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Bulk density calculation methods systematically alter estimates of soil organic carbon stocks in United States forests

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Abstract Soils are the largest terrestrial carbon sink on Earth, yet substantial uncertainty in the size and stability of this pool remains. Much of this uncertainty stems from the characterization of bulk density, which is the mass of a soil sample divided by its volume, a key property in the calculation of soil organic carbon (SOC) stocks. We used data from nearly 2900 plots in the United States (U.S.) Nationwide Forest Inventory to quantify SOC stocks in forests with three common methods of calculating soil bulk density. Mean SOC stocks calculated with these methods varied by up to 13 Mg ha^{-1}, a difference equivalent to more than 70 percent of the 2022 economy-wide carbon dioxide emissions in the U.S. when scaled across all forest area. These differences were primarily driven by inconsistent treatment of coarse materials (i.e. rocks and roots) in soil bulk density calculations, which led to an overestimation of SOC content by 32 percent of the mean SOC stock across all U.S. forests. The largest discrepancies were found in soils with high coarse fragment content, which are more common in ecologically sensitive ecosystems like alpine zones and drylands, and in commercially important softwood forest types. Quantifying the size and stability of SOC in the land sector is essential to understanding how this carbon pool may serve as a nature-based solution to climate change. Consistent and transparent methods are necessary when estimating and reporting SOC content and when comparing SOC dynamics across ecological gradients, with disturbance, and over time.

Keywords Soil carbon · Bulk density · Carbon cycle · National forest inventory

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Introduction

Forest ecosystems are the largest terrestrial carbon sink on Earth (Pan et al. 2011), and the two largest carbon pools in forests are soil and live tree biomass (Domke et al. 2024). Soil, in particular, constitutes over half of the total carbon stored in United States (U.S.) forests (Domke et al. 2017), meaning that even an incremental change in soil organic carbon (SOC) content can result in important shifts in the size of the land carbon sink (Batjes 2014). Further, while rates of carbon storage in live tree biomass may slow with forest age and stand development, soils have the capacity to continue accumulating carbon through inputs of woody debris, leaf and root litter, root exudation, and microbial necromass (Brown et al. 2024). However, quantifying the size of the forest carbon pool is challenging, and estimates vary widely (Sulman et al. 2018; Tifafi et al. 2018). One

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of the major sources of uncertainty stems from the conversion of tree and soil volume to carbon mass per unit area, a calculation that requires information about the density of the materials that constitute each pool (Doraisami et al. 2024; Mo et al. 2024). While live tree biomass carbon is often estimated with allometric models that rely on static estimates of wood density (Westfall et al. 2023; Doraisami et al. 2024), SOC content is generally determined using empirical measurements of soil bulk density (Al-Shammary et al. 2018).

Soil bulk density, the mass of a soil sample divided by its volume, is a key variable in the calculation of SOC stocks which is used to convert soil carbon concentrations to units of carbon mass per soil volume. Soil bulk density can be determined with a variety of sampling methods, ranging from full volumetric excavation of a soil layer, to measuring the mass and dimensions of individual soil clods (Harrison et al. 2003; Vadeboncoeur et al. 2012; Gross and Harrison 2018; Clancy et al. 2023). A common approach, however, is to determine the density of a cylindrical core sample collected at the soil surface (Walter et al. 2016). To calculate SOC stocks, the carbon concentration of the fine soil (<2 mm) within these core samples is generally determined by combustion and scaled to units of carbon per area using the soil bulk density and the dimensions of the coring device. Using the surface core approach, three distinct calculations of bulk density can be applied to calculate SOC stocks (Fig. 1a). These methods vary in their treatment of the coarse fragments (i.e. rocks and roots > 2 mm in diameter) present in most soil core samples (Throop et al. 2012). Each bulk density calculation method results in a different estimate of SOC stock, which must be interpreted in light of the calculation method used.

First, soil bulk density can be determined with the entire oven-dry mass of a soil core sample divided by the volume of the coring device (hereafter $Total_{BD}$). With this method, the mass and volume of the sample includes both fine soil and any coarse fragments contained therein. Using $Total_{BD}$ requires minimal information to calculate SOC stock because the entire core sample can be dried and weighed without extensive processing, and a single value of core volume is determined for all samples collected with a common device. In large inventories, such as the U.S. Nationwide Forest Inventory (NFI; Domke et al. 2017), this streamlined sample process is often used due to time and cost constraints. However, stocks calculated with $Total_{BD}$ can overestimate SOC when dense coarse fragments with low or no organic carbon (i.e. rocks) are present, as the soil carbon percentage is applied to the mass of these fragments as well as the soil material (Poeplau et al. 2017).

