Simulated Soil Respiration is Sensitive to Soil Hydraulic Properties from Intact vs. Repacked Cores

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Abstract:

Soil hydraulic properties, such as water retention and hydrodynamics, play a pivotal role in regulating belowground carbon (C) storage by influencing microbial activity and nutrient availability. However, empirical measurements of these properties are labor-intensive and often fail to replicate field conditions in laboratory settings. Standardizing and increasing the throughput of hydraulic property measurements is essential to improve model predictions of ecosystem-scale soil C dynamics. To address this need, we investigated the hydraulic properties of intact field-collected soil cores and laboratory-repacked soil columns to assess how soil structure impacts hydraulic measurements and subsequent model predictions of soil respiration. Using four distinct soil textures (sandy loam, silt loam, loam, and silt clay) sampled as part of the Molecular Observation Network (MONet), we compared water retention curves derived from both methods to publicly available HiHydroSoil v2.0 database values. We then applied the Millennial model to simulate soil respiration rates and total C stocks based on measured hydraulic properties. Our experimental results show the largest differences in hydraulic properties between intact and repacked approach for the silty soil texture, and the smallest differences in the sandy soil texture. The model predicted increased respiration in repacked sandy loam and loam cores (~6% and ~9%), while repacked silt loam and silty clay showed ~17% lower respiration vs. intact cores. Respiration in sandy loam and loam soils showed higher respiration in repacked associated with lower SOC stocks compared to intact.

However, silt loam and silty clay in repacked cores had ~12–19% higher total C stocks as compared to intact, consistent with SOC protection by clay. These uncertainties in model predictions also varied with whether intact or repacked hydraulic properties were used, emphasizing the need for reliable measurements that account for environmental and anthropogenic impacts on soil structure, with implications for both empirical and modeling efforts.

Main text:

Soil structure (i.e., spatial arrangement of soil particles into aggregates and pore networks) and mineralogy are known drivers of microbial metabolism, nutrient availability, and soil respiration (Angst et al., 2021; Herbst et al., 2016; Schlüter et al., 2019). Well-structured soils, with interconnected pores, facilitate optimal water and air diffusion, thereby enhancing the microbial access to soil organic C (SOC), increasing microbial activity and soil respiration (Moyano et al., 2013). Conversely, compacted or poorly structured soils limit microbial access to SOC and gas diffusivities, reducing respiration and favoring anoxic pathways such as denitrification (Longepierre et al., 2021). Soil mineralogy also plays an essential role in C stabilization, particularly soils high in clay content, which effectively stabilize and sequester C through mineral association (Georgiou et al., 2022).

Soil structure is commonly measured through hydraulic properties using either field-collected intact soil cores or laboratory repacked soil columns (Stenger et al., 2002). Intact soil cores preserve the natural structure and better reflect field conditions, whereas repacking soil into columns, disrupts native soil texture, aggregate distribution, and pore connectivity. Previous literature indicates that repacked soils exhibit altered water retention characteristics compared to intact cores (Fu et al., 2024). However, studies have shown mixed outcomes regarding the influence of intact versus repacked cores on SOC mineralization rates. Some studies reported no significant difference in mineralization rates between intact and repacked samples, despite alterations in microbial abundance (Stenger et al., 2002), while others observed increased respiration in dried sieved samples and upon rewetting of sieved soil (Meyer et al., 2019). To our knowledge, ecosystem scale models have not yet been tested for uncertainties associated with variability in soil structure and hydraulic parameters.

Soil biogeochemical models only implicitly consider soil structural and physical variability through modifier functions that account for moisture impacts on microbial activity (Moyano et al., 2013), resulting in uncertain projections of respiration rates. At low soil moisture, the modifier function reduces potential microbial activity due to limited substrate diffusion, while at high moisture, it suppresses activity due to oxygen limitation. Accurate estimation of key parameters in the moisture modifier function—such as soil hydraulic properties, including porosity and water retention curve parameters—is essential for predicting moisture-driven changes in soil C dynamics (Fatichi et al., 2020).

