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Estimating soil subsidence and carbon loss in the Everglades Agricultural Area, Florida using geospatial techniques

Sumanjit Aich[a], Christopher W. McVoy[b], Thomas W. Dreschel[c,*], Fabiola Santamaria[d]

[a] Photo Science Geospatial Solutions, St. Petersburg, FL, United States
[b] Everglades National Park, FL, United States
[c] South Florida Water Management District, West Palm Beach, FL, United States
[d] Atkins North America, West Palm Beach, FL, United States

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ABSTRACT

Climate change due to elevated carbon dioxide levels in the atmosphere presents a long-term threat to the biosphere. The contribution of soil oxidation to global carbon dioxide levels is of growing concern. Until the past century, for over five millennia, the Everglades has been accreting peat soils and acting as a carbon sink. Anthropogenic drainage of the northernmost one-fourth of the Everglades, one of the largest deposits of organic soils in North America, began in the 1880s. Subsequently, the peat soils of that area began subsiding and releasing carbon dioxide (CO_2) into the atmosphere. We quantified subsidence and CO_2 evolution at the regional scale by calculating the changes in peat volume using surface maps reconstructed from historical and current data. The estimated peat volume was originally about 7×10^9 m^3 and is currently about 3×10^9 m^3. The average subsidence was about two meters and the CO_2 emitted was 4.9×10^8 metric tons. Assuming a constant CO_2 emission rate during the century since drainage, then the regional scale CO_2 flux rate from this study (0.2 g CO_2 m^{-2} yr^{-1}) was similar to short-term, small-scale measurements made under controlled conditions (0.2–6 g CO_2 m^{-2} yr^{-1}).

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1. Introduction

Climate change presents a long-term threat to the biosphere as global carbon dioxide levels rise. The contribution to global carbon dioxide levels by the oxidation of soils is of growing concern. North American wetlands and their associated organic soils are an important component of the global carbon cycle, containing an estimated 2.2×10^{11} metric tons of carbon (Bridgham et al., 2006). The largest contiguous body of organic soils (peats) within the continental United States occurs in the Florida Everglades (Zelazny and Carlisle, 1974), forming an area originally greater than 8900 km^2 (McVoy et al., 2011). Peat deposition began approximately 5000 years ago (McDowell et al., 1969; Gleason and Stone, 1994), reaching a maximum thickness of 3–3.7 m by the 1900s (Baldwin and Hawker, 1915), corresponding to an average accumulation rate of about 0.07 cm yr^{-1}. The deposit thinned with distance southward from Lake Okeechobee to a minimum of 0.3–0.5 m thick (Baldwin and Hawker, 1915; McVoy et al., 2011). Prior to anthropogenic alterations, the Everglades was a broad, shallow freshwater marsh system originating at the southern edge of Lake Okeechobee and flowing more than 150 km south to discharge into the Atlantic Ocean, Biscayne and Florida Bays, and the Gulf of Mexico (Fig. 1).

The combination of thick organic soils and subtropical climate attracted interest in draining the Everglades for agricultural use at least as early as the 1840s (Smith, 1848).

This effort began in earnest in the 1880s, when initial lowering of Lake Okeechobee water levels reduced lake inflows into the Everglades (McVoy et al., 2011). Drainage efforts further intensified during the 1910s and 1920s, when dikes fully isolated Lake Okeechobee from the Everglades and when four major canals were dredged through the Everglades (Light and Dineen, 1994).

The lowering of Lake Okeechobee, dike construction, and unrestrained canal drainage together strongly affected the Everglades. Water tables were lowered from above ground surface to well below ground surface (Sklar et al., 2002), altering vegetation, and exposing the organic soils to subsidence. The occurrence of dramatic soil subsidence is well-documented (Clayton et al., 1942; Neller, 1944; Stephens and Johnson, 1951; Shih et al., 1978, 1979a,b,c, 1997; Cox et al., 1988; Snyder and Davidson, 1994; Ingebritsen et al., 1999; Snyder, 2005). The northernmost portion of the Everglades, approximately 2540 km^2 (23%), was formally designated in the 1950s as the Everglades Agricultural Area (EAA). Drainage and a degree of agriculture had already been present there

* Corresponding author at: South Florida Water Management District, MSC 4352, West Palm Beach, Florida, United States. Tel.: +1 561 682 6686; fax: +1 561 682 5529.
E-mail addresses: tdresche@sfwmd.gov, tdreschel@gmail.com (T.W. Dreschel).

