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ORIGINAL RESEARCH

Soil Organic Carbon Stocks in a Large Eutrophic Floodplain Forest of the Southeastern Atlantic Coastal Plain, USA

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Abstract Anthropogenic land use has significantly altered sediment and nutrient dynamics at watershed-scales, resulting in significant redeposition within large floodplain ecosystems. Some upland land uses have had documented negative effects on soil carbon (C) stocks, although the specific impacts of these disturbances on soil organic carbon (SOC) dynamics in depositional environments are poorly understood. Assessment of SOC stocks in floodplain environments will allow for more precise estimates of C distribution at watershed and regional scales. In this study, we measured SOC pools to depths of 100 and 200 cm in four distinct floodplain landscapes (natural levee, flats, mineral wetlands, organic wetlands) in a large bottomland forest within Congaree National Park, South Carolina, USA. Mean SOC stocks to a depth of 100 cm were 108–109 Mg C ha^{-1} in flats and levees, 193 Mg C ha^{-1} in mineral wetlands, and 533 Mg C ha^{-1} in organic wetlands. In addition, hydric soils contained significantly more SOC in deep horizons (100–200 cm depths). At a regional scale, similar alluvial soils within large floodplains were estimated to store approximately 0.1 Pg of SOC. These results highlight the importance of inclusion of deep SOC storage in alluvial settings when estimating watershed C budgets.

Keywords Floodplain · Soil carbon · Fluvial processes · Riparian forest

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Introduction

Soils are the largest terrestrial reservoir of atmospheric carbon (C) which is estimated to be nearly three times greater than C stored in vegetation (Eswaran et al. 1993; Schlesinger 1997; Lal 2003). Soil organic carbon (SOC), primarily derived from plant productivity, represents the majority (>65 %) of the terrestrial soil C pool (Batjes 1996). Quantification of current SOC stocks has become increasingly important because many soils have the capacity to sequester significant amounts of atmospheric CO_2 via afforestation (Lal 2005). In addition, SOC is necessary for many beneficial biogeochemical functions in soils such as removal of excess nitrate (NO_3^-) from pore, ground, and surface waters via denitrification (Nelson et al. 1995; Karlen et al. 1997; Groffman et al. 2009). Recognition of the many functions and values associated with SOC has led to an increase in the number of C accounting studies undertaken to quantify the spatial extent of SOC at watershed, regional, and global scales (Post et al. 1985; Eswaran et al. 1993; Dixon et al. 1994; Batjes 1996; Davis et al. 2004; Izaurralde et al. 2007).

Alluvial landscapes are depositional environments that have the potential to accumulate and store large quantities of organic C (Stallard 1998; Zehetner et al. 2009). Floodplain soils contain both SOC derived from local vegetation productivity (autochthonous C) and allochthonous C deposited with mineral sediment during flood events (Noe and Hupp 2009). Floodplain ecosystems can be directly influenced by changes in watershed land uses and thus can act as sinks for C eroded from catchment uplands (Stallard 1998; Lal 2003). Increased agricultural or urban land use can result in significant losses of upland SOC stocks (Lal 2005), as well as increasing rates of riparian sedimentation or scour, overbank flooding, and nutrient inputs (Cavalcanti and Lockaby 2005; Trimble 2008; McCarty et al. 2009; Jolley et al. 2010). In addition, large spatially heterogeneous floodplains contain various alluvial landforms that can have significantly different potentials for sequestration of organic C due to variations in annual hydroperiod, plant species composition, soil characteristics, and microbial communities (Clawson et al. 2001; Cierjacks et al. 2011; Wohl et al. 2012). Spatial heterogeneity in freshwater mineral wetland soils and floodplain forests likely contributes to the observed variability of landscape-scale SOC pools in these ecosystems (Kern 1994; Bridgham et al. 2006). Comprehensive data regarding C dynamics in these ecosystems would be invaluable to global C models (Zehetner et al. 2009) because floodplains cover greater than 2.0×10^6 km^2 of the global land area (Tockner and Stanford 2002).

Another important consideration for watershed-scale SOC analyses is the role of floodplains in regulating C losses during land use change. There are many reports of impacts on upland SOC resulting from conversion of native forest to agricultural land use (Schlesinger 1997; Lal 2005). However, it is unclear what proportion of SOC is mineralized during land disturbance and how much is retained within depositional landscapes such as floodplains, wetlands, and freshwater reservoirs (Stallard 1998; Lal 2003; Cole et al. 2007). Agricultural "legacy sediments" are an example of drastic sediment and C redistribution in the eastern United States. Legacy sediments were deposited in riparian areas during periods of unsustainable upland agricultural activities in the 19th and early 20th centuries (Jacobson and Coleman 1986). During this time period, stream sediment loads increased and in many watersheds various dam structures increased sediment trapping efficiencies, resulting in entrainment of eroded materials within riparian areas (Trimble 2008; Walter and Merritts 2008). In many cases, these legacy sediment deposits exceed 100 cm in depth (Jacobson and Coleman 1986) and can exceed 400 cm on some floodplains (Hupp et al. 2009).

Many SOC studies are based on sampling depths of 100 cm, which is typically sufficient in uplands because inputs of autochthonous SOC are greatest at the soil surface resulting in a shallow distribution of C (Jobbágy and Jackson 2000). However, assessment of deep SOC storage (>100 cm) is of greater importance in floodplain ecosystems where soil surfaces undergo episodic burial leading to establishment of a new floodplain surface and rapid incorporation of additional autochthonous SOC (Carter et al. 2009; Zehetner et al. 2009). As a result of these processes, multiple buried surfaces (Ab horizons) can be found within alluvial soils (Blazejewski et al. 2009). Thus, sampling of deep soil horizons in floodplains may be necessary to construct more precise ecosystem SOC budgets and evaluate the fate of eroded C at the watershed scale (Izaurralde et al. 2007). Clearly, additional data regarding the spatial distribution of alluvial SOC are necessary to better understand terrestrial SOC distribution, floodplain soil genesis, and soil biogeochemical functions in riverine forest ecosystems. Therefore, the specific goals of this research were to i) quantify the vertical and spatial distribution of alluvial SOC stocks, ii) quantify SOC pools in common floodplain landscapes of the Atlantic Coastal Plain, and iii) utilize these data to estimate regional SOC storage in large alluvial floodplains of the southeastern USA.

