



Interaction effects of climate and land use/land cover change on soil organic carbon sequestration



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HIGHLIGHTS

- Soils in Florida (FL) have acted as a sink for carbon (C) over the last 40 years.
- Climate interacting with land use/land cover impacted soil C sequestration.
- Land use/land cover in FL changed significantly over the past 40 years.
- Some Florida soils continue to sequester C under projected climate.

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ABSTRACT

Historically, Florida soils stored the largest amount of soil organic carbon (SOC) among the conterminous U.S. states (2.26 Pg). This region experienced rapid land use/land cover (LULC) shifts and climate change in the past decades. The effects of these changes on SOC sequestration are unknown. The objectives of this study were to 1) investigate the change in SOC stocks in Florida to determine if soils have acted as a net sink or net source for carbon (C) over the past four decades and 2) identify the concomitant effects of LULC, LULC change, and climate on the SOC change. A total of 1080 sites were sampled in the topsoil (0–20 cm) between 2008 and 2009 representing the current SOC stocks, 194 of which were selected to collocate with historical sites ($n = 1251$) from the Florida Soil Characterization Database (1965–1996) for direct comparison. Results show that SOC stocks significantly differed among LULC classes – sugarcane and wetland contained the highest SOC, followed by improved pasture, urban, mesic upland forest, rangeland, and pineland while crop, citrus and xeric upland forest remained the lowest. The surface 20 cm soils acted as a net sink for C with the median SOC significantly increasing from 2.69 to 3.40 kg m^{−2} over the past decades. The SOC sequestration rate was LULC dependent and controlled by climate factors interacting with LULC. Higher temperature tended to accelerate SOC accumulation, while higher precipitation reduced the SOC sequestration rate. Land use/land cover change observed over the past four decades also favored the C sequestration in soils due to the increase in the C-rich wetland area by ~140% and decrease in the C-poor agricultural area by ~20%. Soils are likely to provide a substantial soil C sink considering the climate and LULC projections for this region.

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1. Introduction

It has been estimated that soil organic carbon (SOC) constitutes about two-thirds of the Earth's terrestrial carbon pool (Stockmann et al., 2013). Its active interactions with biosphere and atmosphere

carbon pools make it a critical component in the global carbon cycle (Kutsch et al., 2010). Great scientific attention has been drawn to the SOC pool because of the huge potential to deposit carbon belowground with a relatively slow turnover rate (Post et al., 1982). However, the SOC pool is susceptible to human interferences primarily as land use/land cover (LULC) change. Worldwide, conversions from primary forest to agricultural land are thought to be depleting SOC while afforestation is considered a means to restore SOC stocks (Genxu et al., 2002; Guo and Gifford, 2002; DeGryze et al., 2004; Grünzweig et al., 2004; Dawson and Smith, 2007; Maia et al., 2010).

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Climate change has raised concerns about its impact on global SOC stocks. However, there has been no consensus on soil's role as a sink or source in response to global warming (Davidson and Janssens, 2006). The controversy results from the complex interaction between soil and environments. Microbial activity and decomposition of soil organic matter (SOM) depend on the amount, structure, composition of biotic material input to soils and environmental conditions (e.g., temperature, moisture, and nutrient status) (Kutsch et al., 2010). Among these environmental conditions, the effect of temperature on the microbial decomposition of SOM has been extensively studied in the context of global climate change (Kirschbaum, 1995; Giardina and Ryan, 2000; Fierer et al., 2005). Some studies have shown that the warming temperature can accelerate microbial decomposition of SOM and cause a net loss of carbon (C) to the atmosphere (Davidson et al., 2000; Bellamy et al., 2005; Dorrepaal et al., 2009). However, other studies argued that the increasing temperature can lead to a net gain of SOC by promoting biomass input to soil, which exceeds the increase of decomposition (Nemani et al., 2003; Bond-Lamberty and Thomson, 2010). The debate reflects the complexity in temperature sensitivity in respect to SOC decomposition. SOM has a wide range of intrinsic temperature sensitivity of decomposition because it consists of thousands of organic compounds each of which has its own inherent decomposition property (Kutsch et al., 2010). Furthermore, the temperature sensitivity can be confounded by some edaphic and environmental conditions that interfere with the decomposition process. For example, SOM can be physically protected from decomposition when contained within soil aggregates, or be chemically protected if adsorbed onto soil mineral surfaces (Davidson and Janssens, 2006). LULC plays a critical role in the response of SOC to temperature change. On the one hand, LULC controls the quantity and quality of organic compounds that enter soils, and subsequently determines the intrinsic temperature sensitivity of the SOM decomposition. On the other hand, LULC also changes the soil and environmental conditions that can further affect the apparent temperature sensitivity (Post and Kwon, 2000; Jones et al., 2005; Davidson and Janssens, 2006). There is a need to study the interaction effect of LULC and climate on SOC changes in order to better understand how SOC responds to climate change.

Florida soils store approximately 2.26 Pg of SOC – more than any other state in the conterminous U.S. according to the U.S. General Soil Map (Natural Resources Conservation Service, 2006). This is primarily due to the extensive occurrence of Histosols in the 46,951 km² of wetlands in the state especially in south Florida (U.S. Fish and Wildlife Service, 2009). In addition, Florida features the SOC-rich Spodosols which cover about 32% of the land area. The formation of these high SOC soils is attributed to the unique climatic (high temperature and precipitation), topographic (flat landscape) and hydrologic (high water table) conditions (Stone et al., 1993; Vasques et al., 2012). Meanwhile, Florida has been experiencing significant LULC shifts which include rapid urban growth and losses of agricultural and forest land for the past decades (Kautz et al., 2007), which may have caused significant SOC change in Florida. In a recent study, Ross et al. (2013) made the first assessment of SOC stock change over the last 40 years in the northeast and east central regions of Florida (~15% of the area of Florida) and found that soils acted as a net sink for C. However, at state scale there is still substantial lack in knowledge about how SOC stocks changed over the past decades. More importantly, the anthropogenic and natural factors that caused the SOC temporal change in Florida still remain unknown. Understanding the driving factors that determine if soils act as a sink or a source for carbon is critical because future projections for this region indicate substantial climate change and land use shifts (Zwick and Carr, 2006; Konrad et al., 2013). Therefore, the objectives of the study were to 1) investigate the SOC stock change to determine if Florida soils act as a net sink or net source for C over the past four decades, and 2) identify the unique

and interaction effects of LULC and climate on SOC stocks and sequestration.