Several alternative bulk density calculations are commonly used to correct for SOC overestimation due to coarse fragment mass: first, the bulk density of only the fine soil (<2 mm) in the core (hereafter $Fine_{BD}$) can be determined by dividing the mass of the fine soil component by the volume of the fine soil component. Using $Fine_{BD}$, SOC stocks can be interpreted as the mass of carbon per volume of fine soil. Unless the core samples contain no coarse fragments, scaling this value over space results in an overestimation of the true SOC stock because it does not account for the volume of the soil matrix occupied by rocks and roots. In some soils, it may be necessary to use $Fine_{BD}$ to understand how SOC stocks vary across space and time due to large sample-to-sample variability in coarse fragment content, which can obscure patterns in SOC dynamics (Harrison et al. 2003; Fenton et al. 2024). This calculation is therefore most useful in studies comparing effects of experimental treatments or ecological gradients on the formation and retention of SOC (Jevon et al. 2019) or understanding changes in SOC content over time (Speckert et al. 2023).

Finally, using a method that borrows from both of the calculations above, known as the "hybrid" approach (Throop et al. 2012), the mass of fine soil is divided by the total volume of a soil core (hereafter $Hybrid_{BD}$). When using $Hybrid_{BD}$ to calculate SOC stocks, the resulting estimate scaled over an area represents the mass of carbon per unit area that is present in the soil matrix to a given depth. This metric is ideal for calculations of SOC stock on an areal basis, yet it is not always used in large-scale inventories because it is difficult to implement without sample-specific information about soil coarse fragment mass. Accurately quantifying $Hybrid_{BD}$ requires sieving each core to remove material > 2 mm in diameter, oven drying, and weighing the fine soil fraction of the sample.

Each of these methods of calculating bulk density may be desirable in particular situations, but given that they result in different estimates of SOC stocks across landscapes, the calculation method used in a dataset must be clearly defined for accurate interpretation of SOC content. The U.S. NFI conducted by the U.S. Department of Agriculture Forest Service Forest Inventory and Analysis program (https://research.fs.usda.gov/programs/nfi) provides a unique opportunity to link forest properties–including tree species composition, productivity, disturbance, and understory characteristics–to soil properties across the U.S. With over 10,000 co-located observations of soil and forest properties, the NFI database is a critical resource for estimating the carbon stored in U.S. forests. In this public-facing database, bulk density is reported as $Total_{BD}$, and coarse fragment percentage by mass is available for each sample (O'Neill et al. 2005; Forest Inventory and Analysis Program 2023).

To evaluate the effect of bulk density calculation method on the size of estimated SOC stocks in surface (0–20 cm) soils in forests across the continental US, we used SOC data collected as part of the U.S. NFI. Specifically, we (1) calculated SOC stocks using $Total_{BD}$, and adjusted this calculation to account for coarse material mass, as in $Hybrid_{BD}$, and volume, as in $Fine_{BD}$, (2) compared surface SOC stocks estimated using NFI data with each calculation method, and (3) evaluated SOC stock estimates calculated using $Hybrid_{BD}$ and $Fine_{BD}$ to quantify site and tree species effects on soil carbon stocks. This analysis represents the first continental-scale assessment of SOC stocks estimated with different bulk density calculation methods in forests of the US. These results highlight how methodological differences alone can substantively alter estimates of the largest terrestrial carbon pool in forests of the US. Thus, clearly defining sampling and calculation methods is critical to advancing measurement, monitoring, reporting, and verification activities which include soil carbon stocks and stock change estimation across space and over time.

Methods

We collated NFI data about forest composition and soil parameters from the publicly available datasets on the Forest Inventory and Analysis (FIA) program DataMart. The FIA program maintains the largest dataset of co-located observations of forest and soil attributes in the US, designed with a statistically robust sampling frame to accurately represent the diversity of forests across all U.S. states and territories (O'Neill et al. 2005). Using these data, we isolated forested plots for which soil and tree species data were available and combined these data with information about tree species composition, stem diameter, stand density, and biophysical parameters like elevation, slope, and broader ecosystem type. Using information about soil organic carbon concentration, oven-dried sample mass, coarse fragment mass, and soil corer volume, we calculated soil bulk density with three methods: $Total_{BD}$, $Hybrid_{BD}$, and $Fine_{BD}$, and applied these values to calculate soil organic carbon (SOC) stock in units of megagrams of SOC per hectare (Mg SOC ha^{-1}; Eq. 4, below).

We define the three bulk density calculation methods as follows:

$$Total_{BD} = \left(\frac{M_{sample}}{V_{core}}\right) \tag{1}$$

where M_{sample} is the mass of a whole soil core sample, including fine soil material (<2 mm) and coarse fragments (>2 mm), and V_{core} is the total interior volume of the coring device;

$$Fine_{BD} = \left(\frac{M_{finesoil}}{V_{core} - (M_{CF} \div 2.7)}\right) \tag{2}$$

where $M_{fine\ soil}$ is the mass of the fine material in the soil core sample, M_{CF} represents the mass of the coarse fragments in the soil core sample, and 2.7 indicates the standard value used to estimate the density of rocks near Earth's surface (2.7 g/cm^3; (Tenzer et al. 2011; Mehler et al. 2014).