Study Site

Soil samples were taken from an old-growth bottomland hardwood forest within Congaree National Park (CONG). The Park is located in the Upper Coastal Plain physiographic region of central South Carolina, approximately 30 km downstream from the city of Columbia (Fig. 1). The Congaree River is a large eutrophic (red water) river that drains a large portion (>21,000 km^2) of the Piedmont physiographic province of northern South Carolina. The basin has varied land cover characteristics and as of 2006, land area within the watershed was 67.7 % forested or wetlands, 22.7 % agricultural, and 9.6 % developed or barren land, of which about 2.0 % was impervious surface (2006 National Land Cover Dataset, Fry et al. 2011). Historically, the entire Congaree basin underwent widespread deforestation for cotton agriculture during the late 19th and early 20th century (Trimble 2008).

The region has a humid subtropical climate that receives approximately 1220 mm of annual precipitation and has an average annual air temperature of 17.6 °C. The Congaree floodplain contains many fluvial landscapes including the natural river levee, hardwood flats, sloughs, backswamps, oxbow lakes, and depressional seep wetlands. Forest composition within CONG varies by alluvial landforms (Allen et al. 2005) with mixed hardwoods such as, sugarberry (*Celtis laevigata* Willd.), sweetgum (*Liquidambar styraciflua* L.), American sycamore (*Platanus occidentalis* L.), and mixed bottomland oaks (e.g. *Quercus laurifolia* Michx., *Q. nigra* L., *Q. phellos* L.) associated with drier landscapes (levees, flats, ridges) of the floodplain. Bottomland wetlands (sloughs, backswamps, oxbows) are dominated by more flood tolerant overstory species such as baldcypress (*Taxodium distichum (L.) Rich.*), water tupelo (*Nyssa aquatica* L.), and swamp tupelo (*Nyssa biflora* Walter).

Materials and Methods

Soil coring locations representative of common floodplain landforms were selected using available geographical information system (GIS) soil survey geographic (SSURGO, 1:20, 000 map scale) database spatial layers. Samples were taken within the four major soil mapping units (18 total polygons) of the Park (Table 1), which are mapped at a series level as Congaree (Fine-loamy, mixed, active, nonacid, thermic Oxyaquic Udifluvents), Tawcaw (Fine, kaolinitic, thermic Fluvaquentic Dystrudepts), Chastain (Fine, mixed,

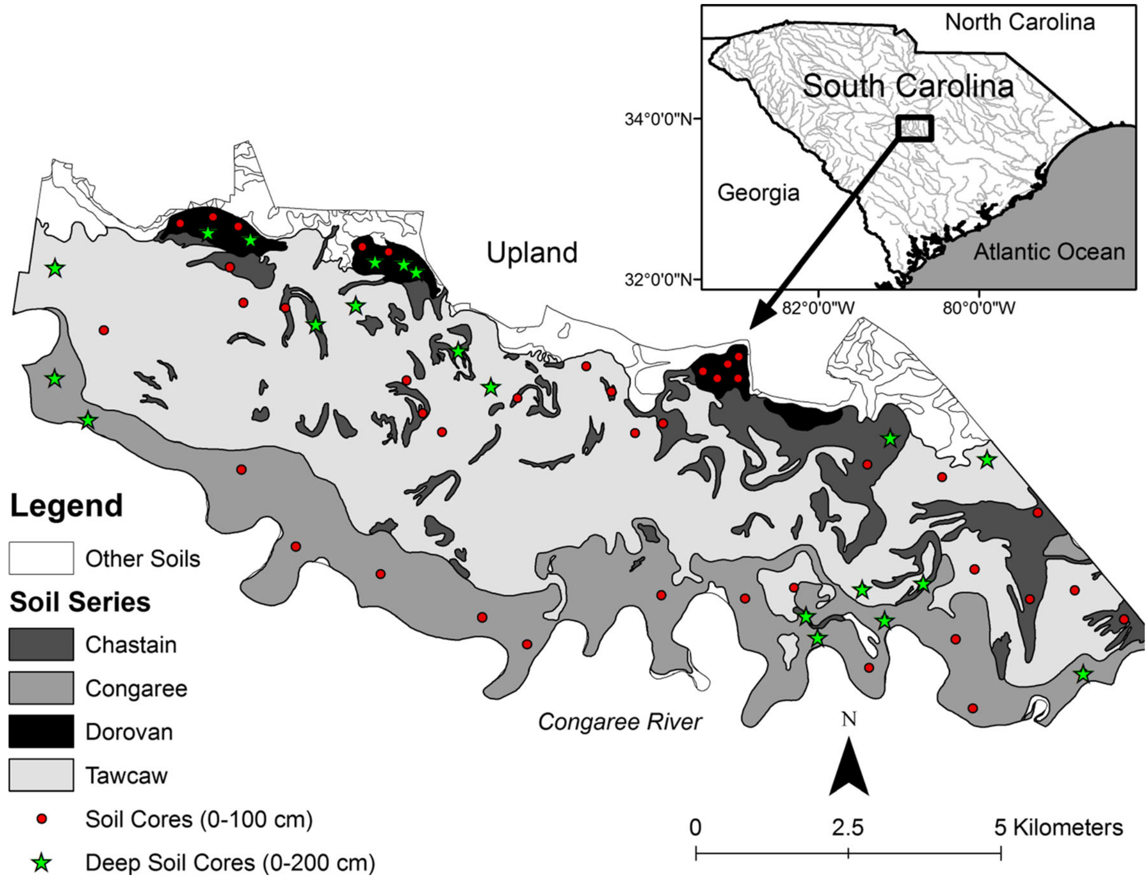

Fig. 1 General location map of Congaree National Park, South Carolina. Soil coring locations from 0 to100 cm and from 0 to 200 cm are indicated by *circle* and *star* symbols, respectively. A total of 15 cores were taken from each of the four major soil mapping units (Congaree, Tawcaw, Chastain, Dorovan series) within the Park