2. Materials and methods

2.1. Study area

The study area is the state of Florida, located in the southeast United States, with latitudes from 24°27' N to 31°00' N and longitudes from 80°02' W to 87°38' W. Florida covers approximately 150,000 km² (United States Census Bureau, 2000). The climate is humid and subtropical in northern and central Florida and is humid and tropical in southern Florida. The mean annual precipitation of Florida is 1373 mm and the mean annual temperature is 22.3 °C (National Climatic Data Center, 2008). Overall, soils in Florida are sandy in texture. Dominant soil orders of Florida are: Spodosols (32%), Entisols (22%), Ultisols (19%), Alfisols (13%), and Histosols (11%). Most frequent soil subgroups are: Aeric Alaquods, Ultic Alaquods, Lamellic Quartzipsamments, Typic Quartzipsamments, and Arenic Glossaqualfs (Natural Resources Conservation Service, 2009). The Florida LULC consists mainly of wetlands (28%), pinelands (18%), urban and barren lands (15%), agriculture (9%), rangelands (9%), and improved pasture (8%) (Florida Fish and Wildlife Conservation Commission, 2003). Florida's topography is muted with gentle slopes varying from 0 to 5% in almost the whole State (United States Geological Survey, 1999).

2.2. Historical SOC data

The historical SOC dataset is from the Florida Soil Characterization Database (FSCD) which includes 1251 site-specific soil profiles (Fig. 1). Each of the soil profiles were collected and described within the time period 1965 to 1996. Soil sampling locations were selected based on tacit knowledge of field soil scientists for the purposes of soil survey development and verification.

The FSCD measured SOC and BD values for each genetic horizon up to 2 m depth. SOM was measured in mineral soils (A, B, C and E horizons) by the Walkley–Black modified acid-dichromate (WB) method (Nelson and Sommers, 1996) and in organic soils, SOM was measured by loss-on-ignition (LOI).

2.3. Current SOC dataset

A new soil sampling campaign was designed and carried out between 2008 and 2009 to quantify the current topsoil SOC stocks across Florida. A total of 1080 sites were sampled in the topsoil (0–20 cm) (Fig. 1). A random sampling design stratified by the combination of soil suborder and LULC was used to pre-select locations. The two spatial layers (soil suborder derived from NRCS (2009) and LULC derived from the FFWCC (2003)) were overlaid to create a strata map (89 strata). Sampling locations were spatially randomly selected in each stratum and the number of samples in each stratum was proportional to the size of the stratum. Among the 1080 sites, 194 were randomly selected to overlap with the historical sites (collocated sites) from FSCD to facilitate the assessment of site-specific SOC change over the past decades. Samples were collected using a 5.7-cm-diameter-steel core at 0–20 cm depth, transferred to ziploc bags, labeled, kept in 0 °C coolers, and transported to the laboratory. Then the samples were air dried, weighted, sieved through a 2-mm sieve, and ball milled for laboratory analyses.

Total carbon (TC) was analyzed by combustion catalytic oxidation at 900 °C and inorganic carbon (IC) was analyzed by phosphoric acid extraction at 200 °C (Shimadzu SSM-5000A). Soil organic C was derived by subtraction (TC – IC). The laboratory SOC measurements in mass units (%) were converted to stock units (kg m⁻²) using the measured bulk density and soil depth (20 cm).