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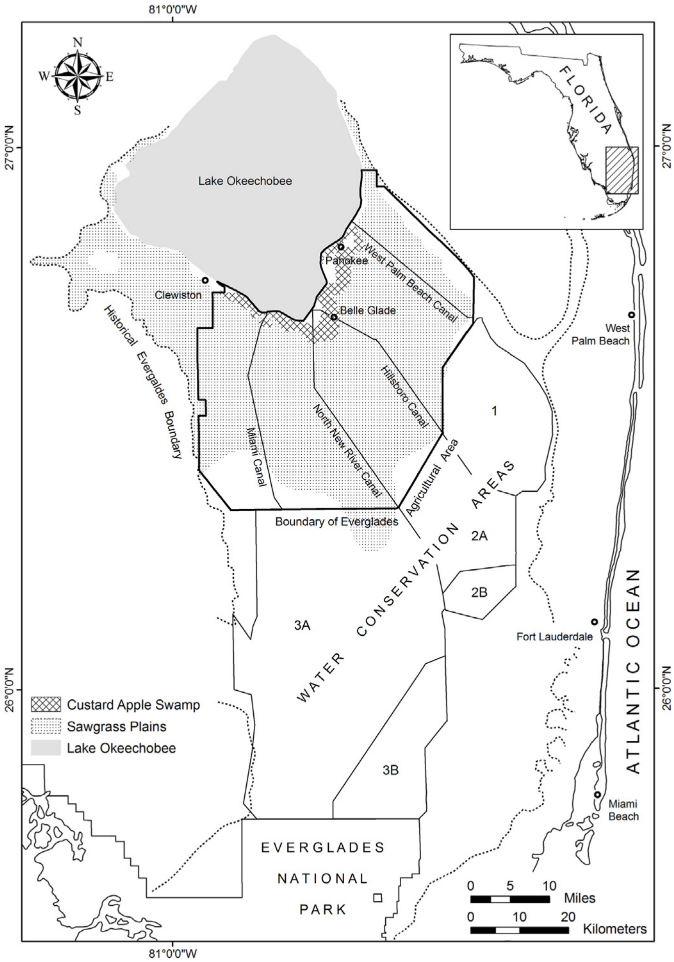

Fig. 1. Location of the Everglades Agricultural Area (EAA; solid line, heavy) within the historical Everglades (dotted line), showing close correspondence of the EAA to the predrainage sawgrass plains and custard apple swamp landscapes.

for a number of decades. A concrete marker at the Agricultural Research and Education Center in Belle Glade shows that the 2.6 m of organic soil present in 1924 (already reduced from predrainage conditions) had been reduced to less than 1.25 m by 1978 (Stephens et al., 1984). Field measurements of subsidence within the EAA indicate loss of elevation at a rate of about 3 cm yr^{-1} (Neller, 1944; Stephens and Speir, 1969; Snyder, 2005).

The EAA encompassed essentially all of the original Sawgrass Plains landscape (Fig. 1), an area dominated by sawgrass, *Cladium jamaicense*, as well as the much smaller Custard Apple Swamp, dominated by pond apple, *Annona glabra*. Both landscapes were associated with similarly sized areas of corresponding soils (Jones et al., 1948; McVoy et al., 2011). The custard apple mucks, found bordering the southeast shoreline of Lake Okeechobee, was described in 1915 as "black, finely divided and well-decomposed vegetable matter, . . . fairly uniform in texture, structure, and color to a depth of 40–75 in. [1–1.9 m]" (Baldwin and Hawker, 1915). The total soil thickness of the custard apple mucks was 2.8–3.8 m and the average organic matter content about 60% (Baldwin and Hawker, 1915). At the time of observation, 1915, the water table had already been lowered 0.5–1 m below the surface, so it is possible that this soil was originally less decomposed than in Baldwin and Hawker's description, that is, more brown than black and more fibrous than finely divided. The soil mineral content may also have increased somewhat but probably always was relatively high. The custard apple muck soils are presently classified as the Torry series of Typic Haplosaprists and in 1988 comprised 7% of the EAA.