And lastly, an approach combining the two above:

$$Hybrid_{BD} = \left(\frac{M_{finesoil}}{V_{core}}\right) \tag{3}$$

We then used bulk densities calculated with each method to estimate SOC stocks in soils from each plot in the NFI where soil information was available:

$$SOCstock = p(C) \times BD \times d \tag{4}$$

where p(C) is the proportion of organic C, by mass, in a subsample of fine material from a soil core sample, d is sample depth, and BD is bulk density.

To prepare these data for analyses of SOC stock, we first selected only plots containing at least one forested condition, and for which data from mineral soil cores at both sampling depths were available (i.e. MIN_1: 0–10.16 cm, and MIN_2: 10.16–20.32 cm). We excluded samples from Alaska, Hawaii, and outlying U.S. territories due to differences in sampling techniques necessary for the specific conditions in each site. We selected only samples collected using an impact-driven soil coring device (AMS Core Sampler Model #910) to allow us to manually calculate bulk density. Finally, we selected only the most recent sampling event for plots which have been sampled multiple times. Filtering on these criteria resulted in a total of 2898 plots for this analysis. We calculated the three bulk density values using a standard core volume of 361.9 cm^3, corresponding to the sum of the interior volume of the two core liners used in FIA soil sampling procedures for both soil depths.

We used simple linear regressions to examine how coarse fragment content and SOC stocks varied with elevation and latitude, in softwood vs. hardwood stands, and across ecosystem classes. While all plots included in the dataset are forested, they are located within landscape-scale ecosystem classifications, including forests ($n = 1237$), alpine zones ($n = 1026$), prairies ($n = 88$), and drylands ($n = 546$). Ecosystem classes were designated using the ecological subregions defined in McNab et al. (2007), which were further reduced to four major categories: forest, alpine, prairie, and drylands. Within each ecosystem class, we evaluated differences in bulk density and SOC stocks with linear mixed effects models, specifying bulk density calculation method as the fixed effect and plot as a random effect. Finally, we used linear regressions to examine relationships between coarse fragment content and SOC stocks in each ecosystem class.

Next, we performed simple linear regressions to examine differences in SOC stocks in different forest types. First, to separate the data into forest types relevant for management and ecological studies, we identified the 19 most abundant forest types in the NFI dataset, which together represented 80% of the plots with available data. Forest types were determined by selecting the tree species with the highest number of stems in each plot and assigning that species to the corresponding forest type group based on the designations in Table 60 A (available at https://www.fs.usda.gov/detailfull/r5/forest-grasslandhealth/?cid=fsbdev3_047974). We then combined forest types with similar functional and geographic characteristics (i.e. Southern pines), resulting in ten distinct major groups of forest composition across the continental US. Finally, we conducted a case study analysis to understand how bulk density methods can impact interpretation of ecological processes. Simulating the kind of analysis commonly performed for state-level forestry and inventory applications, we isolated data from high-elevation plots in Idaho dominated by either true fir (genus *Abies*) or Douglas fir (*Pseudotsuga menziesii*). Using two-sample t-tests, we compared how SOC stocks varied in plots of each forest type using both $Hybrid_{BD}$ and $Fine_{BD}$ to assess whether apparent tree species effects on SOC stocks vary depending on the bulk density calculation method.

Results and discussion

The mean estimated SOC stock in the top 20 cm of soil in the conterminous U.S. was 54.2 Mg/ha when calculated using $Total_{BD}$, 44.9 Mg/ha when calculated using $Fine_{BD}$, and 41.1 Mg/ha when calculated with $Hybrid_{BD}$ (Table 1). Variation in estimated stocks among these calculation methods was primarily driven by larger differences in bulk density in soils with high coarse fragment content (Fig. 1). Consequently, associations between coarse fragment content and forest properties resulted in correlations between SOC stocks and wood type (i.e. hardwood vs softwood; Fig. 1c), forest type (Fig. 2c), and the broader ecosystem classification (Fig. 1d). Further, the degree to which these factors influenced SOC stocks depended on the bulk density calculation method.