The objective of this study is twofold: to evaluate the importance of preserving native soil conditions on soil hydraulic property measurements and secondly, to quantify how variability in measured hydraulic properties may impact predictions from biogeochemical models. We measured soil hydraulic properties for intact and repacked soil cores collected from four disparate soils across the continental United States, compared hydraulic properties by both methods to hydraulic properties published by HiHydroSoil database, and then evaluated the impact of moisture modifier parameters on predictions of soil respiration using the Millennial soil C model (Abramoff et al., 2022).

Soil samples were collected by the Molecular Observation Network and varied in soil texture (a sandy loam, silt loam, loam, and silt clay) and parent bedrock, total C % (Figure 1 and SI Table S1). For each soil sample, soil water retention curves (SWRC) were generated utilizing a HYPROP 2 (Meter Group). SWRC for each soil type was measured twice: one from intact core and then again on repacked core after sieving, homogenization, and repacking the soil to match its original dry mass bulk density. Intact core measurements were completed using a custom adaptor ring (SI Figure S1). Afterwards, the saturated hydraulic conductivity (K_s) of each sample was determined using Meter Group's falling head KSAT. Van Genuchten parameters (α, n, θ_r, and θ_s) were calculated using SoilView Analysis Software from METER Group. These parameters were cross-referenced with data from the HiHydroSoil v2.0 database in order to compare direct measurements of soil hydraulics to publicly available data that is often used to parameterize soil C models.

Comparing SWRCs (Figure 1C) revealed that intact soil cores consistently exhibited higher initial and final moisture content than both repacked cores and HiHydroSoil estimates, as well as slower moisture loss (Figure 1C). These finding suggest that intact soil cores retained interconnected pore networks, while repacked soil cores likely lose moisture and structural integrity during deconstruction, sieving, and homogenization processes (Fu et al., 2024). In addition to differences in moisture retention, discrepancies in saturated hydraulic conductivity (K_s) between intact and repacked soils (Figure 1C) further highlight the impact of structural integrity on hydraulic properties, consistent with findings from previous studies (e.g., (Moret-Fernández et al., 2021)). Intact loam and sandy loam cores exhibited significantly higher K_s values due to preserved preferential flow paths, contrasting with lower Ks values due to the reduced connectivity in homogenized repacked soil cores. Interestingly, silty loam and silty clay soils showed slightly higher K_s in repacked cores, possibly due to better redistribution of pore spaces during repacking. Notably, the retention curves of repacked and intact cores show substantial differences compared to HiHydroSoil data for each soil texture class. Although the HiHydroSoil model predicted the general texture-driven trend, it failed to account the finer-scale variations observed in laboratory measurements, emphasizing the need for models to incorporate structural heterogeneity for accurate predictions.

To evaluate the impact of soil hydraulic properties on C flux predictions, we utilized the Millennial model (Abramoff et al., 2022). The moisture modifier in the original Millennial model formulation does not account for soil structural heterogeneity, which affects the colocation of SOC and microbes. Recent studies have demonstrated that greater colocation increases microbial activity (Chakrawal et al., 2020; Shi et al., 2021). To address this limitation, Yan et al. (2018) proposed a moisture modifier that parameterizes the effect of C-microbe colocation as a linear function of clay content. High clay content can occlude SOC, reducing its availability to microbes and consequently lowering microbial activity (see SI Figure S2 and S3). The effect of colocation is implemented via a multiplicative factor in exponent of the moisture modifier, referred to as colocation factor (See SI section 2 and Figure S3). We utilized the default collocation factor-clay% relationship to simulate processes in intact cores, presuming that C-microbe colocation in intact soils is minimally altered during sampling. Then for repacked cores, we decreased the slope of the collocation factor-clay% relationship by 0.3 to account for the disruption of soil structure caused by homogenization (Figure S3). A steeper slope indicates greater SOC inaccessibility with increasing clay, representing intact soils, while a flatter slope reflects reduced inaccessibility with clay content, as observed in repacked soils.

Using the Millennial model, we estimated steady-state pools and used them as initial pool sizes to simulate annual soil respiration for one year in surface soils (0-30 cm). We only modified soil hydraulic properties to isolate their impact on respiration, assuming the same daily temperature, net primary production, rainfall, and other model forcings across four sites (see SI Figures S5, S6 and Table S2). To account for how soil hydraulic properties changed soil moisture, we developed a separate soil water balance routine to simulate soil moisture dynamics (SI section 2.3) that was coupled with Millennial.