The sawgrass peats that underlaid about 90% of the present EAA originally were highly organic, containing 90% organic matter (Baldwin and Hawker, 1915). While a degree of drainage had already occurred by 1915, surface water was still present in some areas and the soil appears to still have retained much of its original character. Referred to as "Brown fibrous peat," it was described as "uniform in composition and texture for many square miles" and as "typically consist[ing] of brown fibrous to dark-brown semifibrous, slightly decomposed organic matter" (Baldwin and Hawker, 1915). When later mapped again in the 1940s, the sawgrass peats had decomposed further to develop a surface layer of "black, finely fibrous, well decomposed organic material, 6–18 in. [15–45 cm]" thick (Jones et al., 1948; McVoy et al., 2011). Although not part of the formal system of soil taxonomy, the name given by Jones et al. (1948), "Everglades peats," has persisted in general use. By the 1970s the sawgrass peats had further subsided and were classified as the Montverde (sawgrass) muck series of Typic Medifibrists (Volk, 1973). Under the present classification system (Soil Survey Staff, 1998, 1999), all the soils of the EAA are classified as Saprists, the most decomposed suborder of Histosols. Four series are recognized, in order of decreasing soil thickness: the Terra Ceia series, a Typic Haplosaprist, and three Lithic Haplosaprists, the Pahokee, Lauderhill and Dania series. In 1988, less than 10% of the EAA fell within the thickest series (Terra Ceia, >130 cm thick). As noted by Rice et al. (2005), subsidence is causing the soils of the EAA to continually transition from thicker to thinner soil series, and they note that these soils may eventually be classified as mineral soils.

This study estimates the volume and mass of peat soil that has been lost over the last 125 years within the EAA as a result of anthropogenic land use change from Everglades wetlands into drained agricultural fields. The time period of interest was defined as immediately prior to the onset of anthropogenic drainage (i.e., <1880) through the present, which required the use of imperfect historical data sets developed from land and soil surveys conducted in the early 1900s (McVoy et al., 2011). To offset limitations in the historical as well as current data sets, we used two independent methods and sets of data to estimate the volumes of peat lost. The first method was based on historical and current estimates of peat thickness, in both cases measured with sounding rods inserted to the underlying mineral substrate. The second method was based on estimates of the historical and current surface topography. We used a GIS to organize the historical data, to interpolate, and to calculate differences.

We additionally estimated atmospheric releases of CO_2 from the EAA associated with the land use change from Everglades wetlands to agriculture. This estimate required differentiation of the soil volume changes (subsidence) into physical and biochemical processes. Subsidence is caused by a combination of physical consolidation due to loss of buoyancy, physical shrinkage due to increased matric potential, biochemical mineralization of organic C to CO_2 due to microbial oxidation (Volk, 1973; Schothorst, 1977), and, if the soil becomes dry for extended periods, occasionally outright burning (Davis, 1943a,b; Allison et al., 1944; Robertson, 1953; Simpson, 1920; Loveless, 1959; Mayo, 1940). We used historical and current data for bulk density, fraction of organic matter, and carbon content to estimate the portion of subsidence that produced atmospheric CO_2. By prorating the estimated releases over the century of subsidence and by taking into account soil nomenclature changes, we were able to compare our estimated rates of CO_2 release with literature values measured in lab and field column studies of Everglades soils (e.g., Knipling et al., 1970; Volk, 1973; Gesch et al., 2007).

The carbon release estimates made here provide context for ongoing proposals to return surface water to portions of the EAA. Potential plans include the creation of treatment marshes to reduce undesired nutrient concentrations in water destined for the remaining Everglades, the creation of shallow flow ways with