Patterns associated with geography, topography, and coarse fragment mass

All but ten soil cores used in this study contained coarse fragments (99.7%; $n = 2888$). Coarse fragment content ranged from 0 to 99.8% by mass, and was positively associated with both latitude ($F_{1, 2896} = 216.7$, $p < 0.001$) and elevation ($F_{1, 2796} = 868.9$, $p < 0.001$). Further, coarse fragment content varied systematically with the broader ecosystem in which the plots were located, decreasing

Table 1 Summary of bulk density and estimated SOC stock values for the conterminous United States (CONUS) and each of the four major ecosystem classifications in which the forest plots are located

	Ecosystem	$Total_{BD}$	$Hybrid_{BD}$	$Fine_{BD}$	LMM: F_{df}, p
	CONUS	1.23 ± 0.30	0.97 ± 0.37	1.06 ± 0.36	$F_{2,5794} = 2430.1$ $p < 0.001$
Bulk Density (g/cm^3) Mean ± SD	Forest	1.25 ± 0.26	1.12 ± 0.30	1.17 ± 0.28	$F_{2,2476} = 674.1$ $p < 0.001$
	Alpine	1.11 ± 0.33	0.73 ± 0.30	0.84 ± 0.34	$F_{2,2048} = 1836.3$ $p < 0.001$
	Prairie	1.36 ± 0.19	1.28 ± 0.22	1.32 ± 0.21	$F_{2,174} = 32.3$ $p = 0.070$
	Dryland	1.38 ± 0.28	1.03 ± 0.39	1.15 ± 0.37	$F_{2,1090} = 572.1$ $p < 0.001$
Estimated Carbon Stock ($Mg\ ha^{-1}$) Mean ± SD	CONUS	54.18 ± 36.58	41.10 ± 28.27	44.89 ± 29.94	$F_{2,5794} = 1301.0$ $p < 0.001$
	Forest	52.89 ± 35.30	45.89 ± 29.42	48.28 ± 30.78	$F_{2,2476} = 366.8$ $p < 0.001$
	Alpine	63.77 ± 40.03	41.42 ± 28.50	47.21 ± 30.88	$F_{2,2048} = 828.0$ $p < 0.001$
	Prairie	50.03 ± 24.88	47.10 ± 22.95	48.30 ± 23.44	$F_{2,174} = 23.6$ $p < 0.001$
	Dryland	39.74 ± 28.02	28.69 ± 21.42	32.32 ± 23.18	$F_{2,1090} = 343.3$ $p < 0.001$

Bulk density values and SOC stocks (Megagrams per hectare) represent the mean (± SD) value calculated with each of the three methods represented in Fig. 1a and summarized within each ecosystem type. Results of linear mixed-effects models (LMM) indicate significant differences between bulk density and SOC stock values calculated with each bulk density method, where individual plot was designated as a random effect

in the order alpine (mean 33.5% by mass) > drylands (26.2%) > forest (10.8%) > prairie (5.4%; $F_{3,\ 2893} = 325.3$, $p < 0.001$). Estimated SOC stocks calculated using $Total_{BD}$ increased by 79.9% across the range of coarse fragment content ($F_{1,\ 2896} = 136.8$, $p < 0.001$; Fig. 1b). Conversely, stocks calculated with $Hybrid_{BD}$ and $Fine_{BD}$ declined by 59.7% and 28.5% across the same range, respectively ($F_{1,\ 2896} = 132.9$, $p < 0.001$; $F_{1,\ 2896} = 26.9$, $p < 0.001$). This discrepancy is expected given that coarse fragments contribute to the sample mass in the $Total_{BD}$ model and not in either the $Hybrid_{BD}$ or $Fine_{BD}$ models, leading to overestimation of SOC stocks in samples containing coarse fragments. Further, lower SOC stocks over a given area (as with $Hybrid_{BD}$) would be expected with increasing coarse fragment content, as the soil mass will be displaced by rocks and coarse roots. However, decreasing SOC concentration in the fine soil fraction (as with $Fine_{BD}$) across this same range suggests an association between high rock content and factors that limit the formation or retention of SOC at the sub-continental scale. While this pattern is not universal in high-elevation regions (Johnson et al. 2012), it was broadly consistent across ecosystems with the highest soil rock content, including alpine zones ($F_{1,\ 1023} = 47.4$, $p < 0.001$) and drylands ($F_{1,\ 544} = 9.3$, $p = 0.002$; Table 1).

In contrast, we found that coarse fragment content was positively associated with SOC concentration in forests ($F_{1,\ 1237} = 11.1$, $p < 0.001$). These opposing patterns likely result from the generally higher coarse fragment content in alpine and dryland forests, where increases in an already large proportion of coarse material mass may limit tree growth and organic matter production. Conversely, in forest landscapes, greater coarse material mass may reflect more recent glaciation or slightly higher elevations, both of which are associated with lower temperatures, leading to slower decomposition and higher SOC content (Kobler et al. 2019; Zheng et al. 2021). The larger differences in SOC stocks calculated with different bulk density methods in alpine regions are particularly important given accelerated climate change impacts such as decreasing snowpack and rising temperatures in alpine forests (Chersich et al. 2015). Therefore, an accurate representation of the