Our results demonstrate that soil C model predictions are sensitive to hydraulic measurement methods, particularly when microbial access to SOC is constrained by clay-mediated occlusion. Simulated annual respiration rates diverged substantially across soil textures, with differences attributable solely to hydraulic parameterization (Figure 2). For sandy loam and loam soils, repacked cores predicted higher respiration compared to intact cores (by ~6% and 9%, respectively, Figure 2A), aligning with the expectation that repacking increases microbial accessibility to SOC and promotes greater C loss (~5.5% ca. repacked vs. intact) (Figure 2B). However, this pattern reversed for silt loam and silty clay, where repacked cores predicted ~17% lower respiration and ~ 13 and 19% higher SOC, respectively, than intact cores. These discrepancies suggest that in finer-textured soils, repacking changes hydraulic and Damköhler regimes in ways that can suppress microbial activity, potentially overriding accessibility effects. Indeed, despite higher clay content and presumed SOC protection, silt loam and silty clay soils exhibited higher total C stocks (Figure 2B), possibly due to drier moisture conditions that limited respiration (Figure S4).

These model results suggest that even when bulk soil C stocks remain constant, changes in soil hydraulic parameters—such as water retention curves and hydraulic conductivity—can significantly alter soil moisture and flow regimes. These, in turn, influence microbial activity due to their strong control over oxygen diffusion, enzyme kinetics, and substrate transport (Or et al., 2007). In physically protected environments, such as in aggregates or mineral-associated OM, where SOC is not freely accessible, moisture conditions may exert even stronger regulation on microbial access pathways, via desorption or diffusion-limited substrate supply (Keiluweit et al., 2017). Thus, the interplay between soil physical structure (e.g., aggregation, flow regime, and clay content), moisture sensitivity, and microbial accessibility exerts complex functional control over SOC turnover that is often underrepresented or oversimplified in biogeochemical models. The findings presented here corroborate the need (Young and Crawford, 2004)to integrate physically-explicit and hydrologically-sensitive representations of microbial access into SOC modeling frameworks (Young and Crawford, 2004).

A key takeaway from our study is that variability in soil hydraulic properties, derived from intact vs. repacked cores, can significantly influence predictions of C fluxes and stocks. This finding highlight the need to integrate temporal and local spatial variation in soil structure into Earth system models, as soil disturbances, whether environmental or anthropogenic, can substantially alter soil's inherent heterogeneity (Schlüter et al., 2019). The repacking of soil cores in our study serves as an extreme example, representing a far-end of such disturbances. Furthermore, reliance on public databases that interpolate data at coarse spatial resolution, *e.g.*, $\geq$ 1km, can introduce significant uncertainty into C flux simulations. Our results clearly demonstrate that soil C model parameter estimation is strongly influenced by hydraulic measurements, particularly when microbial access to SOC is modulated by clay-mediated occlusion. To improve predictions of SOC stability and persistence, future modeling efforts must prioritize mechanistic integration of soil structure, utilizing high-resolution physical property datasets based on measurements from both intact and repacked soil cores to capture structural differences and their impact on model parametrization.