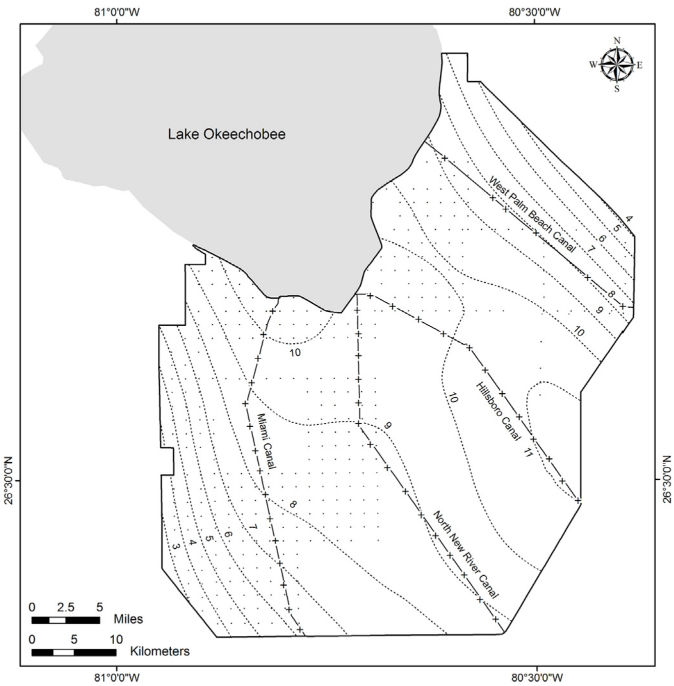

Fig. 2. Map of estimated contours of peat thickness (ft) in the EAA, ca. 1915, showing measurements of peat thickness from township surveys (dots) and from canal surveys (pluses).

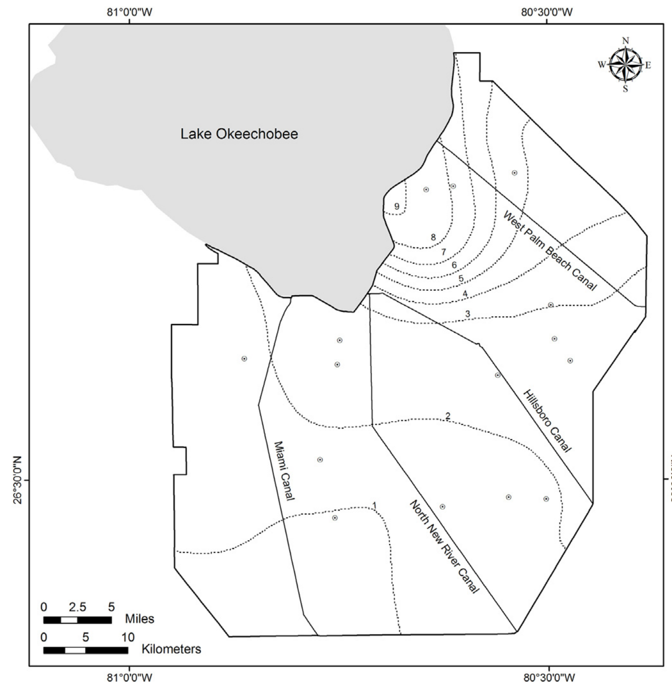

Fig. 3. Map of estimated contours of peat thickness (ft) in the EAA, 2003, showing data points (⊙).
From Snyder (2005).

some resemblance to predrainage sawgrass marshes, or the creation of deeper reservoirs to store water for Everglades restoration. While carbon accumulation rates associated with these potential land use changes have not been quantified, at a minimum, it can be assumed that reflooding of the soils would reduce or eliminate the soil subsidence and CO_2 releases that have been occurring during the previous 125 years.

2. Methods

The Everglades Agricultural Area or EAA, located in southern Florida, USA is the former northern portion of the Everglades that was set aside in the early 1900s and drained for agricultural production. Sugar cane (*Saccharum* spp.) is grown in most of the EAA with a large portion of the nation's winter vegetable crops grown there as well (Gesch et al., 2007). Soil subsidence has been pronounced in this area and is of concern both due to soil loss and to the contribution to atmospheric carbon dioxide. We utilized data from land surveys conducted in the late 19th and early 20th centuries, a bedrock elevation map, and a recent space-based radar topographic survey. Contour maps shown in Figs. 2–6 reflect the English units used in the historic field measurements; these were converted to SI units for the final calculations of peat volume and carbon loss. The calculations were conducted in these units for the two methods discussed and then converted to SI units for the final calculations of peat volume and carbon loss.

2.1. Method 1 (peat thickness)

We estimated the volume of peat lost between approximately 1915 and 2003 as the difference between a map of historic peat thickness (Fig. 2) and a map of current peat thickness (Fig. 3), both created as part of this study.