semiactive, acid, thermic Fluvaquentic Endoaquepts), and Dorovan (Dysic, thermic Typic Haplosaprists) (Soil Survey Staff 2013). Congaree and Tawcaw units are mineral soils mapped on the well drained (WD) natural river levee and somewhat poorly drained (SPD) hardwood flats of the floodplain, respectively. Chastain units denote poorly drained (PD) freshwater mineral wetlands and Dorovan units indicate the presence of very poorly drained (VPD) organic soils (Histosols) in depressional seep wetlands located at the upland margins of the active floodplain (Fig. 1). A total of 15 cores (0–100 cm) were taken from each of the four major soil mapping units for a total of 60 soil cores within the floodplain. A subset of 20 core locations (n=5 per mapping unit) were selected for additional deep (100–200 cm depths) sampling

Table 1 Summary of soil mapping unit characteristics used to define the sampling units within Congaree National Park

Soil series[a]	Soil Order[a]	Drainage class	Flooding frequency[b]	Fluvial landforms	Dominant tree species
Congaree	Entisols	Well/Moderately Well	Occasional	Natural Levee, Ridges	*Celtis laevigata, Liquidambar styraciflua, Quercus* spp.
Tawcaw	Inceptisols	Somewhat Poorly	Occasional	Flats, Ridges	*Quercus* spp., *L. styraciflua, C. laevigata*
Chastain	Inceptisols	Poorly	Frequent	Sloughs, Meander Scars, Backswamps, Oxbows	*Taxodium distichum, Nyssa aquatica*
Dorovan	Histosols	Very Poorly	Frequent	Depressional Groundwater Seeps	*Nyssa biflora, Ilex opaca*

[a] Soil mapping series and Order based on soil survey data and U.S. Soil Taxonomy (Soil Survey Staff 2013)

[b] Flooding frequency for soil map units as defined by (Soil Survey Staff 2013): occasional, 5 to 50 % chance; frequent, >50 % chance of flooding on an annual basis

(Fig. 1). All sample locations were recorded using hand-held GPS instruments and geo-referenced relative to the active river channel.

Field Sampling

Soil pedons were described in the field (Schoeneberger et al. 2002) and sampled incrementally to compare soil properties by depth. Samples were collected from 0 to 10 cm and in 15 cm increments (10–25, 25–40, 40–55, 55–70, 70–85, 85–100 cm) downward to 100 cm. Deep soil samples were collected at 25 cm increments (100–125, 125–150, 150–175, 175–200 cm). Bulk soil samples were taken for each depth increment by hand using bucket or clay augers in mineral soils and a customized Macaulay peat auger in mucky mineral or organic soils. In mineral soils, a second auger boring was taken in close proximity (30–50 cm) to the first and a bulk density probe (5 cm length, 5 cm diameter) was used to collect soil cores of known volume from the approximate center of each vertical sampling increment. Soil samples were sealed in plastic sample bags, placed on ice in coolers during transport, and stored at 4 °C until processed in the laboratory.

Laboratory Analyses

Soil bulk density samples were dried to a constant weight at 105 °C, passed through a 2 mm sieve to remove coarse fragments, and bulk density was quantified using the core method corrected for coarse fragment mass and volume (Blake and Hartge 1986; Soil Survey Laboratory Staff 2004). Soil texture was estimated for mineral soil materials using the hydrometer method (Gee and Bauder 1986). Bulk soil samples were air dried and passed through a 2 mm sieve to remove coarse mineral and organic fragments. A homogenized subsample of approximately 5 g was ground with mortar and pestle and passed through a 0.25 mm mesh (number 60) sieve. Ground subsamples were used to quantify total soil C and N concentrations using thermal combustion on a Perkin Elmer 2400 Series II CHNS/O analyzer (Perkin Elmer, Waltham, MA). A representative subsample of soil materials ($n=15$) were qualitatively analyzed for the presence of carbonates using dilute 1 N HCl, and further quantitative analysis ($n=5$) was carried out using concentrated 3 N HCl (Jackson 2005). All samples contained minimal (<0.1 % mass) carbonates, and total C was therefore assumed to be equivalent to SOC. Sample increment depths and bulk density values were used to convert soil C and N concentrations to a landscape-scale mass per unit area (Mg C ha^{-1}).