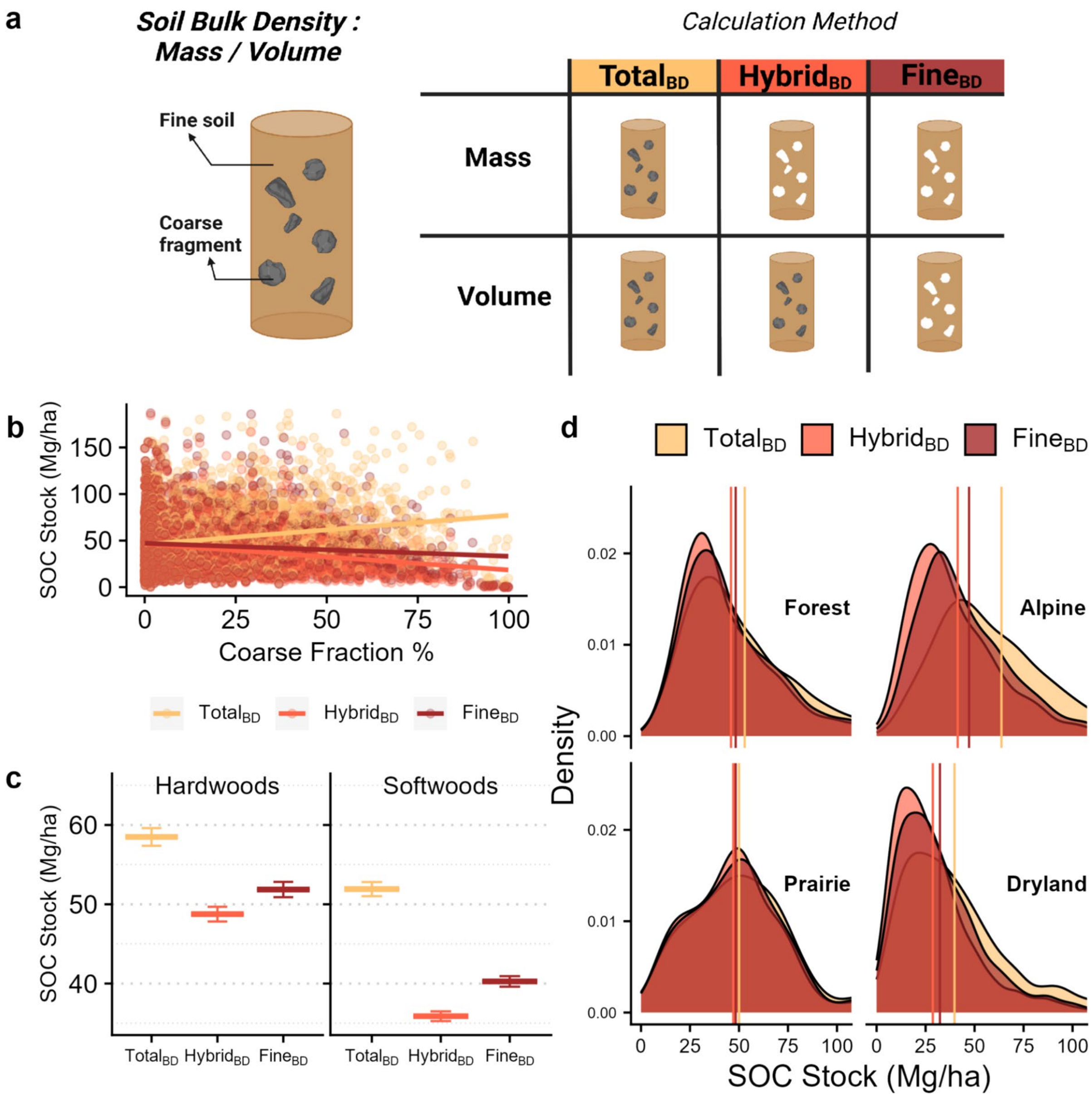


Fig. 1 Three methods of calculating bulk density result in large differences in estimates of SOC stocks in the top 20 cm of soil in forests of the conterminous United States. **a** Illustration of the three bulk density methods used in calculations of SOC stocks; calculation methods differ in whether they include coarse fragments in either the sample mass or volume portion of the bulk density model. Whitespace within the cores indicates subtracting coarse fragments from either the mass or volume of the core. Color scheme indicating bulk density methods is continued in subsequent panels. **b** Linear regressions of estimated SOC stocks (Megagrams per hectare) across the range of coarse fragment mass percentage in the NFI soil dataset. **c** SOC stocks (Megagrams per hectare) in NFI plots dominated by hardwood vs. softwood tree species. Central bars represent the mean of the data and error bars represent standard error of the mean. **d** Distribution of SOC stock estimates among forest plots located within four distinct landscape types: forests, alpine zones, prairies, and drylands. Note that the x axis is truncated at the 95th percentile of the SOC stocks. Vertical bars represent the mean estimate of SOC stock calculated with each bulk density method