2.1.1. Historic peat thickness, ca. 1915 (Fig. 2)

The earliest measurements of peat thickness within the EAA area were made as part of an agricultural survey (Kreamer, 1892). Data covering a larger portion of the EAA did not become available until the 1911–1916 period when peat thicknesses were measured along proposed canal routes (Ensey and Elliot, 1911; FEEC, 1913) and during land surveys carried out for the Trustees of the Internal Improvement Fund, State of Florida (Elliot, 1911a,b,c, 1912a,b; Frederick, 1914a,b,c,d; Horne, 1914a,b,c; Franklin, 1914a,b; Hardin, 1915a,b,c,d,e,f,g, 1916a,b,c,d,e,f,g,h,i,j,k,l,m; field notes for these surveys extracted from the Land Boundary Information System,

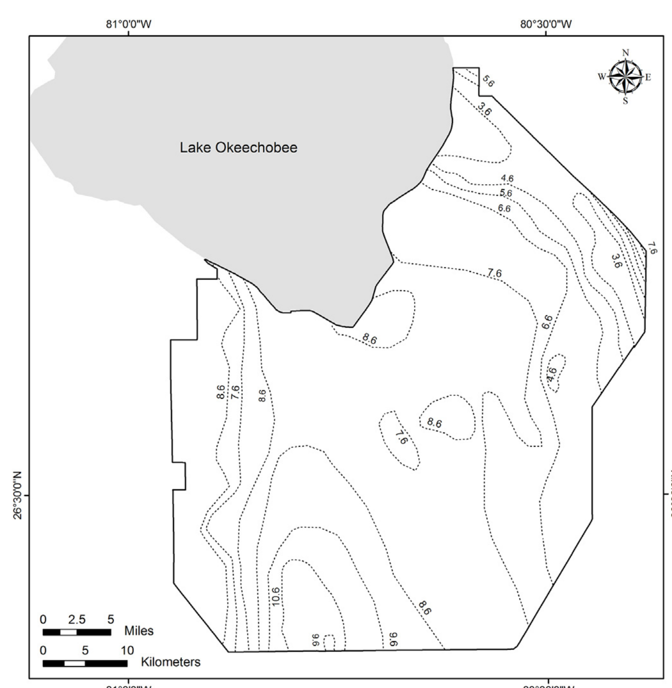

Fig. 4. Contour map of bedrock elevation (ft, NGVD29) for the EAA.
From Parker et al. (1955).

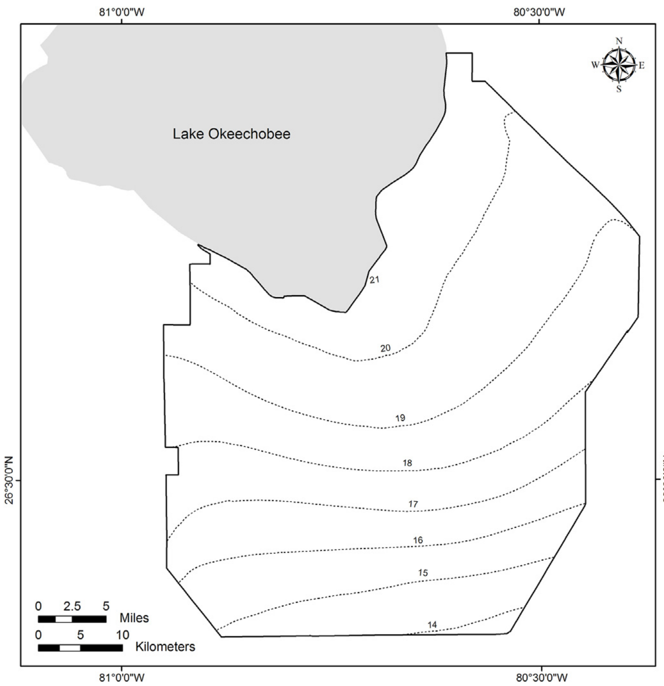

Fig. 5. Contour map of historic peat surface elevation (ft, NGVD29) for the EAA, ca. 1880.
From Said et al. (2006).