Spatial Analysis of Floodplain SOC Stocks at Regional Scales

Digital soil survey data were utilized to estimate total floodplain SOC storage at local and regional scales. The SSURGO data (1:20,000 map scale) used to define the sample units (Fig. 1) were also used to scale-up estimates of SOC storage within CONG. The mean SOC pools (Mg C ha^{-1}) from each major floodplain map unit were multiplied by the area of each map unit to yield the total SOC storage (Mg C) within CONG to a depth of 200 cm. Digital General Soil Map of the United States (STATSGO2, 1:250,000 map scale) data were also used to calculate SOC storage in CONG and to scale-up estimates to the greater southeastern Coastal Plain. STATSGO2 data consist of soil survey data aggregated into broadly defined soil associations. Each association has defined proportions of expected soil landscape units, thus weighted averages that take into account the expected area of each soil mapping series were used to scale-up SOC storage estimates beyond CONG. In addition to the soil associations mapped within the Congaree River floodplain, there are a number of similar STATSGO2 associations mapped along large rivers of the southeastern Coastal Plain (i.e., Riverview-Chewacla-Chastain and Toccoa-Congaree-Chewacla map units). These alluvial soils have similar climate, genesis, and natural drainage classes to those evaluated within CONG (Soil Survey Staff 2013). Thus, these soils were assigned mean SOC pools based on natural drainage class and weighted averages were calculated as described above. Individual weighted averages were summed for each STATSGO2 association and error propagation was used to calculate mean standard errors using equations outlined by Amador et al. 2005. The SOC pools were then multiplied by the total area of these mapped associations within the Coastal Plain of the southeastern USA to obtain regional estimates of alluvial SOC storage.

Statistical Analysis

All descriptive and statistical analyses were performed in SAS 9.2 (SAS Institute, Cary, NC, USA). Mean comparisons between two groups were completed using Student's t-tests, such as hydric mineral soils containing buried surfaces vs. those without and the upper 100 cm SOC pool vs. 100–200 cm SOC pool. One-way analysis of variance (ANOVA) with Tukey's honest significant difference tests (PROC GLM) were used for mean comparisons among three or more groups, such as mean SOC stocks among soil mapping units.

Results

Depth Distributions of Alluvial Soil Properties

Depth distributions of soil C varied across the landscapes of the Congaree floodplain (Fig. 2a). Mean soil C concentration displayed a regular decrease (constantly decreasing concentration) with depth for the mineral soils (Congaree, Tawcaw)

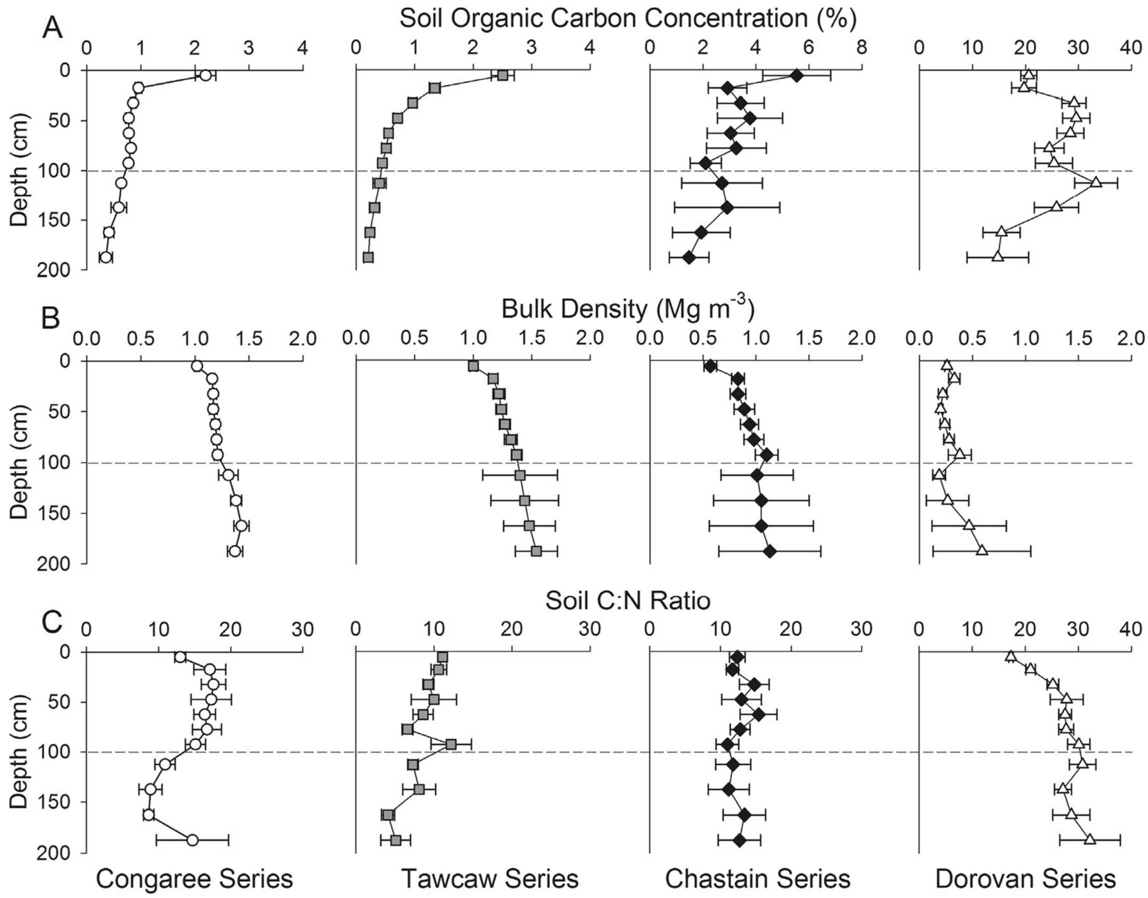

Fig. 2 Mean depth profiles for **a** soil organic carbon concentration (note different x-axis scales for Chastain and Dorovan series), **b** soil bulk density and, **c** soil C:N ratios (note the different x-axis scale for Dorovan series). Means by depth±1 SE, n=15 for 0–100 cm samples, n=5 for >100–200 cm samples