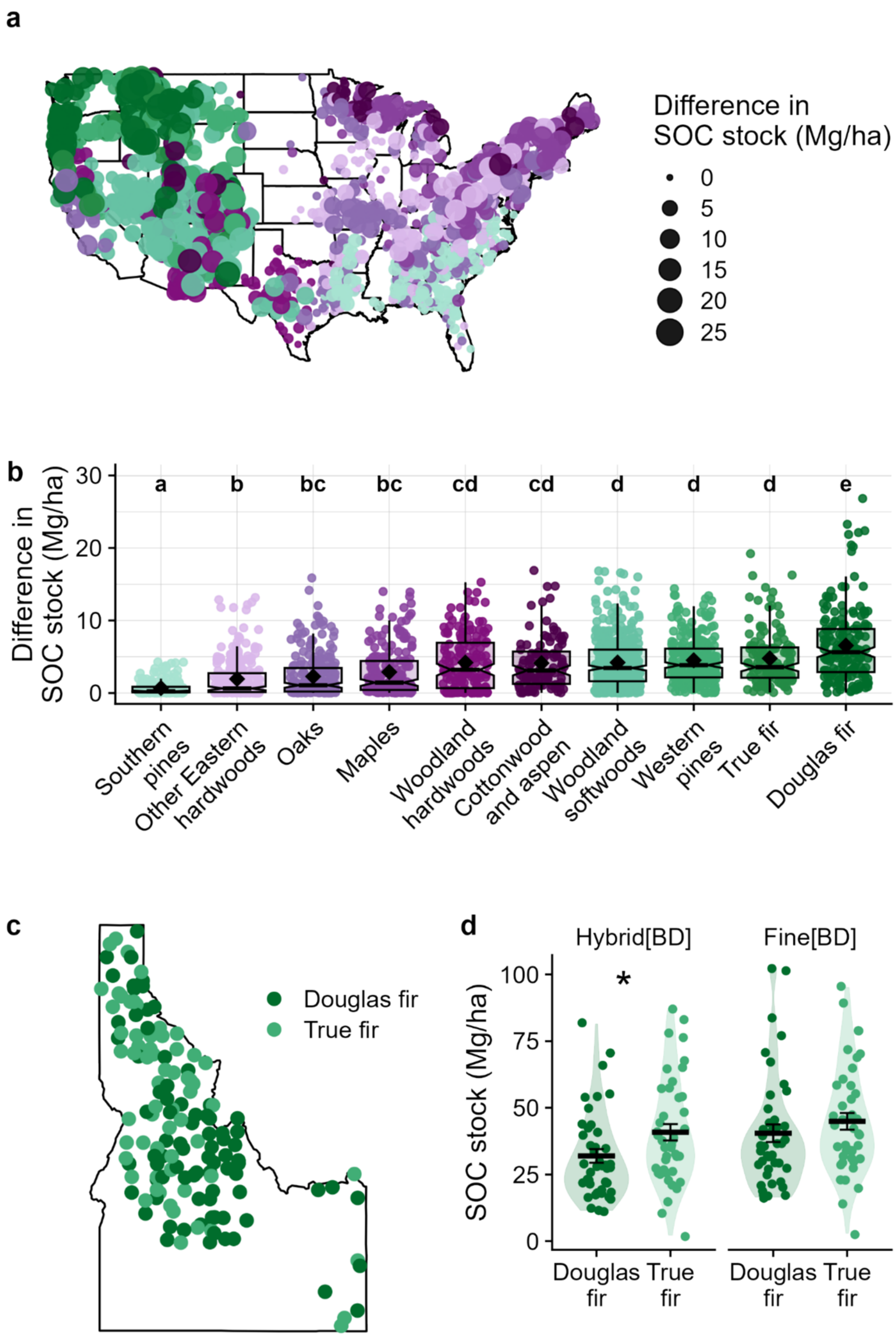
current SOC stock in these ecosystems is necessary to interpret potential changes in soil carbon storage in light of ongoing global change.