FDEP, 1984). Land surveys typically do not include soil depth measurements but because of the interest in converting the Everglades to agriculture, these surveys did. As the large majority of these measurements were made between 1911 and 1916, an average date of 1915 was assigned. As surveys, all of these measurements were georeferenced (e.g., the distance from the corners of a township or from the end of a canal), thus we were able to create a GIS database (Lo and Yeung, 2002) of depth measurements.

Most of the peat depths in the land surveys were recorded as "9 ft" (2.74 m) or "10 ft" (3.05 m), with some indicated as ">10 ft", suggesting that the land surveyors used a 10 ft-long sounding rod that in those cases did not reach bedrock. A total of 34 (7%) of the soundings were reported as ">10 ft"; for lack of additional quantification, we recorded these as 10 ft. Surveyors from a different agency (FEEC, 1913) used longer sounding rods; their measurements of up to 14 ft (4.27 m) along the northern portion of some canals were included in our GIS data base.

Estimation of a thickness surface required additional spatial information in areas. Near the eastern edge of the historic Everglades, where measurements from the late 1800s to early 1900s were absent or scarce, we included peat thicknesses measured by sounding rod in the 1940s by Jones et al., 1948 recognizing that these measurements underestimate 1915 thicknesses. The known boundaries of the Everglades (McVoy et al., 2011), recognized both as a vegetational boundary and as the boundary between peat and sand soils, were used to define the locations of zero peat thickness.

A historical map (raster grid) of peat thickness was calculated from 456 agricultural, land and canal survey points across the EAA. Ordinary kriging with a Gaussian semi-variogram (Bonham-Carter, 1994; ESRI, 2004) was used to create the map. Fig. 2 shows the estimated peat thickness present ca. 1915 within the present Everglades Agricultural Area.

2.1.2. Current peat thickness, ca. 2003 (Fig. 3)

Current (2003) peat thickness was estimated from measurements taken at 15 locations throughout the EAA (Snyder, 2005). Ten replicates were taken at each location (Snyder, 2005). Soil subsidence has tended to level this area substantially (Snyder, 2005) so that a small data set may be appropriate to use. A map of current peat thickness (Fig. 3) was calculated using ordinary kriging with a Gaussian semi-variogram (Bonham-Carter, 1994; ESRI, 2004).

2.2. Method 2 (topography)

A second and independent estimate of the volume of peat lost was made on the basis of predrainage and current surface topography. These two topographic surfaces were converted to peat thicknesses by subtracting the bedrock surface from Parker et al. (1955) (Fig. 4). The two resultant peat thicknesses were subtracted, yielding the volume of peat lost.

2.2.1. Bedrock surface (predrainage and current) (Fig. 4)

A 100 ft by 100 ft (30.5 m by 30.5 m) Digital Elevation Model (DEM) of the bedrock surface underlying the EAA was estimated from the only known source of such information, a set of 1 ft (30 cm) contours shown in Parker et al. (1955). We assumed that the bedrock surface has been constant between 1880 and the current time. Parker's map is a slight modification of an earlier map (Jones et al., 1948), entitled "Approximate contours on the rock surface under the organic soils in the Everglades Region." Jones et al. (1948) indicated that: (1) these contours were drawn from data obtained while running approximately 440 miles (710 km) of survey lines covering the Everglades; (2) land surface elevations were surveyed to 0.1 foot (3 cm) along the lines; and (3) thicknesses of the peat soil (i.e., distance from surface to bedrock) were measured at 660 ft (200 m) intervals. These numbers suggest that approximately 3500 measurement points throughout the Everglades might have been used by Jones et al. (1948) to draw the contours. Jones et al. (1948) described the bedrock surface as "very uneven", i.e., locally variable, and indicated that they mapped only its "general configuration." Shih et al. (1979a,b,c) confirm the local variability, showing a magnitude of about 0.5 m along line transects

