INVESTIGATING PROFILE AND LANDSCAPE SCALE VARIABILITY IN SOIL ORGANIC CARBON: IMPLICATIONS FOR PROCESS-ORIENTED PRECISION MANAGEMENT

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ABSTRACT

Mitigation of rising greenhouse gases concentrations in the atmosphere has focused attention on agricultural soil organic C (SOC) sequestration. However, field scale knowledge of the processes and factors regulating SOC dynamics, distribution and variability is lacking. The objectives of this study are to characterize the profile (0- to 150-cm) and landscape variability in the distribution of SOC within a 37-ha Palouse field under agricultural management. A systematic, non-aligned grid of 177 geo-referenced sample locations was established at the Washington State University Cook Agronomy Farm (CAF) near Pullman, WA. Intact soil cores (0- to 153-cm) were collected, soils were described, classified, the surface divided into 0- to 30-cm increments and then by soil horizon to a depth of 153-cm and analyzed for soil bulk density and SOC. Profile (0- to 153-cm) SOC ranged from 54 to 272 Mg C ha^{-1} over the 37-ha field. The SOC content for the surface (0- to 30-cm) and subsurface (30- to 153-cm) ranged from 26 to 79 Mg C ha^{-1} and 14 to 193 Mg C ha^{-1}, respectively. Thatuna silt loams averaged 149 Mg C ha^{-1} followed by Palouse (125 Mg C ha^{-1}) and Naff (111 Mg C ha^{-1}) silt loam soil series. Landscape SOC redistribution via soil erosion was evident and erosion impacts on field SOC heterogeneity must be quantified if SOC sequestration and management impacts are to be adequately assessed. Furthermore, success in developing precision conservation strategies will require knowledge of site-specific processes and factors contributing to variability in soil productivity, SOC storage and nutrient dynamics.

Keywords: soil organic C, field variability, soil profile C, erosion

INTRODUCTION

Soil organic matter (SOM) is a critical component of agricultural systems and provides a range of functions important to crop production, soil conservation, and environmental performance. This includes enhanced nutrient cycling, promotion of soil productivity (Seybold et al., 1997), and regulating the global C cycle (Lal, 2004). Rising atmospheric concentrations of CO_2, a greenhouse gas, has shifted attention to agricultural soil organic C (SOC) sequestration as one global climate change mitigation strategy (Lal, 2004). However, field scale knowledge of the size and variability in SOC is lacking due to the complex physical, chemical, and biological processes or factors regulating SOM dynamics (Batjes, 1996; VandenBygaart, 2006).

Determining the relationship between terrain attributes and variability in SOC distribution is confounded by pedogenic factors (Jenny, 1941; VandenBygaart, 2006), land use history and management (Batjes, 1996). Variability in SOC has been widely recognized at both the pedon and landscape scale (Pennock et al., 1987; Bergstrom et al., 2001;VandenBygaart, 2006). In agro-ecosystems, SOC content is a balance between C additions from unharvested plant residues and roots, organic amendments and erosional deposits and C losses through decomposition of organic materials and soil erosion processes (Paustian et al., 1997; Follett, 2001; Post et al., 2001). In the Palouse region of eastern Washington, considerable landscape level variability in native SOC was present before the initiation of dryland farming (Busacca and Montgomery, 1992). Native SOC within a given landscape ranged from about 2% on summit positions to almost 4.5% on north-facing footslopes (Rodman, 1988). However, it is often overlooked that soil erosion processes, accelerated by dryland farming practices, are likely to have increased variability in profile and landscape scale SOC distribution (Pennock et al., 1994).

Soil erosion due to agricultural practices has been estimated to have removed 100% of the topsoil from 10% of the Palouse landscape with another 25 to 75% loss from 60% of agricultural land (USDA, 1978). The loess derived soils of the Palouse region of eastern Washington and northern Idaho form a steeply sloping and complex soil-landscape dominated by Mollisol soil orders (Busacca and Montgomery, 1992). Dryland agricultural management has had a tremendous influence on native SOC primarily due to shifts from perennial bunch grass dominated vegetation (Daubenmire, 1970) to annual cropping, coupled with inversion tillage that has resulted in historical soil erosion rates of over 25 Mg soil yr^{-1} (USDA, 1978). Purakayastha et al. (2007) estimated that 50 to 70% of SOC had been lost from upland soils.