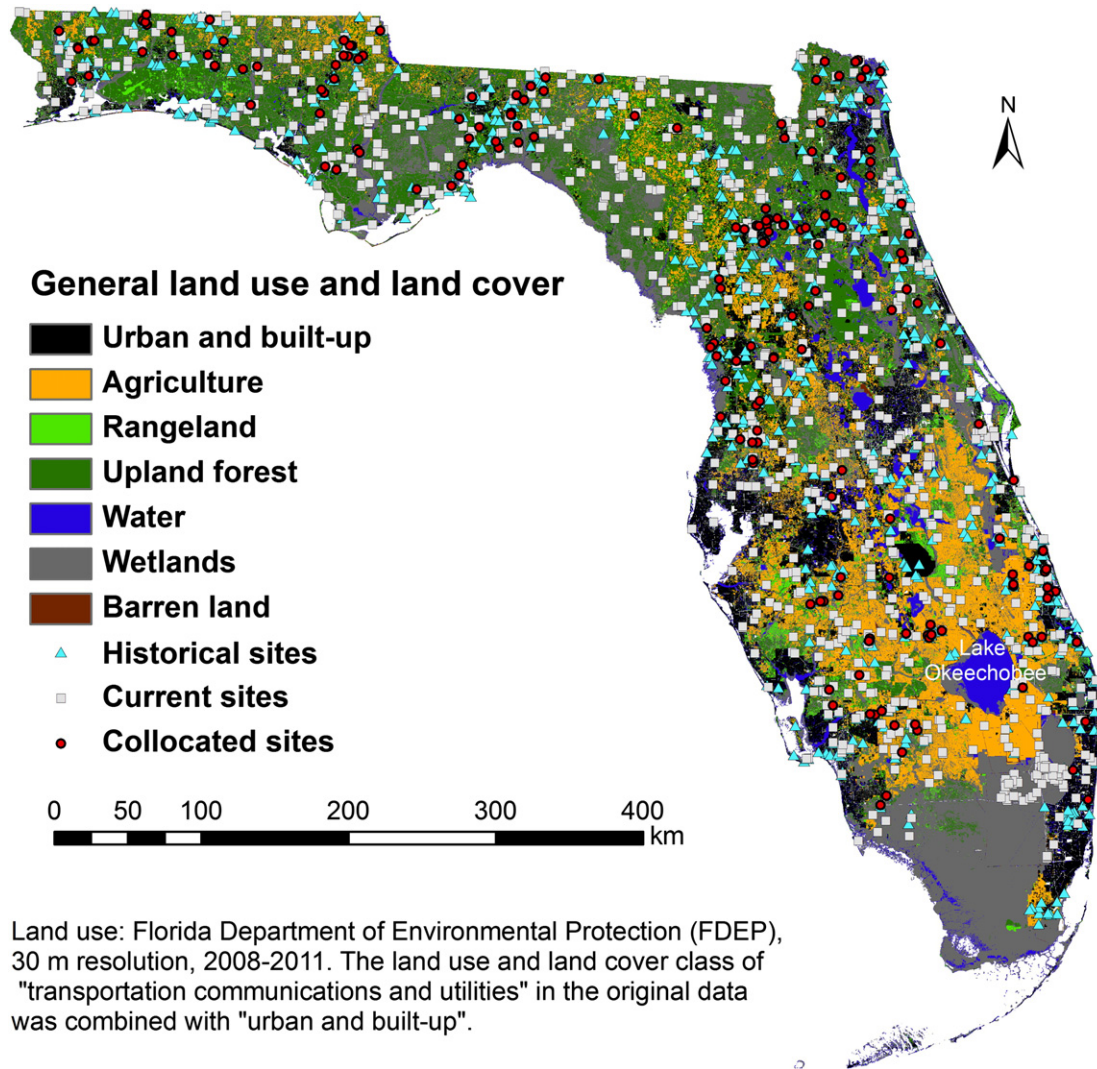


Fig. 1. The historical sites from the Florida Soil Characterization Database (1965–1996), current sampling sites (2008–2009), and the 194 sites where current and historical sites are collocated.

2.4. Harmonization of historical and current datasets

To derive SOC change historical and current data had to be harmonized. The data harmonization procedure has been fully documented in Ross et al. (2013). Briefly, pedotransfer functions (PTFs) were developed using linear regression on a representative soil set (n : 144) that spans across soil types found in Florida to account for the systematic error due to different SOC measurement methods in historic and contemporary soil datasets. Then a depth weighted average of horizon-based SOC density was calculated to standardize them to fixed depth (0–20 cm).

2.5. Carbon sequestration rates

The SOC sequestration rates were calculated according to Eqs. (1) and (2) for all collocated sites.

$$\Delta\text{SOC}(x_0, \text{NY}) = \text{SOC}(x_0, \text{YM}_c)_{\text{DS2}} - \text{SOC}(x_0, \text{YM}_h)_{\text{DS1}} \quad (1)$$

$$\text{SOCseq}(x_0) = \frac{\Delta\text{SOC}(x_0, \text{NY})}{\text{NY}} \quad (2)$$

where, DS1 is the historical (1965–1996) SOC dataset, DS2 is the current (2008–2009) SOC dataset, YM_h is the year of historical measurement (DS1), YM_c is the year of current measurement (DS2), NY is the number of years between historical and current observations ($\text{NY} = \text{YM}_c - \text{YM}_h$), SOC is SOC stocks in g m^{-2} , SOCseq is the SOC sequestration rate ($\text{g m}^{-2} \text{yr}^{-1}$) constrained to collocated historical and current sites (x_0), and x_0 is the geographic coordinate (x and y coordinates) of collocated sites.

Positive SOCseq values represent soil carbon gains (sequestration) and negative SOCseq values represent soil carbon losses over the considered time period.

2.6. LULC and climate data

The Florida LULC data of 1995, 2004 and 2008–2011 were acquired from the Florida Department of Environmental Protection (FDEP) and the data of 1970s (i.e., data collected over a 10-year span) from the United States Geological Survey (USGS). The LULC changes at the collocated sites were tracked by comparing the historical LULC data and the LULC type determined by the sampling crew in the current sampling campaign. In order to confirm the LULC changes, the observed LULC changes were further scrutinized and confirmed with the