Patterns associated with forest composition

SOC stocks in plots dominated by hardwood tree species ($n = 1179$; 44% of plots) were higher than in plots dominated by softwood species ($n = 1501$; 66% of plots) regardless of bulk density calculation method (Fig. 1c). Further, variability in SOC stocks calculated with different bulk density methods were largest in the softwood-dominated plots. This difference is due in part to higher coarse fragment content in softwood-dominated plots ($F_{1,\ 2679} = 252.6$, $p < 0.001$), which leads to overestimation of SOC stocks in softwood stands when using $Total_{BD}$. Softwood tree species are some of the most important timber species worldwide, and there is increasing interest in managing softwood plantations for carbon storage (Bourque et al. 2007; Hennigar et al. 2008; Diao et al. 2022). Further, because they tend to share traits such as litter type and mycorrhizal association, softwoods are often compared with hardwood species to understand effects of tree traits on forest carbon storage (Bateman and Lovett 2000; Thom and Keeton 2019). Given that differences in SOC stocks between hardwood and softwood forest types vary with the method used to calculate bulk density, it is critical to choose the bulk density calculation method that appropriately reflects the mechanisms of interest in a particular analysis. Studies aiming to characterize the effects of softwood and hardwood tree species on soil processes, for example, should focus on SOC stocks calculated with $Fine_{BD}$ to reduce errors associated with systematic differences in rock content. On the contrary, if the goal is to quantify differences in SOC stocks beneath these forest types, using $Hybrid_{BD}$ will highlight patterns in SOC stocks resulting from both species effects on fine soil carbon content as well as differences in rock content.

Comparing SOC stocks calculated with the two bulk density methods that account for coarse fragment content ($Hybrid_{BD}$ and $Fine_{BD}$) highlights geographic patterns related to forest type (Fig. 2a). Because $Fine_{BD}$ includes only fine soil volume in the denominator of the model, SOC stocks calculated with $Fine_{BD}$ will always be higher than the corresponding stock calculated with $Hybrid_{BD}$ unless the sample has no coarse fragments. However, the degree to which these calculation methods differed varied with forest type. Although SOC stocks calculated with each bulk density method were most similar within plots dominated by southern pines, softwood species generally showed greater differences between stocks calculated with $Hybrid_{BD}$ and $Fine_{BD}$ (Fig. 2b).

Discrepancies in SOC stocks estimated with different bulk density calculation methods can impact how researchers interpret patterns in soil carbon content. Without detailed information about the bulk density method used, these patterns could potentially point to misleading conclusions. To illustrate this effect, we examined data from a forest type with the largest discrepancies in SOC stocks among bulk density calculation methods: high-elevation, high-latitude softwood forests. Focusing on a small area to avoid additional confounding effects related to climate or regional geography, we isolated data from forests dominated by either true fir (genus *Abies*) or Douglas fir (*Pseudotsuga menziesii*) within the state of Idaho. We calculated SOC stocks in all plots using both $Hybrid_{BD}$ and $Fine_{BD}$ (Fig. 2c, d). We found that the mean SOC stock beneath Douglas fir (37.1 Mg/ha) was significantly lower than that of true fir (40.8 Mg/ha) when stocks were calculated using $Hybrid_{BD}$ to determine SOC content on an areal basis ($t_{79.3} = -2.22$, $p = 0.029$). However, using SOC stock estimates calculated with $Fine_{BD}$, we found no significant difference in mean SOC stocks (44.2 vs. 46.0 Mg/ha; $t_{81.7} = -0.98$; $p = 0.33$) beneath these tree species. This discrepancy highlights the potential pitfalls of using SOC stock data calculated with $Hybrid_{BD}$ to interpret patterns related to ecological processes. In this case, using SOC stocks calculated with $Hybrid_{BD}$, one may conclude that Douglas fir and true firs have distinct influences on SOC dynamics, when in reality, the soil beneath these species contains similar quantities of carbon per unit soil volume. Instead, higher SOC stocks per area beneath true fir are explained by significantly lower coarse fragment mass, and thus less soil volume displaced by rock, compared with Douglas fir ($t_{76.2} = 3.84$;



p < 0.001). Because coarse material content influences soil moisture dynamics and nutrient content (Johnson et al. 2012), systematic differences in rock mass beneath different tree species is likely common (Baillie et al. 1987), and may lead to spurious inferences about the effects of tree species on the production and retention of soil organic matter.

Implications for future research and reporting using large-scale soil assessments

Soils are the largest terrestrial carbon pool on Earth, and several measurement, monitoring, reporting, and verification activities have emerged recently to quantify soil carbon stocks and stock changes

◂**Fig. 2** Differences in mean estimated SOC stock in NFI plots calculated using $Fine_{BD}$ and $Hybrid_{BD}$ (SOC stock[$Fine_{BD}$]—SOC stock[$Hybrid_{BD}$]). **a** Approximate locations of plots with point color representing major forest type group and point size corresponding to the magnitude of the difference in SOC stock when calculated with $Fine_{BD}$ and $Hybrid_{BD}$ (SOC stock[$Fine_{BD}$]—SOC stock[$Hybrid_{BD}$]). Shades of green represent softwood forest types and shades of purple represent hardwood forest types. The ten forest type groups shown here comprise 80% of all NFI plots for which soil and tree data were available. Differences were restricted to those within three standard deviations of the mean to aid with visualization. **b** Mean differences in SOC stocks calculated with $Fine_{BD}$ and $Hybrid_{BD}$, ordered by the magnitude of the difference in each major forest type group. Letters represent significant differences between forest type groups as determined by post-hoc analysis of variance (Tukey's HSD). Differences were restricted to those within three standard deviations of the mean to aid with visualization. **c** Map of the state of Idaho showing NFI plots dominated by true fir (genus *Abies*) and Douglas fir (*Pseudotsuga menziesii*). Locations are approximate. **d** Differences in the estimated SOC stocks calculated for each species group using $Hybrid_{BD}$ (left) and $Fine_{BD}$ (right). Error bars represent standard error of the mean. Asterisk indicates significant difference between estimated SOC stock in each forest type