Landscape scale research is needed to improve our understanding of the confounding effects of natural or historical topographic variability in SOC and the impact of management on site-specific soil processes regulating SOC pool size, distribution and dynamics (Pennock et al., 1994; Gregorich et al., 1998; Bergstrom et al., 2001; VandenBygaart, 2006; Senthilkumar et al., 2009). Soil erosion processes of particle detachment, sediment transport and deposition either within fields or associated surface waters are receiving increased scrutiny as important factors influencing field-scale SOC budgets (De Jong and Kachanoski, 1988; Starr et al., 1999; Fang et al., 2006; Chaplot et al., 2009). The objectives of this research are to: (i) characterize the profile distribution of SOC (0- to 150-cm); (ii) characterize the variability in SOC distribution across a complex landscape; and (iii) use SOC and soil series data to aid in developing a conceptual framework for assessing farm scale management practice impacts on SOC dynamics within Palouse landscapes under agricultural management.

METHODS

A systematic, non-aligned grid of 369 geo-referenced sample locations was established in 1999 on 37-ha of the Washington State University Cook Agronomy Farm (CAF) near Pullman, WA. Previous history of the land included production of small grains, mostly wheat (*Triticum aestivum* L.) and barley (*Hordeum vulgare* L.), using conventional inversion tillage practices. Intact soil cores (0- to-153 cm depth, 4.1-cm diameter) were collected at alternating points (177 cores) and profiles were described (Soil Survey Manual, 1993) to characterize soil horizon and morphological properties and to classify soil at the series level (field soil map units). Following classification, soil cores were divided by 10-cm increments to a depth of 30 cm and then by soil horizon to a depth of 153-cm for analyses of soil bulk density (subsample dried at 105^{o}C) and SOC. Soil samples were dried at 55^{o}C and ground to pass 180-µm screen for determination of total soil C by dry combustion using a CNS Leco analyzer (Leco Corp., St. Joseph, MI). Inorganic soil C was determined by a modified pressure-calcimeter method (Sherrod et al., 2002) and SOC for each sample was obtained by difference. SOC was expressed on a mass per unit area basis using depth increments of 0- to 30-cm and 30- to 153-cm as well as on a total profile basis for the 0- to 153-cm core using bulk density and soil C concentration (% by weight) data.

Soil organic C data were spatially mapped using inverse distance square interpolation. Analyses of SOC using ordinary kriging and co-kriging did not yield maps with satisfactory error terms and were not used to display spatial patterns. Analysis of variance was used to assess soil series (USDA, 1980) and field soil map unit (field soil description and classification) differences in SOC among the 0- to 30- cm, 30- to 153-cm and 0- to 153-cm depth-increments (Proc Mixed, SAS, v. 9.1.3). Although a soil series approach will not elicit processes or factors controlling SOC variability, it could inform stratification of sampling sites for evaluating spatial patterns of and/or management impacts on SOC dynamics (Bergstrom et al., 2001).

Crop yields of wheat, barley, peas (*Pisum arvense* L.) and canola (*Brassica napus annua* Koch) were sampled at each of the 369 geo-referenced points (2-m^{2} sample area) for five years (1999-2003) to determine relative yield (crop yield at each point divided by the largest crop yield) each year and to calculate the average relative yield for each geo-referenced point. Relative yield data were interpolated using ordinary kriging (GSLIB, Deutsch and Journel, 1998) to display field spatial patterns.

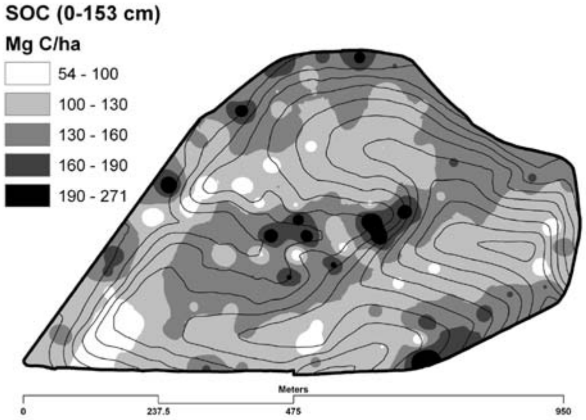

Figure 1. Total profile SOC (0- to 153-cm) within a 37-ha field at the Cook Agronomy Farm near Pullman, WA in 1999.

