Depth distribution of soil organic carbon as a signature of soil quality

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Abstract
Soil organic matter is a key component of soil quality that sustains many important soil functions by providing the energy, substrates, and biological diversity to support biological activity, which affects aggregation (important for habitat space, oxygen supply, and preventing soil erosion), infiltration (important for leaching, runoff, and crop water uptake), and decomposition (important for nutrient cycling). Lack of residue cover and exposure of soil to high-intensity rainfall results in poor aggregation, reduced plant water availability, erosion, and off-site impacts of sedimentation and loss of soil nutrients to receiving water bodies. From a soil survey dataset in Georgia USA, profile distribution of soil organic carbon (SOC) was closely matched with an exponential function (i.e., highest at the soil surface and exponentially declining with depth). It is suggested that if sufficient ecosystem service data associated with profile distribution of SOC could be collected, a strong relationship would develop between SOC stratification ratio and various ecosystem services.

Introduction
Soil, water, and air resources are fundamental components of agricultural systems. Achieving a balance between agricultural production and conservation of natural resources is a necessary step to achieve sustainability. Soil quality can be viewed as an indicator of sustainability, since soil quality is indirectly linked to food production, food security, and environmental quality (e.g., water quality, global warming, and energy use in food production) through its influence on key soil functions. Soil quality is a complex subject, encompassing the many valuable services humans derive from soil, as well as the many ways soils impact terrestrial ecosystems (Doran and Parkin 1994).

Achieving high soil quality requires that soil be able to perform several key ecosystem functions to an optimum capacity within the constraints of inherent soil characteristics and climatic conditions. Some key soil functions of interest in agriculture are:

- supplying and cycling nutrients for optimum plant growth;
- receiving rainfall and storing water for root utilization;
- filtering water passing through soil to protect groundwater quality;
- storing SOC for nutrient accumulation and mitigating greenhouse gas emission;
- decomposing organic matter and xenobiotics to avoid detrimental exposures to plants and the environment.

Soil organic matter – as a source of energy, substrate, and biological diversity – is one of the key attributes of soil quality that is vital to many of these soil functions. Stratification of SOC with depth is common in many natural ecosystems, managed grasslands and forests, and conservation-tilled cropland (Franzluebbers *et al.* 2000; Blanco-Canqui *et al.* 2006; Jinbo *et al.* 2007). The soil surface is the vital interface that receives much of the fertilizer and pesticides applied to cropland and pastures, receives the intense impact of rainfall that can lead to surface sealing following disruption of surface aggregates, and partitions the flux of gases into and out of soil. Franzluebbers (2002a) described a soil quality evaluation protocol that related the degree of soil organic matter stratification to soil quality or soil ecosystem functioning through its conceptual relationship to erosion control, water infiltration, and conservation of nutrients.

Stratification of SOC occurs with time when soils remain undisturbed from tillage (e.g., with conservation tillage and pastures) and sufficient organic materials are supplied to the soil surface (e.g., with cover crops, sod rotations, and diversified cropping systems). Stratification of SOC has been calculated with different depth increments, resulting in somewhat different conclusions of studies. For example, no-tillage (NT) cropland had higher stratification ratio of SOC (1.3, 0-10 cm / 10-20 cm) than under conventional-tillage (CT) cropland (1.0) on an Entic Haplustoll in Argentina (Quiroga *et al.* 2009), but values were lower than in similar evaluations using smaller depth increments on a Typic Kanhapludult in Georgia (3.8 under NT and

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1.1 under CT, 0-6 cm / 12-20 cm) (Franzluebbers and Stuedemann 2008). On a Xerofluvent in Spain, stratification ratio of SOC was greater under conservation tillage than under traditional tillage, but values were higher when calculated as 0-10 cm / 25-40 cm than as 0-10 cm / 10-25 cm (Moreno *et al.* 2006). On reclaimed minesoils in Ohio, stratification ratio of SOC (0-15 cm / 15-30 cm depth) increased with time under pasture and forest management (Akala and Lal 2001). During pasture development in Georgia, stratification ratio of SOC (0-15 cm / 15-30 cm depth) increased from 2.4 at initiation to 3.0 $\pm$ 0.7 at the end of 5 years to 3.6 $\pm$ 0.6 at the end of 12 years (Franzluebbers and Stuedemann 2005; 2009).

