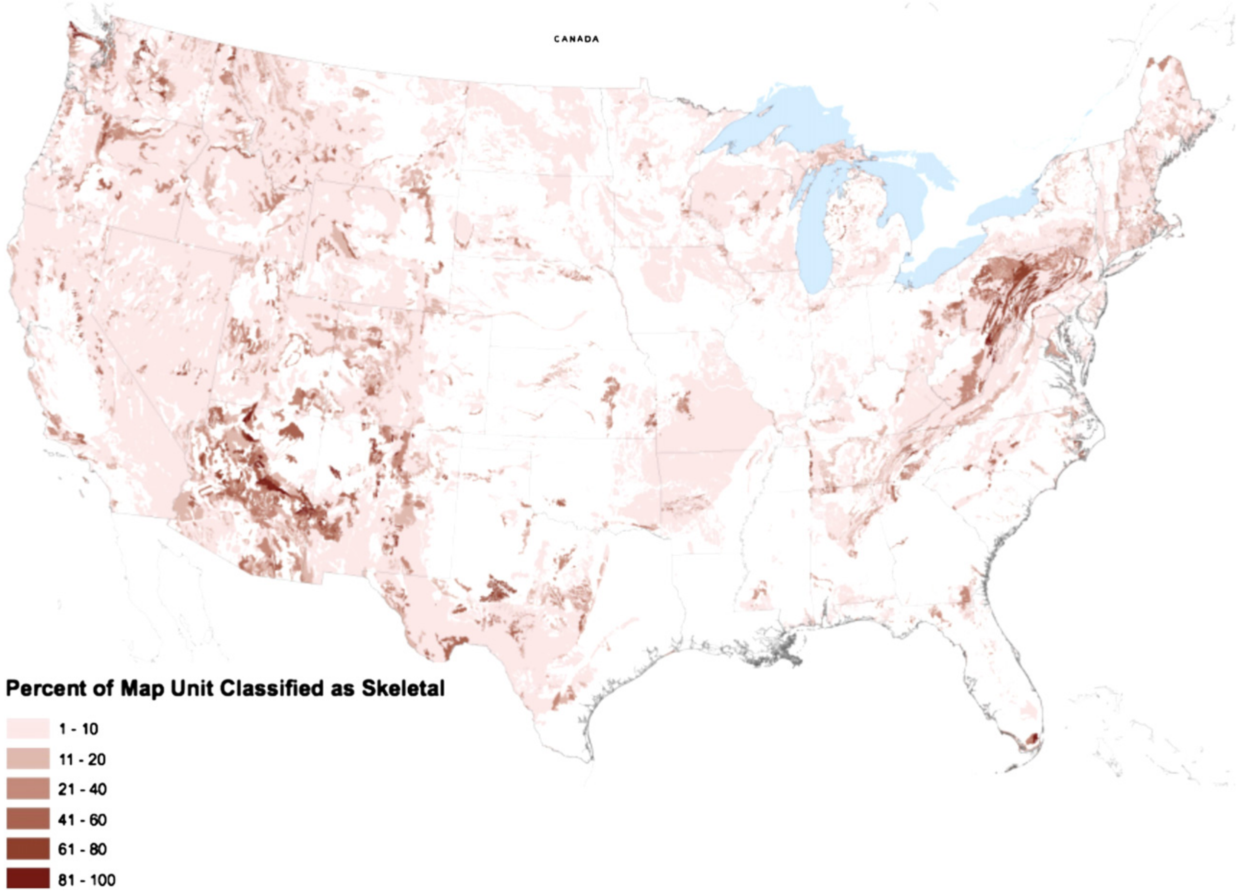

Fig. 3. Spatial distribution of skeletal soils in the United States. Values are the percent of STATSGO2 map units classified as "skeletal" ($\geq$35% but $<$ 90% rock fragment content by volume) (Soil Survey Staff, 2006, 2010).

ρ_b determination using soil cores. Many additional areas have low enough rock fragment content to allow successful coring, but would have great enough stone content to prevent accurate ρ_b determination. However, a large proportion of the United States drylands, including much of the Intermountain West, has only a small percentage of the area classified as skeletal (Fig. 3); and many of these areas would be appropriate for the core method.

Numerous factors are involved in current uncertainties in terrestrial C budgets (King et al., 2007). Some of these reflect inconsistencies in how C mass data are collected and expressed. In the case of SOC, substantial variation in pool sizes can result from methodological inconsistencies in estimating bulk density (Fig. 2). These inconsistencies are largely the result of differences in how coarse fragments are handled in bulk density calculations.

4.2. *Solutions*

How can the impact of coarse fragments on SOC calculations be minimized? We advocate a switch in standard practice for ρ_b calculations from ρ_{FE} and ρ_{core} to ρ_{hybrid}. This change would not affect SOC calculations for soils with small proportions of coarse fractions, but it would reduce chances of inflated SOC values. We see only two possible disadvantages of this switch in methods. First, ρ_{hybrid} determination is slightly more time-intensive than ρ_{core}, as soils must be sieved prior to weighing. However, considerably less time is needed to determine ρ_{hybrid} relative to ρ_{FE}, as it is not necessary to quantify the volume of coarse fragments. The second possible disadvantage of using the ρ_{hybrid} approach is that it may make comparisons with previous studies more problematic. However, because such comparisons are currently confounded by methodological inconsistencies, their value is questionable, regardless. Both issues could be resolved if a body of studies such as the one conducted here were to be initiated. Libraries of correction factors could then be developed for various soil types, which would enable ρ_b reported with one methodological variation to be converted to ρ_b based on other variations. Thus, comparative studies and meta-analyses could take reported ρ_b values and 'standardize' them (and the carbon and nutrient pool estimates derived from them) using the correction factors. In the meantime, we advocate that publications (*i*) explicitly articulate how coarse fragment mass and volume are treated in ρ_b calculations; and (*ii*) report the proportional volume of coarse fragments in their samples. These refinements will facilitate future comparisons among studies and would be a simple, but important, step toward minimizing the extent to which methodological issues affect C budget uncertainties.

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Appendix. Supplementary data

Supplementary data related to this article can be found online at doi:10.1016/j.jaridenv.2011.08.020.

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