RESULTS

The total soil profile (0- to 153-cm) SOC ranged from 54 to 272 Mg C ha-1 (Fig. 1) and averaged 131 Mg C ha-1 (Table 1) over the 37-ha field. Total profile SOC content was highest on northern aspects and bottomlands dominated by moderately well-drained Thatuna silt loams with inclusions of somewhat poorly drained Latah and Caldwell soil series (Fig. 2). The soil survey mapped Thatuna silt loams averaged 149 Mg C ha^{-1} followed by Palouse (125 Mg C ha^{-1}) and Naff (111 Mg C ha^{-1}) silt loam soil series (Table 1). The lowest total profile SOC occurred on upland landscape positions (i.e., ridge-tops and knobs) of southern aspect and in particular the well-drained Staley silt loams (97 Mg C ha^{-1}) (Table 1). Staley silt loam inclusions were identified in well-drained upland positions of the Palouse and Naff silt loam soil series during the field classification (Fig. 2).

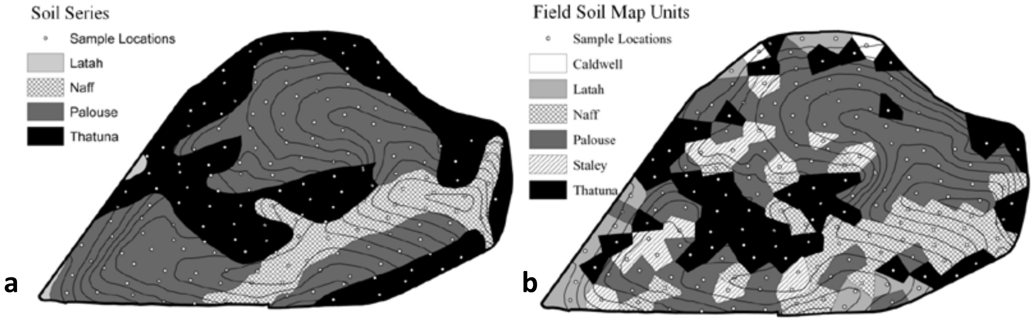

Figure 2. Maps of a. USDA (1980) delineated soil series and b. field soil classification based on descriptions of intact soil cores sampled in 1999 at geo-referenced sites for the 37-ha field at the Cook Agronomy Farm near Pullman, WA.

Table 1. Soil series taxonomic classification, field area, and mean SOC in the 37-ha Washington State University Cook Agronomy Farm, Pullman, WA.

Soil series	Taxonomic classification	Field area	SOC†		
		%	(0-30 cm)	(30-153 cm)	(0-153 cm)
			--------------- Mg ha^{-1} ---------------		
Soil survey					
Naff	Fine-silty, mixed, superactive, mesic Typic Argixerolls	15	49a (17)	61a (31)	111a (22)
Palouse	Fine-silty, mixed, superactive, mesic Pachic Ultic Haploxerolls	50	55b (17)	69a (32)	125b (22)
Thatuna	Fine-silty, mixed, superactive, mesic Oxyaquic Argixerolls	35	59c (18)	90b (41)	149c (29)
Field survey					
Staley	Fine-silty, mixed, superactive, mesic Calcic Haploxerolls	9	49a (20)	48a (38)	97a (25)
Naff	Fine-silty, mixed, superactive, mesic Typic Argixerolls	16	54ab (19)	69bc (35)	122bc (26)
Palouse	Fine-silty, mixed, superactive, mesic Pachic Ultic Haploxerolls	42	55b (17)	77cd (38)	132c (26)
Thatuna	Fine-silty, mixed, superactive, mesic Oxyaquic Argixerolls	25	59c (17)	84d (39)	143d (27)
Latah	Fine, mixed, superactive, mesic Xeric Argialbolls	7	59bc (21)	80bcd (39)	139bcd (27)
Caldwell	Fine-silty, mixed, superactive, mesic Cumulic Haploxerolls	1	59ns (1)	103ns (2)	163ns (1)
	ALL	100	56 (18)	75 (40)	131 (28)

†SOC = Soil Organic Carbon means; mean separation ($p \leq 0.1$) using Tukey; and coefficient of variation (CV) in parentheses.