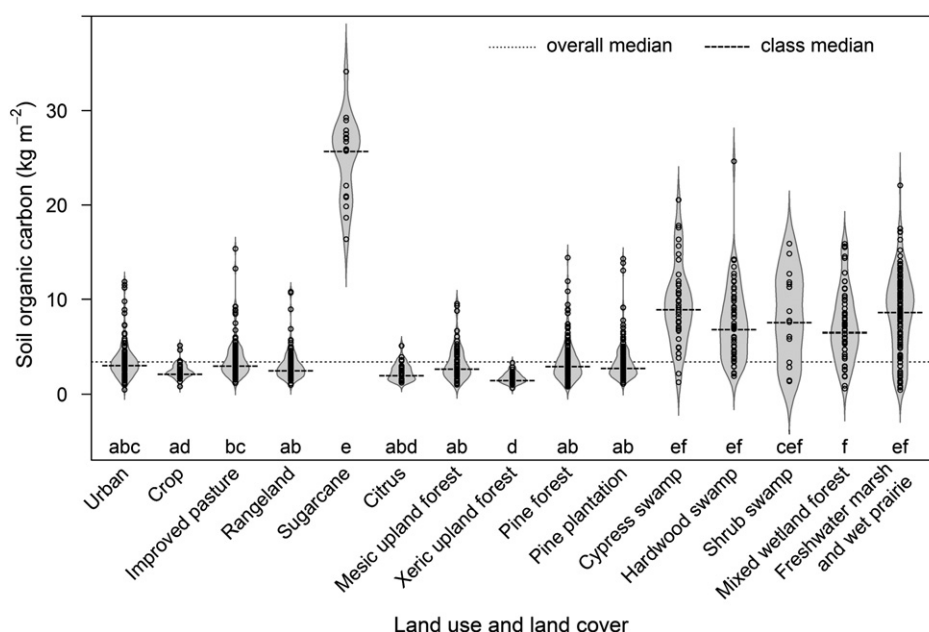


Fig. 2. Violin plot of soil organic carbon (kg m^{-2}) of the 1080 current samples (2008–2009) grouped by the field-observed land use/land cover (LULC). The Kruskal–Wallis test shows the significant effect of LULC on SOC at the significance level of 0.0001 and post hoc multiple comparison results are denoted by the letter codes above the class names (classes share no common letter contained significantly different SOC at $\alpha = 0.05$).

historical satellite imagery from Google Earth™. Climate conditions represented by the maximum annual temperature and mean annual precipitation averaged over 1981–2010 were obtained from Parameter-elevation Regressions on Independent Slopes Model (PRISM) Climate Group (2013).

2.7. Data analysis

The relationship between LULC and SOC was investigated using the Kruskal–Wallis test. The post hoc multiple comparisons were then conducted to compare the SOC of LULC types with each other.

In order to compare between the current and historical SOC stocks, the Mann–Whitney test was used on the current ($n = 1080$) and historical ($n = 1251$) sites. Furthermore, the paired Mann–Whitney test was applied on the collocated sites ($n = 194$).

The general linear model was used to test the effects of LULC and climate factors (temperature and precipitation) on SOC sequestration rate. The interaction effect of LULC and climate was accounted for in the cross-effect term in the models. Then statistically significant interactions were plotted to show the relationships between climate and SOC sequestration rates.

3. Results

3.1. Effects of LULC on SOC

The distribution density functions along with the current SOC observations (2008–2009) grouped by field-observed LULC are shown in Fig. 2. The Kruskal–Wallis test shows that SOC was different for LULC classes at the significance level of 0.0001. Generally, wetland soils had significantly higher SOC than almost any other LULC class except sugarcane. No significant difference of SOC was found among the five types of wetlands, although the SOC median of the wetland types varied from 6.7 kg m^{-2} (mixed wetland forest) to 9.1 kg m^{-2} (cypress swamp). Natural upland forests, including mesic upland forest, xeric upland forest and pine forest, had comparable SOC stocks to urban and agriculture (except sugarcane). Cropland and improved pasture showed even higher SOC than xeric upland forest primarily grown on well-drained soils such as Udults and Psamments. Natural upland

forests, pine forest and mesic upland forest showed quite similar SOC stocks and both were higher than xeric upland forest. Within the agricultural LULC types, improved pasture was observed to have significantly higher SOC compared with crop. It is worth noting that no significant difference in SOC was detected between pine plantation and natural pine forest. Similarly, improved pasture and rangeland did not significantly differ in SOC. Urban soils, primarily characterized by lawn and grassland soils, contained relatively high SOC which was comparable to improved pasture, mesic upland forest, pineland and rangeland.

3.2. SOC change

Comparing the current SOC observations with the historical observations shows that obvious SOC change occurred between 1965–1996 and 2008–2009. The Mann–Whitney test indicates that the current SOC median (1080 sites) was significantly higher than that of the historical one (1251 sites) ($p < 0.0001$) as shown in

Table 1
Descriptive statistics of historical and current soil organic carbon observations at 0–20 cm in Florida.

	All sites		Collocated sites	
	Historical	Current	Historical	Current
N	1251	1080	194	194
Mean (kg m^{-2})	4.67	4.98	3.81	3.99
Median (kg m^{-2})	2.69 ^A	3.40 ^B	2.44 ^a	2.93 ^b
SD (kg m^{-2})	6.65	4.38	5.28	3.75
SE (kg m^{-2})	0.19	0.13	0.38	0.27
MAD (kg m^{-2})	1.69	2.05	1.49	1.31
Skewness	4.33	2.52	4.98	3.54
Kurtosis	23.58	8.48	28.91	14.82
Min. (kg m^{-2})	0.34	0.45	0.36	0.45
Max. (kg m^{-2})	68.09	34.15	46.06	25.90

The uppercase letters in the superscripts of medians indicate significant difference in medians between current and historical observations of all sites at 0.001 significance level using Mann–Whitney test. The lowercase letters indicate significant difference in median between current and historical observations of collocated sites at 0.001 significance level using paired Mann–Whitney test. Abbreviations: N = number of observations, SD = standard deviation, SE = standard error, MAD = median absolute deviation.

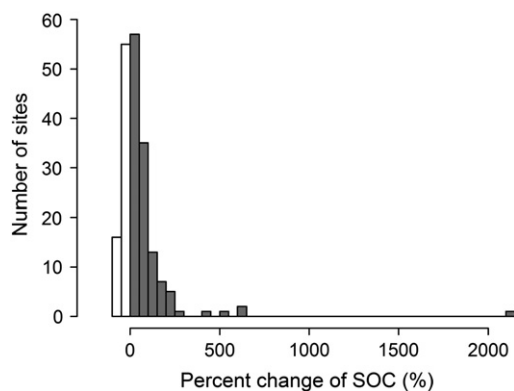


Fig. 3. Histogram of soil organic carbon (SOC) change between 1965–1996 and 2008–2009 at the 194 collocated sites.

