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Soil organic matter accumulation in relation to changing soil volume, mass, and structure: Concepts and calculations

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ABSTRACT

Change in soil organic matter (SOM) stocks over time is a critical issue for soil fertility, soil development (pedogenesis) and the global carbon (C) cycle. Measuring such change typically relies on sampling to constant depth (CD) which is well known to be inaccurate if bulk density (BD) has changed between sampling sites or times. The usual solution to this problem is to sample an equivalent mass (EM), but in most cases soil mass also changes over time. Indeed, the whole point in measuring ΔSOM is to quantify a change in C mass. As SOM accumulates, soil volume increases (soil dilation) unless all added SOM fills in existing pores. Soil dilation as a result of root ingrowth is well documented in the geological literature but has rarely been considered in conjunction with studies of ΔSOM. Other processes that can alter soil volume include eluviation, bioturbation and dissolution/decomposition of both mineral and organic soil particles.

Here, we present a method (the volume/mass corrected or VMC method) for calculating potential effects of processes that alter soil volume (V) and/or mass (M) on calculated values for ΔC and other soil characteristics. We first present a hypothetical example to illustrate the expected differences in soil V, M, bulk density (BD), porosity and ΔC when determined via CD, EM, and VMC methods. We then compare these three approaches for assessing the actual changes in soil characteristics across four soil chronosequence studies in which ΔV was actually measured, allowing ΔC to be calculated correctly. Results show errors of −75% to +49% in ΔC had the profiles been sampled via the CD method and even larger errors (−87% to +54%) had they been sampled via the EM method. Studies where V had increased (dilation) generally showed underestimates for ΔC for both CD and EM methods, whereas those where V had decreased (collapse) over time showed overestimates for ΔC for the CD and EM methods. Results are discussed in light of the few laboratory, field, and simulation studies comparing effects of changes in soil volume on ΔC measurements as well as the processes that cause changes in soil V.

We hope that the VMC method provides a conceptual framework for addressing the interplay between changes in soil volume, porosity, and structure, one that will provide the foundation for a new set of mechanism-based SOM models that take into account changes in soil volume, mass, and physical structure across a wide range of spatial and temporal scales.

1. Introduction

Understanding the dynamics of soil organic matter (SOM) is critical because of the potential for changes in SOM (ΔSOM) to exacerbate or help mitigate global climate-change. Mineral soils most often decrease in bulk density (BD) as SOM accumulates. This happens even though input of roots and surface litter to the mineral soil adds mass to the soil volume. Thus, adding mass should increase BD but instead BD decreases. The explanation is simple: the soil volume increases, and because the volume cannot increase downward or laterally, the soil becomes thicker (i.e., the soil surface must rise with respect to the parent material). This simple fact has consequences for both sampling soil and understanding and modeling soil dynamics but has not received the attention it deserves.

Soil volume change (ΔV) has been measured at relatively few sites worldwide. This is because tracking an initial volume of soil (hereafter the "reference volume") over time requires tracking an "index" element, one that can be assumed to be immobile over the time period. Thus, any change in concentration of that element must be due to changes in the mass and/or volume of the reference volume. Bern et al. (2015) review the history of this field at the interface between soil science and geology. Although SOM accumulation was a primary focus

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of only one of these studies, all used the index-element method to calculate ΔV for the A horizon and acknowledged that much of the ΔV was attributable to ΔSOM.

A simple example of the impact of changes in soil volume (ΔV) and mass (ΔM) on ΔC measurements is when BD changes between measurements, which often happens in less than a century. Discussion of this problem dates back at least to the 1960s (Gifford and Roderick, 2003). The problem, of course, is that changes in BD mean that sampling to constant depth (i.e., constant volume) samples too little soil if BD has decreased and too much soil if BD has increased. Admittedly, in all cases soil can be sampled deeply enough that virtually all SOM is included but this approach by itself provides no quantitative information on SOM dynamics by horizon. In some cases, bedrock or saprolite can be used as a vertical reference point (e.g., Berhe et al., 2008), which ensures that the entire profile is sampled, but again this does not help quantify effects of volume change by soil horizon.

Sampling an equivalent mass is the widely accepted solution to the problem of changed BD (e.g., Gifford and Roderick, 2003; Mikha et al., 2013; Wendt and Hauser, 2013). The assumption here is that mass has remained constant between successive measurements even though volume has changed. Thus, by increasing or decreasing the sampling volume (i.e., depth) so that sampled mass remains constant across successive measurements, the proper volume will be automatically sampled. Unfortunately, in many studies soil M does not remain constant. Indeed, the whole point in measuring ΔSOM is to quantify a change in C mass (ΔC). Rovira et al. (2015) recently revisited a method first used by David Jenkinson (1971), ignition of the soil to remove the bulk of the SOM, which likely solves the ΔC problem for most short-term monitoring studies, but in most chronosequence studies mineral mass also changes markedly. In any case, thorough reexamination of the processes that change soil volume, and especially porosity, is needed.

