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Spatiotemporal modeling of soil organic carbon stocks across a subtropical region

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HIGHLIGHTS

- Soils acted as a net sink for atmospheric carbon over the last 40 years.
- Two contrasting methodologies demonstrated soil carbon sequestration.
- Space-time assessment of soil carbon change proved valuable.
- Wetland soils contributed nearly 50% of soil organic carbon stocks.
- Digital soil modeling provides a cost effective solution to traditional mapping.

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ABSTRACT

Given the significance and complex nature of soil organic carbon in the context of the global carbon cycle, the need exists for more accurate and economically feasible means of soil organic carbon analysis and its underlying spatial variation at regional scale. The overarching goal of this study was to assess both the spatial and temporal variability of soil organic carbon within a subtropical region of Florida, USA. Specifically, the objectives were to: i) quantify regional soil organic carbon stocks for historical and current conditions and ii) determine whether the soils have acted as a net sink or a net source for atmospheric carbon-dioxide over an approximate 40 year time period. To achieve these objectives, geostatistical interpolation models were used in conjunction with "historical" and "current" datasets to predict soil organic carbon stocks for the upper 20 cm soil profile of the study area. Soil organic carbon estimates derived from the models ranged from 102 to 108 Tg for historical conditions and 211 to 320 Tg for current conditions, indicating that soils in the study area have acted as a net sink for atmospheric carbon over the last 40 years. A paired resampling of historical sites supported the geostatistical estimates, and resulted in an average increase of 0.8 g carbon m^{-2} yr^{-1} across all collocated samples. Accurately assessing the spatial and temporal state of soil organic carbon at regional scale is critical to further our understanding of global carbon stocks and provide a baseline so that the effects sustainable land use policy can be evaluated.

1. Introduction

The amount of carbon (C) stored in the world's soils is substantial and has been estimated to be approximately four times greater than the atmospheric C pool and five times greater than the biotic pool (Jacobson et al., 2000). Because of this magnitude, relatively small losses from the soil C pool could substantially increase levels of atmospheric carbon-dioxide (CO_2), and therefore alter climate conditions (Cox et al., 2000). Soil organic C (SOC) is of particular concern because of its ability to modify climate by actively exchanging C with the atmosphere. Due to the sensitivity of SOC decomposition to soil moisture and temperature, it is possible that warmer climate conditions could accelerate SOC decomposition (Craine and Gelderman, 2011). If SOC losses outpace accumulation, the terrestrial biosphere as a whole becomes a net source for atmospheric CO_2, leading to a positive terrestrial C cycle-climate feedback (Cox et al., 2000; Davidson and Janssens, 2006). As such, international treaties, including the Kyoto Protocol and Rio +20 Earth Summit, call for the quantification and mapping of SOC to allow the protection and enhancement of C sinks to mitigate anthropogenic CO_2 emissions (Cramer et al., 2001; Meersmans et al., 2011).

Numerous studies have quantified SOC at the global scale (Bolin, 1970; Bohn, 1982; Batjes, 1996; Gower, 2003) with findings ranging from 1200 to 1600 Pg C for surface soils (Post et al., 1990) to approximately 2000 Pg C for soils to 1 m depth (Bolin et al., 2000). However, the effectiveness of these maps in terms of quantifying soil properties, such as SOC, is debatable. A major shortcoming of traditional, polygon based global scale studies is that they are generally performed by

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aggregating data from large scale studies that do not capture the highly variable nature of SOC (Jobbágy and Jackson, 2000; Grunwald et al., 2011b). Additionally, global scale studies often incorporate legacy data that do not necessarily represent current landscape conditions. At the other end of the scale, studies investigating the vertical or profile distribution of SOC at the site-specific (pedon) scale have also received considerable attention from researchers around the world (Jobbágy and Jackson, 2000; Rumpel et al., 2002). These studies are useful for accurately quantifying SOC in a pedon, but still do not capture the spatial heterogeneity of SOC across the landscape. Regional scale studies attempting to accurately quantify SOC while also capturing the spatial heterogeneity across a climatic region are least prominent, but essential for more accurate global stock assessments and a better understanding of the significance of soil C pools (Meersmans et al., 2008).

Digital soil mapping and modeling (DSMM) provide a solution to the problems associated with traditional polygon-based maps by addressing the need for more accurate and cost effective soil analysis at appropriate scales (Grunwald, 2009; Grunwald et al., 2011b). Furthermore, the uncertainty of pixel-based soil maps can be assessed using error metrics such as validation and/or cross-validation. The lack of detailed, digital SOC assessments at the regional scale within Florida's (USA) topsoils served as the motivation for this research. The specific objectives of this study were to i) quantify regional SOC stocks for historical and current conditions and ii) determine if soils have acted as a net sink or a net source for atmospheric carbon-dioxide (CO_2) over an approximate 40 year time period.