Table 1. In the more straightforward one-to-one comparison at the collocated sites, the paired Mann–Whitney test also detected that the current SOC dataset had a significant higher median than the historical one ($p = 0.00027$). In addition, the means of the current SOC datasets were also numerically higher than their historical counterparts, even though the historical SOC datasets had much higher maximum SOC observations as shown in Table 1. Fig. 3 displays the percent change of SOC at collocated sites between the two soil sampling campaigns. Approximately 63% of the collocated sites had experienced a net SOC gain compared to the ~37% sites with SOC loss. These results depict an overall trend of SOC gain in the surface soils (0–20 cm) of Florida between the two soil sampling campaigns (1965–1996 to 2008–2009).

3.3. Impact of LULC and its change on SOC

The collocated sampling allowed a one-on-one comparison between historical and current SOC elucidating on the change in SOC and relating

it to LULC types and also LULC change (Fig. 4). At the sites without LULC conversion, improved pasture, mesic upland forest, xeric upland forest, pineland, rangeland, urban and wetland showed overall gains of SOC while in citrus and sugarcane overall losses were observed, particularly for the sugarcane sites that experienced substantial SOC losses from the highly organic soil. In the cropland, about half of the sites had SOC losses and the other half had SOC gains, resulting in slight SOC increase in the overall mean value (Fig. 4). Improved pasture was the only one under agricultural use that noticeably gained SOC.

At the sites that had undergone LULC changes, conversion of wetland to other LULCs resulted in dramatic SOC losses. For instance, the conversion from wetland to urban led to an average loss of $\sim 16 \text{ kg m}^{-2}$ SOC and from wetland to rangeland showed a loss of $\sim 5 \text{ kg m}^{-2}$. On the contrary, conversion from other LULC to wetland promoted SOC accumulation, e.g., from both pineland and rangeland to wetland, $\sim 3 \text{ kg m}^{-2}$ SOC was gained on average. The outlier in Fig. 3 was the site of 'rangeland converted to wetland' that resulted in a high SOC sequestration rate ($101.2 \text{ g m}^{-2} \text{ yr}^{-1}$). From barren land to urban, a slight SOC increase was observed, and similar gains were found from converting pineland and cropland to urban.

3.4. Impact of LULC and climate on SOC sequestration rate

Because the time factor plays an important role in the amount of SOC change, the SOC sequestration rate was calculated which allowed comparing SOC change on the same time scale. Table 2 presents six general linear models that show the effect of LULC and climate factors (MAT, maximum annual temperature and MAP, mean annual precipitation) on the SOC sequestration rate. Again, LULC was significant in differentiating the SOC sequestration rate and explained 27% of its variance, while MAT and MAP did not show significant effect on their own. However, both of the two climate factors had significant interaction effects with LULC. A three-dimensional significant interaction effect was also observed among LULC, MAT, and MAP (Model 6). However, accounting for the three-dimension interaction consumed a large number of degrees of freedom ($DF = 51$) considering the sample size of 194,

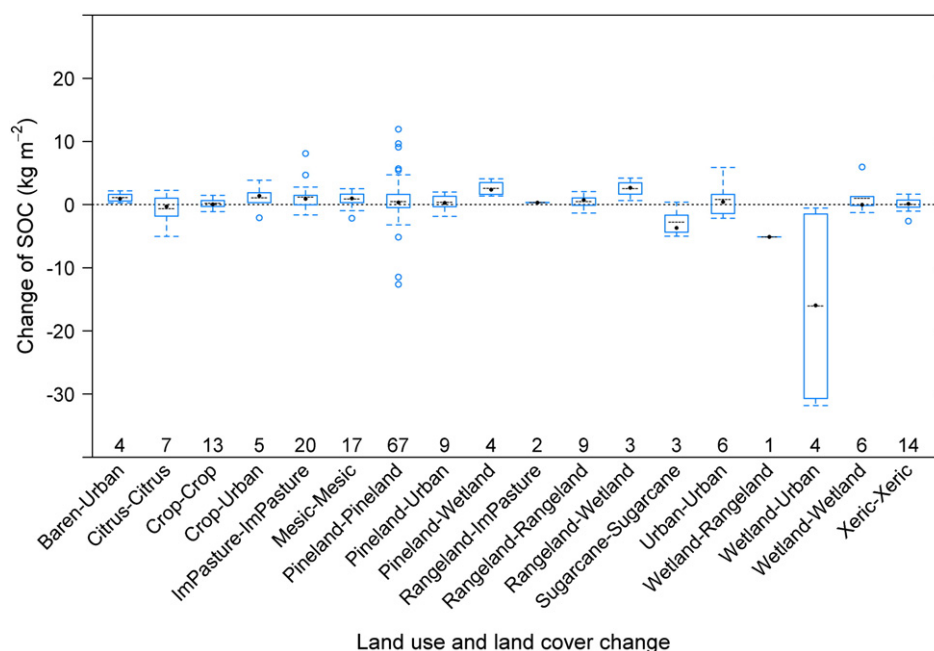


Fig. 4. Soil organic carbon change between 1965–1996 and 2008–2009 at the 194 collocated sites, grouped by land use/land cover (LULC) and LULC change. For the horizontal axis label, the LULC listed before and after the hyphen are the historical (1970s) and observed LULC in the current sampling (2008–2009), respectively. Barren = barren land, ImPasture = improved pasture, Mesic = mesic upland forest, Xeric = xeric upland forest. The blue boxes denote the first and third quartiles, black dots and dashed lines in boxes denote the medians, and the whiskers embracing the boxes extend to the most extreme point which is no more than 1.5 times of the box length. The number above the horizontal axis is the number of sites in each group.

Table 2

General linear models showing the effects of land use/land cover, temperature and precipitation on the soil organic carbon sequestration rate.