Here, we present a method for using measured ΔV to calculate correctly ΔC and other soil characteristics. We refer to this method as the volume/mass corrected, or VMC method. We first use a hypothetical example in which soil V increases over time to illustrate the difference in ΔC as measured via constant depth (CD) and equivalent mass (EM) methods compared to the VMC method. We next compare these three approaches for assessing changes in soil characteristics in four soil chronosequence studies in which the change in soil volume was actually measured,

Lastly, we formulate a set of empirical equations that describe the processes that cause the changes in soil volume. Although volume is not generally considered a pool or flux, it is a state variable and mathematically the concepts of pool and flux apply equally well to V (including pore space) as to M. Results are discussed in light of the few laboratory, field, and simulation studies of the processes that control ΔV and the implications of these processes for understanding soil C dynamics.

2. Methods

2.1. Overview

The VMC method has three parts. In the first we work only with values for the M, C, and V pools and their ratios (e.g., density and %C) at two points in time (initial and final). We first calculate final values for all pools from measured values for final V sampled, %C, bulk density (BD), mineral-particle density and published values for SOM density and %C in SOM.

The second part of the analysis is quantitative comparison of the CD, EM, and VMC sampling approaches with regard to ΔC, ΔM, and ΔV (including pore volume). This part uses only the information on pools generated in Part 1.

In the third part, we calculate the mass and volume fluxes, that is, the processes responsible for the changes in pool sizes between t_1 and t_2. For the mass fluxes, we must assume a value for one flux (mass moved upward in the profile by bioturbation). With that assumption made, we can calculate minimum values for the two remaining mass fluxes (net input of SOM and transport of mineral material downward from the reference volume). We then calculate minimum values for the volume fluxes resulting from these mass fluxes.

Table 1
Naming conventions for variables and subscripts used in the VMC equations. Note that in what follows all pools are indicated by upper-case bold italics (e.g., $\boldsymbol{M}$, $\boldsymbol{V}$) with fluxes in upper-case regular font (M, V).

Variables (units)
$\boldsymbol{M}$ = mass (Mg)
$\boldsymbol{V}$ = volume (m^3)
ρ = density ($Mg\ m^{-3}$)
$\boldsymbol{C}$ = carbon mass (Mg)
φ = void ratio (porosity)
K = ratio of pore volume increase to mass flux

Subscripts
i = initial deposit or soil at beginning of study period
f = final soil at end of study period
m = measured
c = calculated by VMC method
d = calculated if sampling by constant-depth method
e = calculated if sampling by equivalent-mass method
p = mineral particles
o = organic matter
t = transport downward of mineral material by eluviation and leaching
u = bioturbation upward of both mineral and organic matter
v = void

Overall, the VMC method can be applied to an entire soil column, individual horizons, or depth intervals. However, an important assumption is that soil properties are uniform across the vertical dimension of the reference volume. Also, to calculate soil M and V stocks, a soil surface area of 1 m^2 is assumed. For all equations, volume is given in m^3 and mass in Mg.

2.2. Measured variables

Variable naming and subscript conventions are given in Tables 1 and 2. Additional information regarding measurement of these variables is provided in Supplemental Material. Note that in what follows all pools are indicated using bold italics (e.g., $\boldsymbol{M}$, $\boldsymbol{V}$) whereas fluxes appear in regular font (M, V). Several variables that were obtained from published literature are also considered “measured” for our purposes.

2.2.1. Measured final variables

In this category, we include variables measured on field samples and those calculated directly from these measured variables.

Table 2
Variable used in the VMC equations. Note that the four “final measured” variables (listed next) are identical to the four “VMC output” variables (listed last). This is because a critical step in Part 3 of the VMC analysis is to alter the three “adjustable” parameters until the calculated VMC output variables match the final values as measured on field samples in the chronosequence studies.

Measured variables
Final: $\boldsymbol{V}_{fm}$, $\Delta\boldsymbol{V}_m$, ρ_{fm}, $\%C_{fm}$
Initial: ρ_i, $\%C_i$
Time independent: ρ_p, ρ_o, $\%C_o$, $\%C_u$
Pools (calculated from the measured variables, initial and final for each)
Mass pools: $\boldsymbol{M}$, $\boldsymbol{M}_p$, $\boldsymbol{M}_o$,
Volume pools: $\boldsymbol{V}$, $\boldsymbol{V}_p$, $\boldsymbol{V}_o$, $\boldsymbol{V}_v$
Ratio of pools: φ
Adjusted parameters: M_u, K_o, K_t
VMC-calculated fluxes (based on the three adjusted parameters)
Mass fluxes: M_o, M_t, M_{ou}, M_{pu}
Volume fluxes: V_o, V_t, V_{ou}, V_{pu}, V_{vo}, V_{vt}
VMC-calculated output variables: $\boldsymbol{V}_{fc}$, $\Delta\boldsymbol{V}_{\mathbf{c}}$, $\rho_{\mathbf{fc}}$, $\%C_{fc}$