across the land sector. This study highlights the large discrepancies in SOC stocks that can occur from using different soil bulk density calculations. When scaled across all forest area in the US, the mean difference in SOC stocks calculated with and without coarse fragment mass (i.e. $Total_{BD}$ vs $Hybrid_{BD}$) amounts to more than 70 percent of economy-wide carbon dioxide emissions in the U.S. in 2022 (Domke et al. 2024).

While different bulk density calculations may be suited to specific research questions, careful documentation of the calculation method in reports that include SOC stocks will improve clarity and accurate interpretation of the data. Further, this documentation will facilitate efforts to harmonize soil datasets by ensuring consistency in the methods used to quantify bulk density across studies, or by allowing researchers to re-calculate bulk density in a consistent manner when different methods are used. Ideally, data would allow the end user to calculate bulk density with the method most appropriate for their research needs: this would require, at minimum, (1) reporting of the dimensions of the coring device, (2) the oven-dry mass of the sample, and (3) the mass of any coarse material (> 2 mm) contained within the sample. When possible, information about the volume of coarse material would allow the calculation of all metrics of bulk density without the uncertainty associated with using estimates of coarse fragment density. With these data freely accessible, researchers can calculate bulk density as needed and describe the calculation used, improving transparency in soil research and reporting, and reducing uncertainty around estimates of SOC stocks. Improving the measurement and reporting of soil bulk density is an important step in accurately quantifying SOC stocks in forests, but other sources of uncertainty in these calculations remain difficult to quantify.

Determining bulk density using surface core samples remains the standard in soil science, but issues inherent to the process of core sampling may result in variability in soil bulk density measurements (Gross and Harrison 2018). First, data collection is limited to observations from soils where coring is not precluded by large rocks or shallow depth to bedrock. In this analysis, for example, we excluded plots (n = 277) where observations to 20 cm depth were not available. Thus, our analysis does not reflect dynamics specific to shallow soils and soils with large rocks that impede sampling. Rocks larger than the diameter of the coring device are common in some forest soils and can be quantified with pit excavations (Clancy et al. 2023). Though ignoring these features can lead to overestimation of the SOC stock, in large-scale inventories, the volume occupied by large rocks is rarely quantified. Further, forests underlain by shallow (< 20 cm) soils often occur at high elevations. These forests can contain high concentrations of SOC per unit mass, as the proportion of organic material from litter and root inputs is likely large (Johnson et al. 2012). Therefore, by restricting our analysis to deeper soils, we may not have captured forest types with a disproportionate impact on soil carbon dynamics in the US. Lastly, core-based methods of determining bulk density introduce bias due to soil compaction that occurs during the coring process. Because the degree of compaction depends on soil texture and moisture properties, the level of bias inherent to this process will vary from sample to sample, making landscape-scale comparisons highly uncertain (Harrison et al. 2003; Walter et al. 2016).

Conclusion

Using three common calculation methods for determining soil bulk density, estimates of SOC stocks in U.S. forests can vary by as much as 13 Mg ha^{-1}, roughly 32% of the mean SOC stock estimate for the top 20 cm of soil in U.S. forests. Our analyses highlight the importance of clearly defining soil bulk density in soil carbon research and reporting activities and in the metadata associated with soil data. Given the increasing need to combine soil data collected by different agencies and institutions for national and international assessments, a unified approach to publishing datasets that includes information about the dimensions of the soil sampling device and the mass of both the fine soil and coarse material fractions is needed. With these data, users can calculate bulk density with the method most suited to specific research questions: areal stocks (Hybrid$_{BD}$) for analyses of soil carbon content over landscapes, and fine soil carbon content (Fine$_{BD}$) for understanding change over time, with disturbance, or across ecological gradients. Though simplest to measure, the total bulk density approach (Total$_{BD}$) is appropriate only for quantifying the density of the soil matrix, but not in calculations of elemental stocks.

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Data availability The dataset analyzed during the current study is available through the USDA Forest Service Forest Inventory and Analysis program, https://research.fs.usda.gov/products/dataandtools/tools/fia-datamart.

Declarations

Competing interests The authors have no relevant financial or non-financial interests to disclose.

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