Model	Model ID	Df	F	P-value	R ²	AIC
SOC seq. rate ~ LULC***	1	14	6.19	<0.001***	0.27	2404
SOC seq. rate ~ LULC*** + MAT	2	15	6.03	<0.001***	0.28	2402
SOC seq. rate ~ LULC*** + MAT + LULC × MAT**	3	27	4.96	<0.001***	0.38	2386
SOC seq. rate ~ LULC*** + MAP	4	15	5.79	<0.001***	0.28	2401
SOC seq. rate ~ LULC*** + MAP + LULC × MAP***	5	27	5.22	<0.001***	0.40	2381
SOC seq. rate ~ LULC*** + MAP + MAT + LULC × MAT*** + LULC × MAP + MAT × MAP + LULC × MAT × MAP**	6	51	3.67	<0.001***	0.46	2382

Significance code: *** <0.001, ** <0.01, and * <0.05. Abbreviations: SOC seq. rate ($\text{g m}^{-2} \text{yr}^{-1}$) = soil organic carbon sequestration rate, LULC = land use/land cover, MAT ($^{\circ}\text{C}$) = maximum annual temperature average over 1981–2010, MAP (mm) = annual precipitation average over 1981–2010. AIC = Akaike Information Criterion.

which may raise the question of overfitting. In fact, there is a sign of over-parameterization as indicated by the increased Akaike Information Criterion (AIC) value that not only rewards goodness of fit but also penalizes the increase in the number of model parameter. In cropland, mesic upland forest and pineland which remained unchanged between 1970s and 2008–2011, the SOC sequestration rate showed an increasing trend with the MAT increasing from about 25 to 29 $^{\circ}\text{C}$ (Fig. 5). The same effect was also observed in the sites that had been converted from pineland to urban. In contrast, elevated MAP slowed down the SOC accumulation in cropland and pineland (Fig. 6).

4. Discussion

4.1. Impact of LULC and its change on SOC

Quite a few reviews have shown that LULC and its change are a major human-induced driver of SOC change in a wide range of climate zones (Post and Kwon, 2000; Guo and Gifford, 2002; Don et al., 2011; Poeplau et al., 2011). In this study, it is found that any LULC conversion involving wetlands resulted in a large SOC change. Wetland soil generally had significantly higher SOC than any other LULC due to its high soil moisture creating anaerobic conditions that are favorable to SOC accumulation (Euliss et al., 2006; Vasques et al., 2012; Ziegelgruber et al., 2013). The conversion of wetland to urban or rangeland greatly altered the hydric soil condition and resulted in significant amount of SOC losses. Conversely, change of LULC from drier soil condition (i.e., pineland) to wetland led to marked SOC accumulation. However, the SOC gain in recreated wetland was much lower than the SOC decline

in the lost wetland (SOC sequestration rate: $+101.2 \text{ g m}^{-2} \text{yr}^{-1}$ for rangeland converted to wetland vs. $-422 \text{ g m}^{-2} \text{yr}^{-1}$ for wetland lost to urban and rangeland), showing a 'slow in fast out' effect (i.e., SOC accumulates slowly but loses fast) in SOC change due to LULC conversion (Poeplau et al., 2011; Vasques et al., 2012).

Agricultural practices, such as tillage, have been reported worldwide to decrease the SOC level (Wu et al., 2003; Maia et al., 2010). However, no substantial change in SOC for cropland sites under constant LULC was observed between the two sampling campaigns in this study. This is because these cropland sites had been under agricultural use for a long history and the SOC balance had already reached equilibrium. As reported by Poeplau et al. (2011), it required approximate 17 and 23 years for croplands converted from grassland and forest to reach their equilibriums of SOC change rates, respectively, while the cropland sites in this study had been under agricultural use for more than 19 to 39 years.

The sugarcane collocated sites were in the Everglades Agriculture Area (EAA) in south Florida which is one of the prime farming areas developed on Histosols (Armentano, 1980). To maintain the agricultural productivity, drainage systems that consist of farm canals, ditches, and pump stations have been used to manage the hydrology in EAA (Kwon et al., 2010). In an average year, the EAA receives more rainfall than it needs for agriculture so water is pumped to Lake Okeechobee to the north (Bottcher and Izuno, 1994). The net water loss, oxidation of the organic soils (Histosols), and agriculture practices in the EAA were likely responsible for the dramatic SOC loss from 6.44 to 2.78 kg m^{-2} for the last four decades in this study.

In citrus soils, the SOC was relatively low with mean and median of 2.38 kg m^{-2} which was the second lowest among all the LULC (Fig. 2).

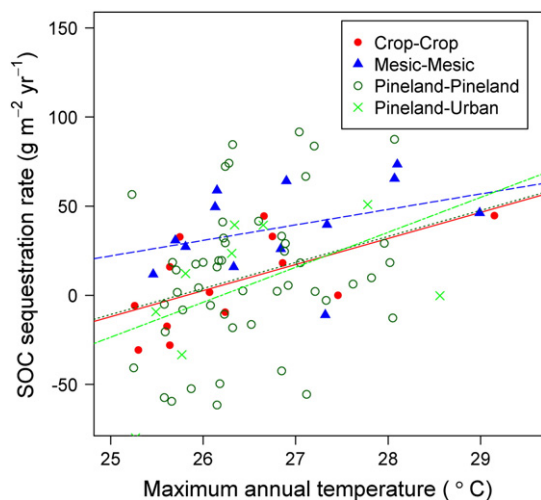


Fig. 5. The effect of maximum annual temperature on the soil organic carbon sequestration rate in four land use/land cover (LULC) and LULC change types. Filled red circles denote crop, filled blue triangles mesic upland forest, open dark-green circles pineland and light-green crosses change from pineland to urban between 1970s and 2008–2011.