The objective of this evaluation was to identify the impact of different sampling depths on the calculated value of stratification ratio among different land uses from historical soil cores collected throughout Georgia. Relationships of stratification ratio to water runoff, soil erosion, nutrient loss, and SOC sequestration are implied from a review of literature. Such relationships need to be quantified in the future.

Materials and methods

SOC data were evaluated from 267 soil-survey profiles collected from 1954 to 1986 throughout Georgia (Perkins, 1987). SOC was determined by wet oxidation (Peech *et al.* 1947). Concentration of SOC was regressed upon depth of sampling (mid-point of sampling interval, which averaged a 10-cm interval) using the following equation:

$$SOC = a + b \cdot \exp(-c \cdot D)$$

where, SOC is soil organic C (g /kg), a is the minimum concentration of SOC deep in the profile (g/kg), b is the peak SOC concentration at the surface (g /kg), c is a decay coefficient controlling the magnitude of decline in SOC concentration with depth (cm^{-1}), and D is depth (cm). Number of sampling intervals was 6 $\pm$ 1 per profile. The mid-point of the upper-most sampling interval was 9 $\pm$ 3 cm (14.0 $\pm$ 8.9 g SOC /kg) and the lowest mid-point was 140 $\pm$ 37 cm (1.2 $\pm$ 1.0 g SOC /kg). Mean soil-profile distributions were developed from predictions with a unique equation for each soil profile at 0.1, 5, 10, 20, 30, 40, 50, 60, 70, 80, 90, 100, 125, 150, 175, and 200 cm depths. Stock of SOC was determined from concentration and bulk density of 0-5, 5-10, 10-20, 20-30, 30-40, 40-50, 50-60, 60-70, 70-80, 80-90, 90-100, 100-125, 125-150, 150-175, and 175-200 cm intervals. Bulk density was assumed to be negatively related to SOC concentration using the equation (Franzluebbers 2010):

$$BD = 1.71 \cdot \exp(-0.013 \cdot SOC)$$

Where, BD is bulk density ($Mg\ m^{-3}$) and SOC is soil organic C concentration (g /kg). Stock of SOC was also calculated summed to various cumulative depths from the surface.

Mean soil-profile distributions of SOC and stocks of SOC were compared among soil orders, major land resource areas, and land uses. Significant differences were declared at $p \leq 0.05$.

Results and discussion

From the 1492 samples collected from 267 soil profiles, SOC concentration was highly stratified with depth (Figure 1). A large amount of variation occurred among all sampling depths, as evidenced by the coefficient of variation ranging from 74 to 98%. Soil profiles were, therefore, sorted into categories of soil orders (205 Ultisols, 35 Alfisols, 11 Entisols, 8 Inceptisols, 6 Spodosols, and 2 Mollisols), major land resource area within the large group of Utlisols (102 Coastal Plain, 47 Piedmont, 25 Ridge and Valley, 17 Blue Ridge, and 14 Flatwoods), and land use within soil orders and major land resource areas (130 cropped, 68 forested, 49 pasture, and 20 miscellaneous use). Depth distribution of SOC was significantly affected by land use category (Figure 2). At 5- and 10-cm depths, SOC concentration was greater under pastureland and forestland than under cropland. At 20-, 30-, and 40-cm depths, SOC concentration was greater under pastureland than under forestland and cropland. At 50- to 100-cm depths, SOC concentration was greater under pastureland than under cropland; forestland was not different from either of the extremes. Stratification ratio of SOC was similarly different between the less-disturbed land uses of forestland and pastureland compared with the more-disturbed land use of cropland. Stratification ratio of SOC was 4.9 under forestland, 4.7 under pastureland, and 3.2 under cropland when calculated as 0-10 / 20-30 cm ($LSD_{p=0.05}$ of 1.7), was 3.6 under forestland, 3.5 under pastureland, and 2.7 under cropland when calculated as 0-20 / 20-40 cm ($LSD_{p=0.05}$ of 0.9), and was 3.8 under forestland, 3.6 under pastureland, and 3.1 under cropland when calculated as 0-30 / 30-60 cm ($LSD_{p=0.05}$ of 0.8). Calculation of stratification ratio of SOC was more discerning among land uses when the numerator was limited to the surface 10 to 20 cm only.