from 2.2±0.2 % near the surface to <0.4±0.1 % C at 200 cm. Among the mineral soils, Congaree units along the natural river levee had higher C concentrations with depth compared to the Tawcaw units. By contrast the hydric mineral soils (Chastain) displayed an irregular decrease (variable decrease or increase in concentration with depth) in C concentration (range 5.5±1.3 to 1.5±0.7 %). In addition, these data had larger standard errors because of the presence of buried surface horizons at various depths within the sampled units. The VPD organic soils (Dorovan) had significantly higher C concentrations (range 15±5.8 to 33±4.0 % C) compared to mineral soils of the floodplain, but showed an irregular decrease in C concentration similar to the mineral hydric soils (Fig. 2a). Soil bulk density increased with depth in all soil mapping units investigated (Fig. 2b). The non-hydric floodplain soils had the highest bulk density values, ranging from 1.0±0.03 to 1.5±0.2 Mg m^{-3}. Dorovan organic soils had the lowest mean bulk density values, ranging from 0.19±0.06 to 0.59± 0.5 Mg m^{-3}. Bulk density mean variability increased in samples >100 cm as a function of smaller sample sizes and increased sand content within certain floodplain landscapes (Fig. 2b).

Depth distributions of soil C:N ratios were variable among the CONG mapping units (Fig. 2c). The non-hydric soils generally displayed decreasing C:N ratios with depth, from mean values >11±0.6 at the soil surface to <8±2 at depths >100 cm. The Chastain units had similar C:N ratios with depth and means only ranged from 11±1.6 to 15±2.6. The Dorovan organic soils showed a large increase in C:N ratios with depth from a mean value of 17±0.4 at the soil surface to 32±5.7 at 200 cm depths (Fig. 2c).

Landscape-Scale SOC Pools

Measurements of soil C concentration, bulk density, and depth were used to construct landscape-scale SOC pools for CONG (Fig. 3). Within the upper 100 cm there was a clear gradient of significantly (p<0.01) greater SOC storage from the non-hydric soils (108–109 Mg C ha^{-1}), to the PD Chastain mineral soils (193±27 Mg C ha^{-1}), and the VPD Dorovan units (533± 25 Mg C ha^{-1}). In addition, approximately 47 % of the PD Chastain soils contained buried floodplain surfaces (Ab horizons) within the upper 100 cm. Separation of the Chastain soils based on these horizons resulted in significantly

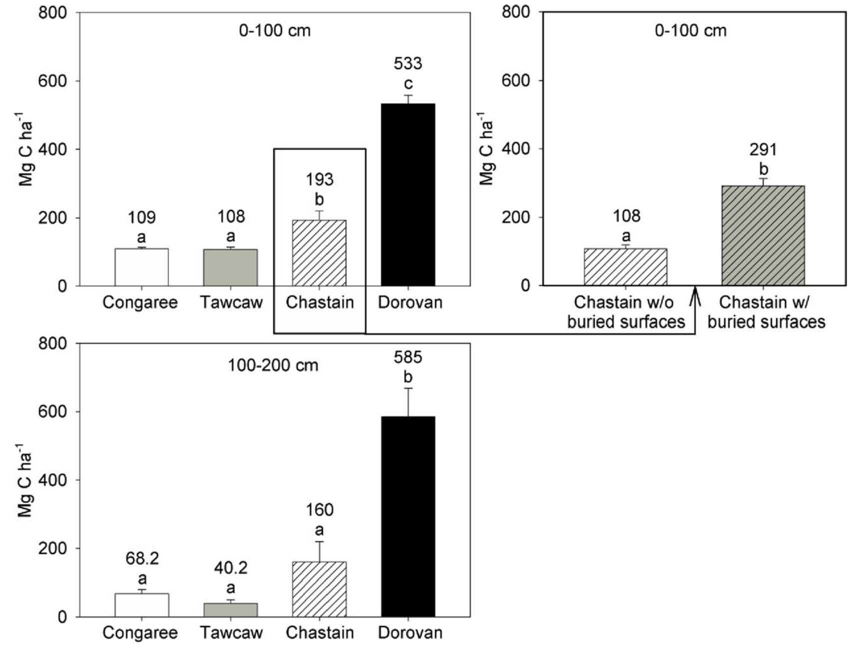

Fig. 3 Mean soil organic carbon (SOC) pools for 0–100 cm (n=15 per series) and 100–200 cm (n=5 per series) depths, ± 1 SE. Means with different letters are significantly different according to one-way ANOVA (α=0.05) and Tukey's HSD tests. Chastain mineral wetland soils separated by soil morphology (without buried surfaces (n=8) vs. contained buried surfaces (n=7)) were significantly different according to Student's t-tests (α=0.05)

($p<0.001$) greater SOC in the soils that contained buried surfaces (Fig. 3). In addition, mean SOC pools of the PD Chastain units that lacked these horizons were similar to the non-hydric soils of CONG (108±7 Mg C ha^{-1}).

Landscape-scale SOC pools were also calculated for the 100–200 cm depths. These data were more variable than the upper 100 cm due to fewer samples (n=5 per soil unit). However, there was a numerical increase in deep SOC from <100 Mg C ha^{-1} in the non-wetland units to 160±60 Mg C ha^{-1} in the PD Chastain units. There was significantly ($p<0.001$) more SOC storage at depth in the organic Dorovan soils compared to that of the mineral soil units (Fig. 3). Depth distributions, displayed as a percent of the total SOC pool to 200 cm, showed significantly ($p<0.01$) more SOC in upper 100 cm for both Congaree and Tawcaw soils (Fig. 4). In contrast, there were no significant differences in SOC storage between the upper 100 and 100–200 cm depths for both Chastain (p=0.79, 48 % SOC below 100 cm) and Dorovan (p=0.19, 56 % SOC below 100 cm) series.