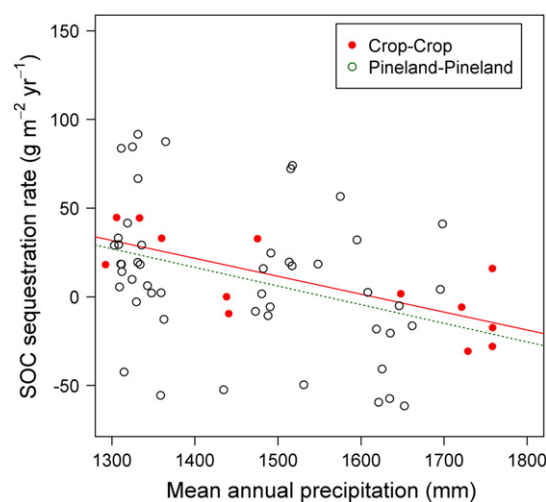


Fig. 6. The effect of mean annual precipitation on soil organic carbon sequestration rate in two land use/land cover types. Filled red circles denote crop and open dark-green circles pineland without change between 1970s and 2008–2011.

In addition, it was observed that the SOC slowly declined at the rate of $22.9 \text{ g m}^{-2} \text{ yr}^{-1}$ on average. A similar finding was reported in coarse-textured soils ($\leq 200 \text{ g clay kg}^{-1}$) in citrus and other low-intensity agriculture uses, such as perennial crops in Brazil where 20% SOC loss at 0–20 cm depth was detected (Zinn et al., 2005). In contrast, the improved pasture soils tended to accumulate SOC at an average rate of $42 \text{ g m}^{-2} \text{ yr}^{-1}$. This can be attributed to the management for high grass productivity such as fertilization and cultivar selection, which enhances the SOC input from roots, root exudates and plant residues (Post and Kwon, 2000). Moreover, improved pasture maintained relatively high SOC stocks which were significantly higher than those in crop and citrus soils (Fig. 2). Other studies also found that the conversion of row crops to managed pasture in the subtropical moist climate zone resulted in a net gain of SOC at $33.2 \text{ g m}^{-2} \text{ yr}^{-1}$ (Lugo et al., 1986). These results show the encouraging potential of improved pasture soils in sequestering carbon under low-intensity agriculture use.

In urban soils, relatively high SOC stocks were observed compared with other human-managed LULC systems such as citrus and cropland (Fig. 2). In addition, urban soils also showed a relatively large SOC accumulation of 0.79 kg m^{-2} on average (Fig. 4). These results suggest that urban soils, especially in residential areas, can serve as an ideal soil C sink because of the high level of management, such as irrigation and fertilization, and the lack of soil disturbances that may occur in other systems, such as tillage and harvesting in agriculture and prescribed fire in forest management (West and Post, 2002). Pouyat et al. (2006) investigated C storage by urban soils in the conterminous U.S. and found that residential lawns consistently contained high SOC stocks in all urban landscapes – even higher than many forest soils. In addition, cities located in warmer climate (e.g., the southeast U.S.) tended to accumulate SOC after urban establishment on non-wetland areas (Pouyat et al., 2006). This trend was also reflected in our result where the conversions of crop to urban and pineland to urban soils resulted in substantial overall gains of SOC between the historical and current sampling campaigns.

Another interesting finding is that the SOC stocks of pine plantation were not significantly different from the natural pine forest, suggesting that the (human) management of forests did not have significant impact on SOC stock. Overall, pineland (including both pine forest and pine plantation) showed an average SOC accumulation rate of $18.2 \text{ g m}^{-2} \text{ yr}^{-1}$. However, the SOC change in pineland was extremely variable (Fig. 4). This can be attributed to disturbances, such as natural and prescribed fire, that are common to pineland systems in Florida, which has been shown to greatly remove SOC in the surface soils (Certini, 2005).

4.2. Impact of LULC and climate on SOC sequestration rate

In this study, LULC alone explained 27% of the variability of SOC sequestration rate, while climate factors explained little (Table 2). It was the interactions between LULC and climate factors (MAP and MAT) that explained up to 46% of the variability of SOC sequestration rate. Elevated temperature tended to accelerate SOC accumulation under cropland, mesic upland forest, pineland and urban converted

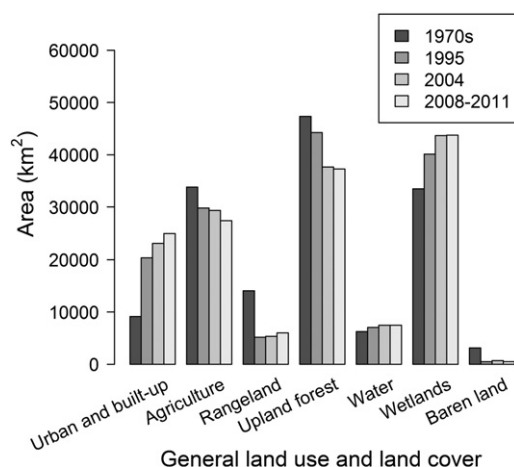


Fig. 7. General land use/land cover change between 1970s and 2008–2011 in Florida. The data of 1970s come from the United States Geological Survey (USGS), and the data of 1995, 2004 and 2008–2011 come from the Florida Department of Environmental Protection (FDEP).