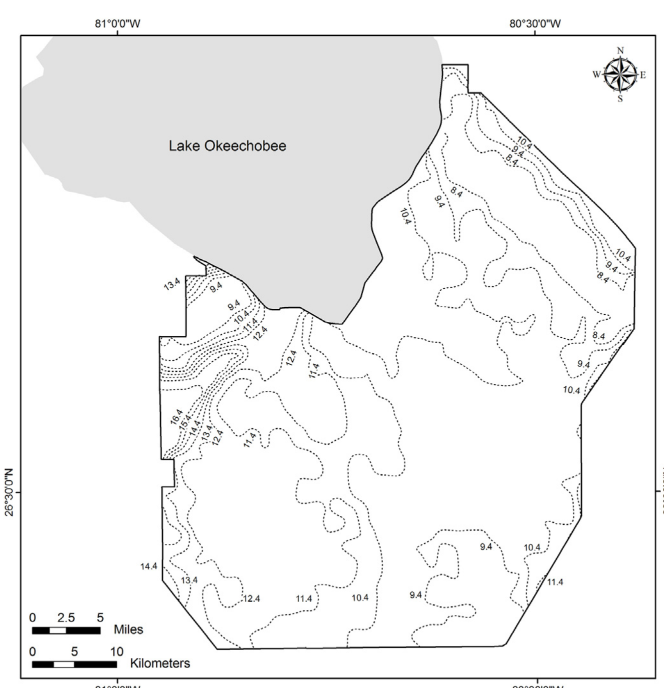

Fig. 6. Contour map of current peat surface elevation (ft, NGVD29) for the EAA, ca. 2005.
Modified from Holt et al. (2006).

300–1000 m long. At the scale of the 2540 km^2 EAA, the contours obtained from Parker et al. (1955) and shown in Fig. 4, likely are a good regional representation of the average bedrock surface. We converted the Parker et al. (1955) contours from 'Punta Rassa datum' to NGVD29 by subtracting 1.44 ft (0.44 m) (Parker et al., 1955; U.S. Army Corps of Engineers, 1978).

2.2.2. Predrainage peat surface, ca. 1880 (Fig. 5)

Said et al. (2006) estimated the predrainage topography of the Everglades by combining known elevations of the borders of the Everglades with contour shapes within the Everglades estimated from peatland directionality. The predrainage eastern and western border elevations were known from modern measurements, based on the assumption that the mineral soils along those borders had not been altered by drainage. The elevation of the northern border of the predrainage Everglades, that is, the southern, peat-based shoreline of Lake Okeechobee, seasonally overflowing into the Everglades, was known from predrainage stages of Lake Okeechobee. Contour shapes for the peat-filled predrainage Everglades were estimated based on the assumption that contours were perpendicular to predrainage directions of surface water flow. Directions of flow were assumed to have been parallel to landscape directionality, as reported by a number of predrainage and early post-drainage observers (McVoy et al., 2011). The estimates of predrainage topography compared well with the ground surface elevations derived from early post-drainage surveys along the lengths of muck canals (FEEC, 1913). For this study we used the EAA portion of the 100 ft by 100 ft (30.5 m by 30.5 m) DEM grid estimated by Said et al. (2006), assigning to it the date of 1880, representing the end of predrainage conditions.

2.2.3. Current peat surface, ca. 2000 (Fig. 6)

A corresponding 100 ft by 100 ft (30.5 m by 30.5 m) DEM grid of the current peat surface (Fig. 6) was created from the South Florida Digital Elevation Model (SFDEM). This was produced from data collected during an 11-day Space Shuttle Radar Topography Mission (SRTM) in February of 2000, which utilized a specially modified radar system aboard the Space Shuttle Endeavor (Holt et al., 2006). Holt et al. (2006) processed the SRTM data using additional, later data collected in the surrounding regions. We converted the data reported by Holt et al. (2006) from NAVD88 vertical datum to NGVD29 by applying a uniform offset of 1.39 ft (0.42 m). The decision to apply a uniform offset was based on results from the CORPSCON program (U.S. Army Corps of Engineers, 2009) when applied to a 2 by 2 mile (3.22 km) grid of 251 points covering the EAA. The results indicated an offset of 1.39 ± 0.05 ft. The small standard deviation, 0.05 ft, suggested that applying a single offset for the whole EAA was an appropriate approximation.