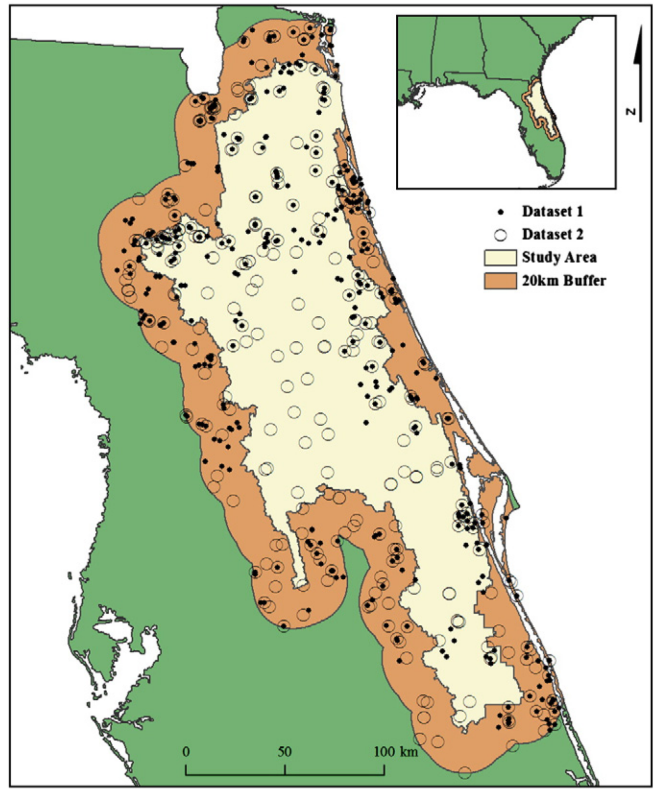

Fig. 1. Spatial distribution of historical (Datset 1) and current (Dataset 2) samples across the study area and 20 km buffer.

2. Materials and methods

2.1. Study area

This study was conducted in the northeast and east central regions of Florida located between latitudes 30.48° to 27.51°N and longitudes −82.43° to −80.74°W. The study area includes the Lower, Middle and Upper St. Johns River Basins as well as the Ocklawaha River Basin and encompasses an area of approximately 22,266 km^2 (Fig. 1). The climate is predominantly warm and humid with an average annual precipitation of 1224 mm and mean annual temperature of 20.5 °C (National Climatic Data Center, 2011). Elevation within the study area is flat to mildly undulating and ranges from below sea level (−1 m) to 95 m above sea level (United States Geological Survey, 2006). Due to the topography, erosion and deposition are relatively minor, and therefore expected to have negligible effects on soil carbon dynamics. The soils in the study area were formed in sandy to loamy marine derived parent material with sand as the dominant particle size fraction. Dominant soil orders include Spodosols (31%), Entisols (24%), Alfisols (11%) and Histosols (9.8%). Pineland (16%), Urban (12%), Rangeland (10%) and Improved Pasture (7%) make up the dominant land use/land cover (LULC) classes (Florida Fish and Wildlife Conservation Commission (FFWCC), 2003).

2.2. Data sources

A combination of geostatistical and geoprocessing techniques was used on historical and current soil-environmental datasets to quantify historical and current SOC density (kg m^{-2}, 0–20 cm soil depth) as well as total stock for the study area (Tg C). Together, these data cover a temporal scale of approximately 40 years. Dataset 1 (DS1) represents historical conditions (1965–1996) and Dataset 2 (DS2) represents current conditions (2008–2009). A thorough description of the datasets follows.

Dataset 1 ($n = 402$) is a subset of legacy data from the “Florida Soil Characterization Database” (FSCD) (Grunwald and Harris, 2012) and includes over 1300 site specific soil profiles and more than 8300 soil horizons that were collected and described across Florida over an approximate 30 year time period (1965–1996). Sampling locations were selected based on tacit knowledge of soil surveyors at the time and, to our knowledge, no strategic sampling design was implemented. Data was collected for 144 physical, chemical, biological, morphological, and taxonomic soil properties, including soil organic matter (SOM) and bulk density. Walkley–Black dichromate extraction (WB) and loss on ignition (LOI) were used to measure soil organic matter for mineral (SOM_{WB}) and organic soils (SOM_{LOI}), respectively.

Dataset 2 (DS2) ($n = 304$) represents current conditions (2008–2009) and is a subset of data from a statewide project known as the “Florida Soil Carbon Project” (FLSCP) which consists of 1014 samples collected throughout the state of Florida (Grunwald et al., 2011a). The FLSCP sampling design was based on two criteria: i) A stratified-random approach identified representative soil-landscapes and ecosystems across Florida, and ii) 50% overlap with the historical FSCD dataset. Two primary strata, soil suborder and LULC were used to capture the broad range of expected soil C variability across Florida. Both properties were selected due to their strong relationships to soil C documented in the literature (Powers et al., 2011). The stratification scheme used 13 classes of LULC (Florida Fish and Wildlife Conservation Commission (FFWCC), 2003) and 10 soil suborders (Natural Resource Conservation Service, 2006). Not all combinations of soil suborder and LULC classes existed in Florida's landscape and some combinations had minor (<1%) coverage, and thus were excluded from the sampling scheme, resulting in a total of 63 stratification classes.

Dry combustion was used to measure total C (TC) on DS2 soil samples accomplished using a Shimadzu TOC-V/SSM-5000 gas analyzer (Shimadzu Scientific Instruments, Kyoto, Japan). Total C and inorganic carbon (IC) were measured by separate gas analysis procedures. Total C was measured by carbon-dioxide (CO_2) evolution using 50–500 mg of ball milled soil samples combusted at 900 °C. Inorganic C was also measured by CO_2 evolution and derived by reacting 20–250 mg of ball milled soil with 42.5% phosphoric acid (H_3PO) in the gas analyzer at 200 °C. Soil organic carbon was derived by subtracting IC from TC.