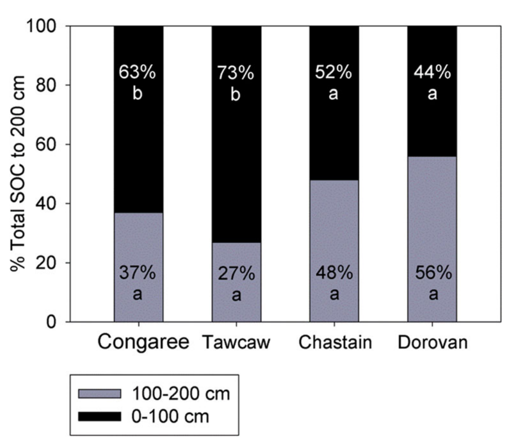

Fig. 4 Distribution of total soil organic carbon (SOC) to 200 cm stored in the upper 100 cm vs. 100–200 cm depths. Mean percentages with different letters are significantly different according to Student's t-tests (n=10, α=0.05)

Total Alluvial SOC Stocks at Local and Regional Scales

Landscape-scale SOC pools to a depth of 200 cm and SSURGO data were utilized to estimate total floodplain SOC storage within CONG (Table 2). Spatial analyses indicated that the majority of the floodplain area within CONG was mapped as Tawcaw (4420 ha) or Congaree (2031 ha) units. The wetland landscapes mapped as Chastain (1013 ha) and Dorovan (244 ha) comprised the remainder of the floodplain area. The total SOC storage within CONG was estimated to be 1.64×10^6 Mg C, with approximately 62 % of this SOC stored in the upper 100 cm (Table 2). Congaree and Chastain units contained similar percentages (21.8 %) of the total SOC storage despite Congaree units representing nearly double the land area of the Chastain landscapes. Dorovan units had minimal extent within CONG (244 ha), yet contained 16.6 % of the total SOC within the Park.

Spatially averaged SOC pools were utilized in conjunction with coarse-scale soil survey data (1:250,000 map scale STATSGO2) to calculate CONG SOC storage and extrapolate to a regional-scale (Table 3). CONG is mapped at a 1:250,000 scale as a Chastain-Tawcaw soil association. These data indicated that total SOC storage, to a depth of 200 cm, in CONG was 1.75×10^6 Mg C (Table 3). Chastain-Tawcaw associations cover over 210,000 ha of major floodplains (4th order rivers and above) within six states (Alabama, Florida, Georgia, North Carolina, South Carolina, Virginia) encompassing the

Table 2 Estimated soil organic carbon (SOC) storage within the Congaree National Park floodplain forests using the Soil Survey Geographic (SSURGO, 1:20,000 map scale) database. Means±1 standard error

Congaree National Park		Mg C ha^{-1}			Total SOC pool (Mg C)[b]			
SSURGO soil mapping unit(s)	Drainage class[a]	Mean SOC pool (0–100 cm)	Mean SOC pool (100–200 cm)	Area (ha)	0–100 (cm)	100–200 (cm)	0–200 (cm)	% Total SOC
Congaree	WD/MWD	109±4.2	68±12	2031	2.21×10^5	1.38×10^5	3.59×10^5	21.8
Tawcaw	SPD	108±6.9	40±10	4420	4.77×10^5	1.77×10^5	6.54×10^5	39.8
Chastain	PD	193±27	160±60	1013	1.96×10^5	1.62×10^5	3.58×10^5	21.8
Dorovan	VPD	533±25	585±83	244	1.30×10^5	1.43×10^5	2.73×10^5	16.6
Total				7708	1.02×10^6	6.20×10^5	1.64×10^6	100

[a] *WD* well drained, *MWD* moderately well drained, *SPD* somewhat poorly drained, *PD* poorly drained, *VPD* very poorly drained

[b] Rounded to 3 significant figures

southeastern Coastal Plain. Total SOC storage in these alluvial landscapes was estimated to be 4.85×10^7 Mg C (Table 3). Similar floodplain soil associations are found throughout the region, primarily mapped as Riverview-Chewacla-Chastain or Toccoa-Congaree-Chewacla. SOC storage estimates, based on natural drainage class, were 4.94×10^7 Mg C in these associations. The total SOC storage to a depth of 200 cm in these three regional soil associations was 9.79×10^7 Mg C (Table 3).

Discussion

Depth Distribution and Relationships Between Soil Properties

SOC concentrations decreased with depth in the Congaree and Tawcaw landscapes of CONG (Fig. 2a). The regular decrease in SOC is similar to many upland soils, suggesting the total C pool is influenced mainly by modern autochthonous additions from NPP (Batjes 1996; Jobbágy and Jackson 2000). By contrast, the hydric soil landscapes (Chastain, Dorovan) had irregular decreases in SOC content with depth, indicating that episodic burial and preservation of SOC in previously stable soil surfaces has occurred. This was not surprising since alluvial hydric soils preserve buried SOC more efficiently than non-wetlands due to anaerobic soil conditions that slow the mineralization of buried C (Ricker et al. 2013).

The variation in C:N ratios with depth among the CONG landscapes suggest that alluvial soils store and cycle C in relatively different ways (Fig. 2c). The soil C:N ratios tended to decrease with depth in non-hydric floodplain soils, similar to the distribution of C:N observed in uplands. In many soils this relative decrease in C:N ratio results from oxidation of C exceeding losses of N in highly decomposed organic matter at

Table 3 Estimated soil organic carbon (SOC) storage within the Congaree National Park floodplain forests and the Atlantic Coastal Plain using U.S. General Soil Map (STATSGO2, 1:250,000 map scale) data. Means±1 standard error, calculated using error propagation from weighted averages of values in Table 2