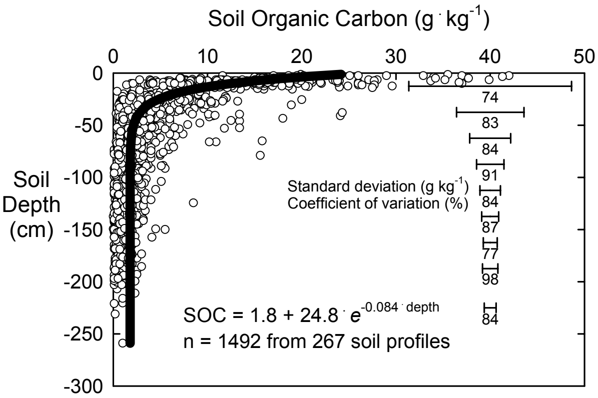

Figure 1. Soil organic C depth distribution from all 267 soil profiles in Georgia.

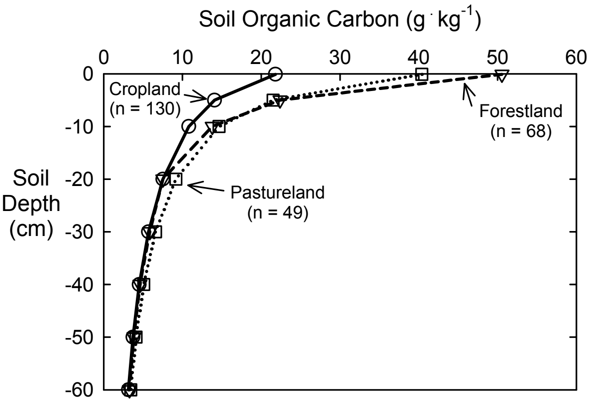

Figure 2. Soil organic C depth distribution when averaged across data within a land use category.

This survey approach resulted in unequal distribution of observations among soil orders, major land resource areas, and land use systems. Due to the low number of observations in Alfisols, Entisols, Inceptisols, Mollisols, and Spodosols, no differences in SOC stock at various depths and in stratification ratio of SOC were detected (data not shown). Only in Ultisols with sufficient observations were there differences in SOC stock and in stratification ratio of SOC (Table 1). Pasture land use contained significantly greater SOC stock than cropland in Blue Ridge, Piedmont, and Coastal Plain MLRAs, but not in Ridge / Valley and Flatwoods MLRAs (Table 1). Across all soil orders and MLRAs, cropland contained lower SOC than other land uses at 0-10, 0-30, and 0-100 cm depths. Stratification ratio of SOC was greater under forestland and pastureland than under cropland. Unfortunately, detailed management information from this soil survey approach was not reported. There are a diversity of crop and pasture management strategies (e.g. crop rotation sequence, cover cropping, manure application, tillage type, stocking rate, fertilization regime, etc.) that could influence SOC sequestration, but such differences could not be separated in this analysis.

Table 1. Stock of soil organic carbon (SOC) at various depths and stratification ratio of SOC among major land resource areas (MLRA; among Ultisols) and general land use category. All is for all soil orders and MLRAs.