In the surface 30-cm SOC ranged from 26 to 79 Mg C ha^{-1} (mean of 56 Mg C ha^{-1}) and subsoil SOC (30- to 153-cm) ranged from 14- to 193-Mg C ha^{-1} (mean of 75 Mg C ha^{-1}) (Fig. 3). Surface 30-cm SOC was positively related in many, but not all, locations to subsoil SOC but subsoil SOC values exhibited greater variation compared to the surface soils. The CV was up to 2.3 times greater in the subsurface compared to the surface SOC within a given soil map unit (Table 1). Field description of the 177 soil cores revealed inclusions of Staley, Latah and Caldwell series soil within the field (Fig. 2). The total profile SOC content of Staley silt loams was significantly less ($p \leq 0.05$) than that of the other soil series. The Latah and Caldwell silt loam inclusions, which occupy similar landscape positions of the Thatuna silt loams, were not significantly different in profile SOC content than the Thatuna series soil (Table 1).

The ratio of surface to subsurface SOC averaged 0.83 and ranged from 0.33 to 3.91 (Fig. 4). In this study, the large ratios of surface to subsurface SOC are indicative of field areas where soil erosion processes of detachment and transport have been more dominant than soil deposition. In contrast, low surface to subsurface SOC ratios indicate areas where deposition of SOC has occurred and/or areas where transported subsoil from historically eroded upland areas with low SOC concentrations, have buried the previous topsoil. In general, areas with surface to subsurface ratios between 0.5 and 0.65 exhibited higher subsurface SOC contents (Figs. 3 and 4). In southern aspects, high ratios appeared to correspond with areas of low surface and subsurface SOC (Figs. 3 and 4). However, for some northern aspect landscape positions, high ratio values were not associated with lower surface SOC but did correspond well with areas of low subsurface SOC (Figs. 3 and 4). Areas of higher relative yield were generally associated with areas of higher SOC; however, many exceptions to this relationship were apparent (Figs. 1, 3 and 4).

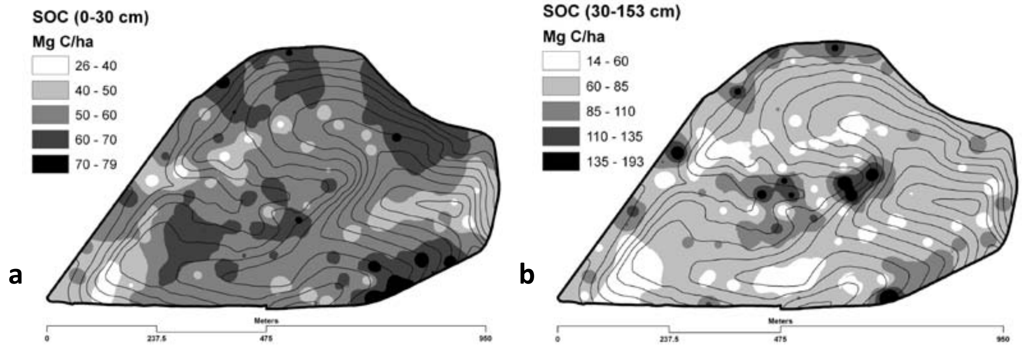

Figure 3. The SOC content within the 37-ha field at the Cook Agronomy Farm for (a) surface (SOC, 0-30 cm) and (b) subsurface (SOC, 30-153 cm) depths.

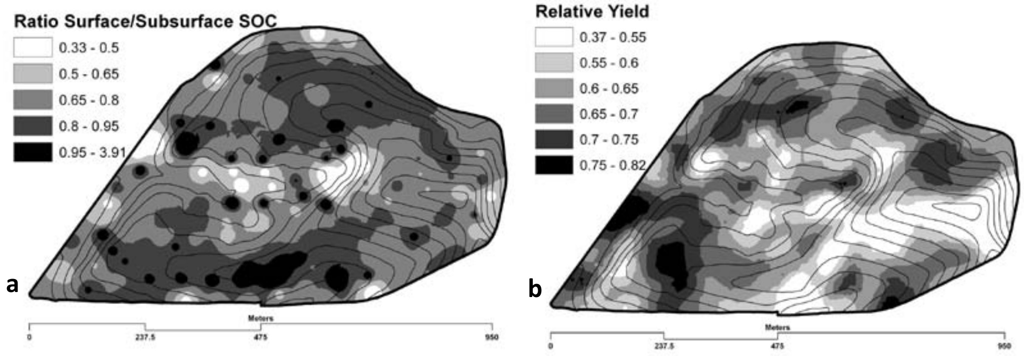

Figure 4. The (a) surface to subsurface SOC ratio (0-to 30-cm/30- to 153-cm) and (b) relative yield for the 37-ha Cook Agronomy Farm field.