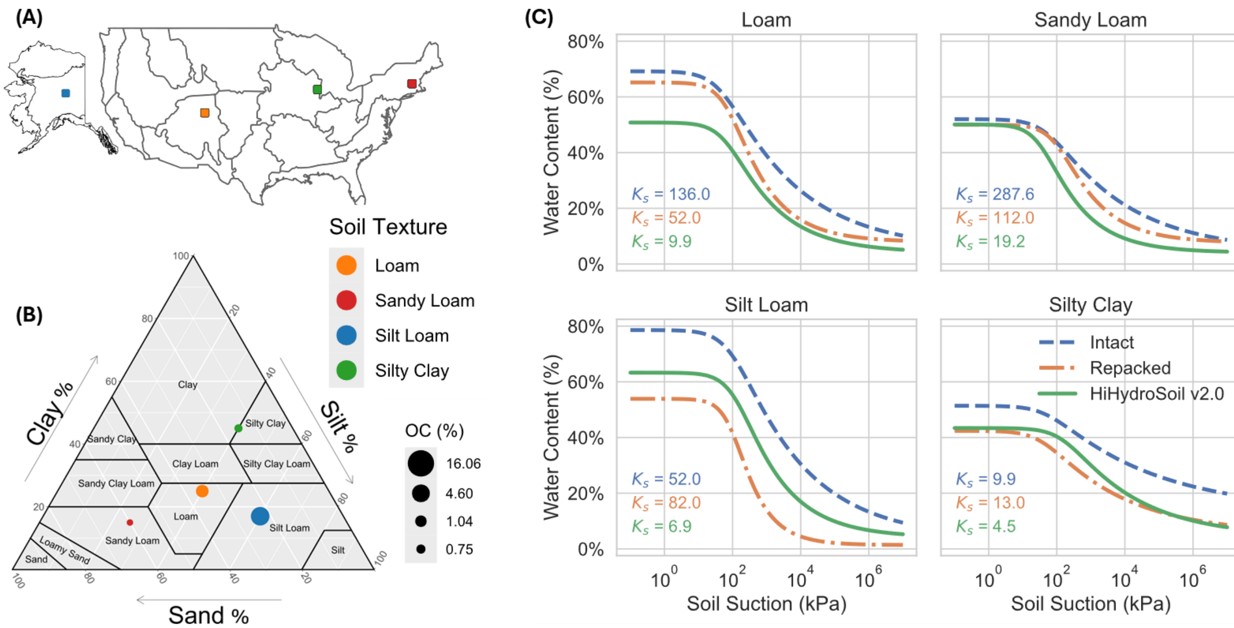

Figure 1 (A) Geographical locations of soil samples, (B) soil texture and their organic C content, and the water retention curves for intact, repacked and simulated values using Van Genuchten parameters from HiHydro database. The saturated hydraulic conductivity values (K_s) are in cm/d.

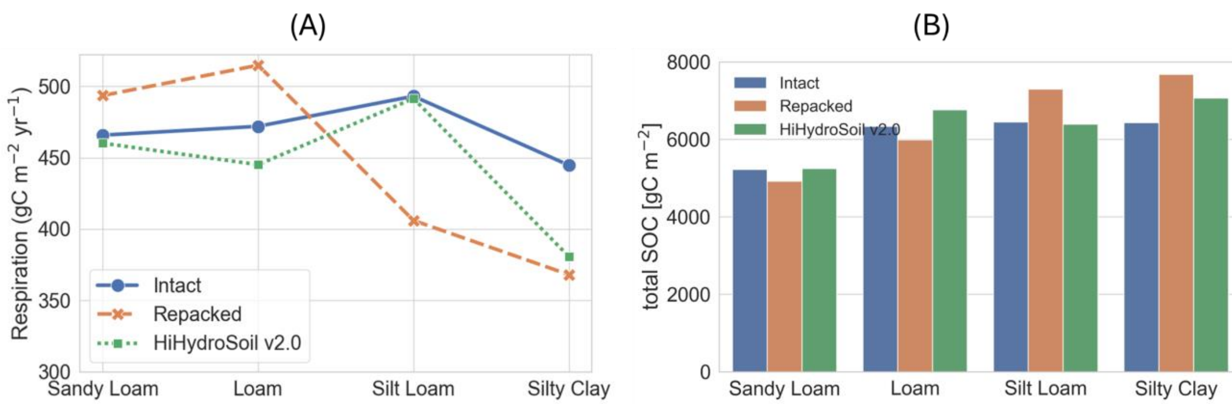

Figure 2 A) Variation in predicted annual respiration rates across soil textures using intact, repacked core measurements and HiHyroSoil database; B) Predicted soil organic C stocks at steady-state across soil textures used in this study. Simulations were conducted using the Millennial model with a soil moisture modifier following Yan et al. (2018) for which the soil hydraulic properties were derived from intact cores, repacked cores, or obtained from the HiHydroSoil database. All simulations used identical climate and C inputs to isolate the effects of hydraulic parameterization.

Author contributions:

AT conducted laboratory experiments using intact and repacked soil cores, and helped prepare figures. AC performed model simulations, and led the manuscript writing. All authors contributed by providing critical feedback, editing, and reviewing the final version of the manuscript.

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Code availability statement

All code and data used in this study is available at https://github.com/EMSL-MONet/HiProp_repo

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