		Mg C ha^{-1}			Total SOC (Mg C)[b]		
STATSGO2 soil mapping unit(s)[a]	Drainage classes[a]	Mean SOC pool (0–100 cm)	Mean SOC pool (100–200 cm)	Area (ha)	0–100 (cm)	100–200 (cm)	0–200 (cm)
Congaree National Park							
Chastain-Tawcaw	PD-SPD	137±11	90±23	7708	1.06×10^6	6.94×10^5	1.75×10^6
Southeastern USA Coastal Plain							
Chastain-Tawcaw	PD-SPD	137±11	90±23	213786	2.93×10^7	1.92×10^7	4.85×10^7
Similarly mapped alluvial soils[c]							
Riverview-Chewacla-Chastain	WD-SPD-PD	122±8	82±19	218884	2.67×10^7	1.79×10^7	4.46×10^7
Toccoa-Congaree-Chewacla	WD-MWD-SPD	109±6	54±11	29326	3.20×10^6	1.58×10^6	4.78×10^6
Total				461996	6.36×10^7	4.12×10^7	9.79×10^7

[a] *WD* well drained, *MWD* moderately well drained, *SPD* somewhat poorly drained, *PD* poorly drained

[b] Rounded to 3 significant digits

[c] Spatially averaged SOC pools based on natural drainage class

depth (Rumpel and Kögel-Knabner 2011). In contrast, there was a relatively uniform vertical C:N profile for the hydric mineral soils mapped as Chastain. Burial of organic matter in anaerobic soils limits C mineralization in the subsoil horizons because of limited oxygen diffusion (Mausbach and Richardson 1994). Sedimentation processes in wetlands that result in rapid burial have been shown to preserve organic matter in a chemical state similar to that at the time of deposition on the surface (Gurwick et al. 2008), which explains the relatively uniform C:N ratios with depth in the Chastain mapping units. In contrast, organic Dorovan soils displayed an increase in soil C:N ratios with depth. This trend is due to the occurrence of constantly saturated conditions, allowing for more efficient C mineralization at the soil surface and limiting microbial respiration at depth (Post et al. 1985). Greater C:N ratios at depth within the CONG peat deposits could also indicate preferential loss of N from the subsurface relative to C (Kuhry and Vitt 1996). This process could be a result of long-term phytocycling involving plant uptake of inorganic N and subsequent deposition at the soil surface as litter-bound organic N. The varying trends in C:N ratios suggest aerobic floodplain soils may cycle C rapidly, similar to uplands, while anaerobic floodplain soils can store significant subsurface SOC due to combined effects of burial and limited C mineralization at depth.

Alluvial SOC Pools

CONG landscape SOC pools significantly increased as a result of soil drainage class (Fig. 3). Mean SOC pools from 0 to 100 cm in non-hydric soil landscapes of CONG were similar to those reported for alluvial soils (Fluvisols) by Batjes (1996) of 93 Mg C ha^{-1}, but greater than estimates reported for the contiguous USA (Fluvents, 74 Mg C ha^{-1}, Kern 1994). Batjes (1996) also reported a mean content of 68 Mg C ha^{-1} from 100 to 200 cm in alluvial soils, which was greater than estimates for Tawcaw, but similar to those of the Congaree soils in our study. Mean estimates of SOC storage to 100 cm in hydric mineral soils of CONG (Chastain units) were greater than those reported for Aquepts (135 Mg C ha^{-1}) by Kern (1994), but less than those in hydric riparian soils of the northeastern USA (246 Mg C ha^{-1}, Ricker et al. 2013). SOC pools in CONG wetlands were significantly greater (2.7-times) if buried surfaces were present within the upper 100 cm (Fig. 3). These findings were similar to those reported by Ricker et al. (2013), who indicated significantly (1.5-times) greater SOC storage in riparian landscapes containing buried surfaces. These trends suggest floodplain landscapes that undergo episodic sedimentation (C burial) combined with high water tables store the most SOC.

High spatial variability in SOC pools of freshwater mineral wetlands has been noted (Bridgham et al. 2006). Aggregation based on ecosystem type (i.e., freshwater swamps, etc.) encompasses many soil types with varied natural drainage classes and plant species composition (Kern 1994; Davis et al. 2004; Trimble 2008). Separation of soil mapping units based on their capacity for burial and preservation of previously deposited SOC would be beneficial to model floodplain SOC storage, construct watershed-scale C budgets, and predict the location of biogeochemical "hot spots" within large riparian ecosystems (Stallard 1998; Groffman et al. 2009). Currently, alluvial soil-landscapes are delineated similarly (i.e., all hydric mineral soils in CONG are mapped as Chastain, despite significant differences in morphology and SOC storage), but future incorporation of map phase criteria with spatial soil survey data could differentiate between units with high and low SOC storage (Ricker et al. 2013).

Estimates of SOC storage in the upper 100 cm of organic soils in CONG were less than the average for conterminous USA peatlands (1500 Mg C ha^{-1}, Bridgham et al. 2006). Total SOC storage to a depth of 200 cm in the Dorovan units was 1118 Mg C ha^{-1}, which was significantly greater than any of the mineral soils of CONG (Fig. 3), but less than global estimates for Histosols (Batjes 1996; Bridgham et al. 2006). Dorovan soils in CONG are located at the margins of an active floodplain within a humid subtropical climate (Fig. 1), and were composed of highly decomposed organic matter (sapric material) mixed with thin alluvial mineral deposits. Therefore, SOC storage was highly variable in the Dorovan units, ranging from 380 to 687 Mg C ha^{-1} to 100 cm. The organic soils in CONG differ from Histosols that form in cooler northern latitudes because most peatlands there contain organic inputs derived from bryophyte production (e.g., *Sphagnum* spp.), and form in closed depressions with little mineral input (Kuhry and Vitt 1996; Bridgham et al. 2006). The Histosols of CONG are located within open ground water seep wetlands that are dominated by tree species and the peat deposits are composed of highly decomposed (sapric) leaf and woody litter derived from overstory production. The depressional seep wetlands of CONG also receive some sediment influx from the Congaree River or adjacent upland slope erosion, as evident by thin stratified mineral layers preserved within the peat. Influx of mineral materials coupled with climatic conditions that favor rapid litter decomposition has likely limited the ability of these organic soils to store SOC relative to closed depressional systems located at more northern latitudes. Thus, a closer approximation to our mean SOC pool estimates was that reported for forested wetlands containing highly decomposed organic matter (Haplosaprists) in New England, USA (586 Mg C ha^{-1} to 100 cm depth, Davis et al. 2004).