DISCUSSION

The five-fold range in profile SOC (0- to153-cm) highlights the tremendous within-field variability of SOC previously reported for the Palouse region (Fig. 1; Rodman, 1988; Busacca and Montgomery, 1992). Field SOC was usually greater and more variable in the subsoil (30-to 153-cm) than in surface (0- to 30-cm) soil (Table 1; Fig. 2). These data strongly support the necessity of soil sampling beyond surface depths if SOC sequestration is to be adequately assessed (Baker et al., 2007; Huggins et al., 2007; Blanco-Canqui and Lal, 2008). Heterogeneity of SOC content was expressed within all soil map units (Table 1, Figs. 1 and 2). The lower SOC concentrations in Staley silt loams compared to all other soil series are evidence that the combination of soil erosion and mixing of surface and subsurface horizons by tillage has likely diluted surface SOC over time.

Not often recognized or measured, however, is the effect of soil erosion processes on within-field soil deposition and site-specific increases in SOC. Soil erosion is a selective process and transported sediments are enriched in clay-sized particles (Ongley et al., 1981) as well as particulate and dissolved organic C (Lal, 1995). The close proximity of areas with low and high surface to subsoil SOC ratios indicates a coupling of soil detachment, transport and deposition within the field that has likely contributed to the large within-field variability of SOC stocks (Fig. 2, Table 1). Furthermore, scouring of soil from field areas susceptible to concentrated water flow and the formation of surface gullies followed by subsequent deposition of soil with low SOC concentrations could explain the occurrence of low SOC stocks and surface to subsoil SOC ratios in footslope positions (Fig. 3, Fig. 4).

Erosion-related processes that laterally redistribute SOC may be as important as biologically mediated processes in determining SOC stocks at a specific site. Historical soil erosion processes have likely decoupled current SOC stocks from the common expectation that SOC will be linearly related to C inputs (Larson et al., 1972; Rasmussen and Collins, 1991; Huggins et al., 1998). This raises the question as to whether or not current C inputs and decomposition regimes are capable of maintaining the SOC in areas with disproportionately large SOC stocks if soil erosion is curtailed. This will be somewhat dependent on the mean residence time of the buried, subsoil SOC and is an interesting area for future research.

Topography and terrain attributes have been increasingly utilized to provide insights into explaining field-scale SOC variability (Moore et al., 1993; Gessler et al., 2000; Bergstrom et al., 2001; Mueller and Pierce, 2003; Terra et al., 2004; Senthilkumar et al., 2009). Palouse soils generally exhibit strong profile and plan curvature (across-slope) that likely influences the lateral distribution of pedologic, hydrologic and geomorphic processes (Pennock et al., 1987) involved in regulating soil productivity, SOC storage and nutrient dynamics. The development of precision conservation strategies that tailor management practices to site-specific conditions requires knowledge of within-field SOC variability. For example, locations of Conservation Reserve Program plantings or other conservation-based practices might target field areas with low SOC, while precision nutrient management will require knowledge of SOM cycling and the bioavailability of N, P, S and other essential nutrients associated with different within-field levels of SOC or as affected by decreased SOM buffering, soil acidification or other adverse subsoil properties (Pan and Hopkins, 1991; Pan et al., 1992; Fiez et al., 1995; Brown et al., 2008).

CONCLUSIONS

An understanding of the effects of landscape processes on SOC redistribution as well as the effects of this redistribution on site-specific SOC dynamics is needed for assessment of agroecosystem services and functions (e.g., the dynamics of SOC in depositional areas where large stocks of SOC have accumulated). Soil sampling methodology and process-oriented simulation modeling of SOC will need to incorporate landscape processes and effects that result in extreme SOC variability and redistribution if within-field stocks of SOC are to be quantified and the impact of management changes assessed. This is particularly important in landscapes where erosion processes are operative. The large within-field variability in SOC should be considered in the application of precision conservation practices such as site-specific nutrient management and placement of vegetative buffers and conservation plantings.

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