MLRA	Land use	No. obs.	Stock of SOC (Mg/ha)			Stratification ratio		
			0-10 cm	0-30 cm	0-100 cm	0-10/20-30 cm	0-20/20-40 cm	0-30/30-60 cm
Blue	Crop	7	21.5	46.7	80.7	2.4	2.2	2.5
Ridge	Pasture	2	34.8	76.7	120.4	2.9	2.7	3.2
	Alternate	3	37.3	72.1	108.6	5	3.7	3.8
	Forest	5	26.4	48.9	76.7	3.8	3.2	3.7
LSD $_{(p=0.05)}$			*13.4**	*24.7**	*33.7**	*2.9*	*1.6*	*1.7*
Ridge	Crop	13	23.6	49	76.7	3.2	2.8	3.3
and	Pasture	4	29	48.2	69.2	8.8	6	5.8
Valley	Alternate	4	26.5	59.2	99.1	2.3	2.2	2.7
	Forest	4	27.1	52.9	79.6	3.7	3.2	3.6
LSD $_{(p=0.05)}$			*13.1*	*24.9*	*29.7**	*4.3**	*2.7**	*2.6**
Piedmont	Crop	27	19.5	40	64.6	3	2.6	3.1
	Pasture	8	29.6	53.8	78.6	5.3	4.1	4.5
	Forest	12	28	55.9	86.4	3.8	3.2	3.5
LSD $_{(p=0.05)}$			*5.1**	*9.6**	*13.9**	*1.9**	*1.1**	*1.1**
Coastal	Crop	67	16.8	34.7	57.1	3.1	2.7	3.1
Plain	Pasture	13	25	47.2	70.1	6.9	4.5	4.2
	Alternate	10	20.9	46.2	78.1	2.5	2.3	2.7
	Forest	12	25.6	48.9	83.6	7.4	4.6	4.3
LSD $_{(p=0.05)}$			*7.0**	*13.6**	*23.8**	*3.4**	*1.6**	*1.3**
Flatwoods	Crop	2	15.1	25.8	33.4	4.9	4.4	5.9
	Pasture	2	9.2	20.9	34	1.9	1.9	2.2
	Forest	10	17.7	28.5	42.6	6.3	4.7	4.8
LSD $_{(p=0.05)}$			*10.4*	*14.9*	*18.3*	*6.5*	*4.3*	*4.7*
All	Crop	130	19.1	39.9	66.1	3.2	2.7	3.1
	Pasture	49	25.9	52.5	86.2	4.7	3.5	3.6
	Alternate	20	25.2	53.2	85.5	3.1	2.7	3.2
	Forest	68	25	48.3	77.7	4.9	3.6	3.8
LSD $_{(p=0.05)}$			*3.7**	*7.4**	*12.9**	*1.7**	*0.9**	*0.8*

Stratification of SOC with depth has been shown to (a) positively impact soil structural integrity and water infiltration (Franzluebbers 2002b), (b) reduce soil loss and nutrient runoff (Franzluebbers 2008), (c) enhance soil biological activity (Franzluebbers 2009), and mitigate greenhouse gas emissions (Franzluebbers 2010). Much more research is needed to bolster these relationships so that this broad measure of soil quality can help promote greater resource efficiency and sustainability in the future.

Conclusions

Soil organic matter under conservation management (pastureland and forestland) is typically more stratified with depth than under conventional cropping. This stratification should be viewed as an improvement in soil quality, because several key soil functions are enhanced, including soil structure, water infiltration, soil conservation, cycling of nutrients, and sequestration of C from the atmosphere. This analysis of deep-soil profiles throughout Georgia indicates that stratification ratio of SOC could be best calculated as 0-10/20-30 cm or 0-20/20-40 cm, because management induced changes in SOC are generally restricted to the surface 10 to 20 cm in soils of this warm and humid region.

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