Total SOC Storage in Large Floodplains

Determination of the spatial extent of hydric soils on large floodplains is critical, because they store disproportionately high SOC relative to non-hydric alluvial soils. Our data suggest that floodplain wetland landscapes are particularly important for SOC storage. Moreover, organic soil (Histosol) units encompass small areas of southeastern USA floodplains and may be underrepresented in regional-scale soil survey data. For example, Dorovan units were found to store 16.6 % of the total SOC within the CONG boundaries, yet these units are not included in broader soil associations (STATSGO2 Chastain-Tawcaw units) of the same spatial area (Table 3).

Quantifying SOC pools from individual pedons that represent soil map units and multiplying these estimates by the spatial area of the units (measure-and-multiply) has been a common approach to scale-up SOC data (Post et al. 1985; Eswaran et al. 1993; Grossman et al. 1998; Bridgham et al. 2006). Although this method is widely used, it tends not to account for inherent spatial variability of soil-landscapes. For example, the Chastain soil mapping units we sampled had statistically similar SOC pools for the 0–100 and 100–200 cm depth intervals. These data suggest that hydric mineral soils contain more SOC at greater depths when compared to non-hydric units. However, the deep SOC results are more variable (mean standard errors were twice as large) due to smaller sample sizes (n=5). These results have implications for upscaling to a regional scale, because total alluvial SOC storage values have increased errors associated with using a small sample size to quantify mean SOC content (Meersmans et al. 2008). Therefore, more deep alluvial soil sampling is likely needed for more effective modelling of floodplain SOC dynamics.

Recent modeling approaches that take into account both lateral and vertical variability in soil properties have been utilized to map SOC distributions in uplands (Mishra et al. 2009). However, modeling approaches may not be as effective for large floodplain soils because processes contributing to SOC production, entrainment, and burial today may not reflect past conditions (Jacobson and Coleman 1986; Hupp et al. 2009; Lockaby 2009). For these reasons, many contemporary watershed-scale factors (i.e., land use, slopes, soil erodibility) are poor predictors of total alluvial SOC pools (Blazejewski et al. 2009; Ricker et al. 2012). Therefore, more accurate approaches to floodplain SOC accounting must be used to develop models relating C dynamics to temporal trends in watershed land use, climate, and geomorphic factors.

Extensive research in uplands has demonstrated significant losses of SOC stocks (20–50 %) during conversion of forests to agricultural land use (Lal 2005). These estimates have been used to evaluate the impact of anthropogenic activities on the terrestrial SOC cycle. While a considerable amount of SOC is mineralized as a result of clearing of forested land, previous studies have also noted that some portion of SOC is likely eroded, transported, and retained in watershed sinks (Meybeck 1993; Stallard 1998; Lal 2003). Recent watershed-scale C budget analyses have shown that erosion associated with anthropogenic activities can result in net losses or in some cases gains of SOC within the watershed (Izaurralde et al. 2007). Therefore, to properly assess net terrestrial SOC fluxes, both erosion and depositional processes must be accounted for. Our data suggest that typical soil sampling depths from 0 to 100 cm may not be adequate to construct complete watershed SOC budgets (encompassing the start of land use until present), because significant quantities of post-disturbance C are stored below 100 cm. Although we did not obtain radiometric dates for alluvial deposits, distinctive morphological features indicative of legacy sediment boundaries, such as buried wetlands (Walter and Merritts 2008) and abrupt textural or color changes (Jacobson and Coleman 1986; Trimble 2008) were not observed in the mineral soils of CONG. Given trends of legacy sediment deposition within the region (Trimble 2008) it would not be surprising if the entire mineral SOC pool to 200 cm in CONG represented only alluvium deposited over the past 400 years. Thus, future efforts need to be undertaken to link total upland SOC losses with complete depositional gains (modern to pre-historic alluvial deposits of varying depths) to evaluate anthropogenic impacts on modern SOC dynamics at watershed-scales.

Conclusions

Results from this study indicate that alluvial hydric soils contain significantly greater amounts of SOC to depths of 100 and 200 cm compared to non-hydric floodplain landscapes. C depth distributions suggest that deep (>100 cm) SOC storage is particularly important in hydric floodplain soils, with no significant difference in the amount of SOC stored from 0–100 to 100–200 cm. These trends reflect episodic burial and preservation of former floodplain surfaces in mineral wetlands versus progressive thickening of peat deposits in organic soils. Spatial analysis of SOC storage within CONG and the greater regional Coastal Plain indicate that approximately 0.1 Pg of SOC is stored in large floodplains of the southeastern USA. This estimate is significant considering the spatial extent of major floodplains used for the regional SOC analysis represents <0.06 % of the total contiguous USA land area. These data suggest that large floodplains may serve as watershed sinks for terrestrial C derived from anthropogenic land disturbance and atmospheric sources. In addition, the largest quantities of alluvial SOC were stored in hydric relative to non-hydric soil landscapes, but coarse-scale soil associations tended to omit small spatial components, such as organic Histosols. These analyses suggest that determination of the spatial extent of floodplain wetlands is critical for obtaining accurate estimates of SOC stocks and regional estimates may underestimate the true extent of SOC storage in alluvial settings if deep (>100 cm) or Histosol SOC pools are not properly accounted for.

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