from pineland, while precipitation had an opposite effect in cropland and pineland. Various studies reported that elevated temperature can have opposite effects on SOC change concomitantly enhancing SOC input by promoting primary production and accelerating SOC decomposition rate as well (Davidson et al., 2002; Bond-Lamberty and Thomson, 2010; Gao et al., 2013). In this study, the higher SOC sequestration rates in warmer climate under both changed and unchanged LULC conditions indicate that the SOC balance was dictated by SOC input rather than SOC decomposition. A similar result was reported by Poeplau et al. (2011) from a meta-analysis of 95 studies conducted in the temperate zone, in which they found that mean annual temperature had a positive effect on SOC accumulation in five LULC change conditions (cropland to grassland, grassland to cropland, forest to cropland, cropland to forest, and grassland to forest). Altogether these results suggest that soils are able to sequester C at a faster rate to reduce greenhouse gas emission under the current global warming trend. Precipitation has been known to promote primary production and increase the roots, root exudates and plant residues into soils as SOC input (Kirschbaum, 1995; Gao et al., 2013). However, a negative relationship was observed between SOC sequestration rate in the top soils and mean annual precipitation. This may be due to the sandy texture of Florida soils with high permeability that allows more organic material to migrate vertically to lower layers under higher precipitation (Jobbágy and Jackson, 2000).

4.3. Implications for future SOC change

For the past four decades, Florida has experienced profound LULC change primarily due to urbanization (Mulkey, 2007). From the 1970s to 2008–2011, the urban area in Florida increased by more than 140%

Table 3
Confusion matrix showing the area of land use/land cover (LULC) change between 1970s and 2008–2011 in Florida. Row names represent the LULC in 1970s and column names represent the LULC 2008–2011.

	Urban km ²	Agriculture	Rangeland	Upland forest	Water	Wetlands	Barren land
Urban	7254	248	220	637	353	379	24
Agriculture	6231	18,497	1127	4461	603	2731	175
Rangeland	2393	4366	1733	2178	259	3070	51
Upland forest	5377	2615	2217	26,093	377	10,577	89
Water	321	89	38	128	4773	896	17
Wetlands	1219	1454	557	3495	978	25,679	78
Barren land	2105	97	99	271	107	422	38

The data of 1970s and 2008–2011 were derived from the United States Geological Survey (USGS) and Florida Department of Environmental Protection (FDEP), respectively.

to about 24,900 km², primarily converted from agriculture and upland forest (Table 3). Due to a variety of wetland restoration projects in Florida, the wetland area kept increasing for the past four decades from 33,458 km² in 1970s to 43,752 km² in 2008–2011, primarily converted from upland forest (Fig. 7 and Table 3). For example, the South Florida Water Management District alone has restored about 300 km² of wetlands (also known as Stormwater Treatment Areas) in south Florida, which represents the largest constructed wetland in the world (South Florida Water Management District, 2013). The wetland area in Florida reported by the National Wetland Inventory as of 2009 was 46,951 km² (U.S. Fish and Wildlife Service, 2009), which is slightly higher than the 2008–2011 data from FDEP. The National Land Cover Dataset (NLCD) also confirmed that the Florida wetland area increased by 21.5% between 1992 and 2006, while the agricultural area declined by about 20% (Multi-Resolution Land Characteristics Consortium, 1992, 2006). These LULC conversions that are favorable to SOC accumulation could further explain the overall SOC increase between 1965–1996 and 2008–2009 and support the argument that soil acted as a net sink for C over the past four decades.

In the context of global climate change, the findings of interaction LULC–climate effects have strong implications for future SOC sequestration. Since the 1970s, temperatures in the southeast U.S. have been reported to steadily increase, particularly in the last decade (2001–2010), and are expected to increase through the end of the 21st century (Konrad et al., 2013). Given the positive effect of temperature on the SOC sequestration rates in agriculture and upland forest that account for about 45% of Florida's land area (Fig. 5 and Table 3), the warming trend not only explains the SOC sequestration over the last four decades, but also indicates a possibility to enhance soil C sequestration. The mean annual precipitation in south Florida, on the other hand, is projected to decrease by as much as 15% by the mid-21st century (Keim et al., 2011; Konrad et al., 2013). This trend may also benefit the SOC increase in Florida's cropland and pineland surface soils.

5. Conclusions

This study is a major development from the previous study by Ross et al. (2013) on temporal change of SOC by scaling up from a subregion that covers ~15% area of Florida to the whole state. The key innovation of this research is that it investigates and reveals the natural and anthropogenic factors that caused the SOC sequestration in Florida, i.e., LULC, climate, and the interaction effect between LULC and climate.

This study shows that LULC strongly related to SOC variation in Florida. Generally, sugarcane and wetland contained the highest SOC stock, followed by improved pasture, urban, mesic upland forest, rangeland, and pineland while crop, citrus and xeric upland forest remained the lowest. Our comparative analyses of current and historical SOC datasets showed a significant SOC accumulation between 1965–1996 and 2008–2009. The amount of SOC change was dependent on LULC and LULC change types. In most of the LULC classes an overall sequestration of SOC was observed, except in sugarcane and citrus. Remarkable site-specific SOC losses were involved in the conversions of wetland to other LULC types, and vice versa. At regional scale restoration of wetlands contributed to the buildup of SOC stocks. Urban soils contained moderately high SOC stocks and conversions of crop, pineland and barren land resulted in SOC accumulation, which suggests that urban soils can serve as a promising SOC sink if managed properly. In general, the LULC change in Florida for the past four decades followed a trend that favored SOC accumulation – the wetland and urban areas increased and the agriculture area decreased as shown by different LULC data sources (FDEP and NLCD).

The SOC sequestration rate was not only LULC dependent but also controlled by climate factors interacting with LULC. Warmer climate tended to accelerate SOC accumulation, while higher precipitation reduced the SOC sequestration rate in the topsoil. These major findings

provide insights into how LULC and LULC change and their interaction effects with climate factors (temperature and precipitation) have impacted SOC change over the past four decades, suggesting that under near-decadal climate and LULC projections for this region soils are poised to provide a substantial soil C sink.

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