2.3. Calculation of carbon emissions

The above calculations quantify the drainage-induced loss of volume in the organic soils of the EAA. The volume loss reflects a combination of physical consolidation, biochemical oxidation, and possibly erosive losses. We assumed that losses to water erosion were negligible due to the extremely low surface slope and to the absence of surface water during most of the post-drainage period. Wind erosion from EAA soils has rarely been reported; additionally, most eroded particles would have been deposited on dry land where they would ultimately have oxidized and been released as CO_2, a pathway equivalent to in situ oxidation. Carbon emissions were estimated here as the fraction of volume loss not due to physical consolidation. Following Schothorst (1977), we used changes in the soil bulk density and organic matter to distinguish

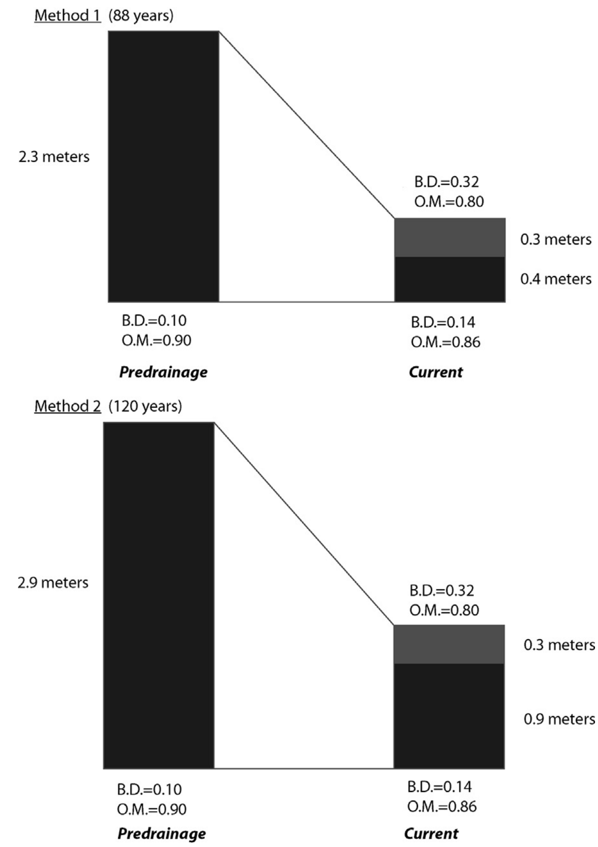

Fig. 7. Estimated values of soil parameters for predrainage and current soil profiles in the Everglades Agricultural Area.

consolidation from oxidation using the following general formulation for an organic soil with k layers:

$$C_{\text{loss}} = A\sum_k (\rho_{\text{bIk}} f_{\text{ocIk}} OM_{\text{Ik}} z_{\text{Ik}}) - A\sum_k (\rho_{\text{bFk}} f_{\text{ocFk}} OM_{\text{Fk}} z_{\text{Fk}}) \quad (1)$$

where C_{loss} (Mg C) is the metric tons of C transferred from the soil to the atmosphere by oxidation from an area A (m^2), ρ_b is bulk density (Mg m^{-3}), f_{oc} is the fraction of organic carbon in the soil organic matter (kg C kg OM^{-1}), OM is the fraction of soil organic matter (kg OM kg $soil^{-1}$), and z is the thickness of the layer (m). The subscripts I and F refer to the initial (i.e., predrainage) and final (i.e., current) time periods.

The summation signs in Eq. (1) reflect the possibility of up to k distinct layers of soil being present within the full soil profile. The available current and predrainage soil profile information for the EAA suggests that these organic soils were vertically highly uniform. We therefore represented the initial predrainage profile as a single layer and the current profile as two distinct layers (Fig. 7). Division of the current, post-subsidence EAA soil profile into two layers was based on soil tillage: an upper layer from 0 to 30 cm thick corresponding to the tilled root zone, and a lower layer from −30 cm down to bedrock.

The predrainage parameters needed for Eq. (1) were the soil bulk density, ρ_{bI}, and the soil organic matter content, OM_I. No predrainage measurements of soil bulk density were found. We estimated ρ_{bI} by selecting from measurements made in the currently remaining soils (Table 1), adjusted for location and the effects of drainage. We chose $\rho_{\text{bI}} = 0.10$ Mg m^{-3}, the lowest of the Saunders et al. (2008) values. We chose the lowest value because all areas sampled by Saunders et al. have experienced increased post-drainage drying and can therefore be expected to have increased slightly in density. We avoided the even lower values of 0.06–0.08

Table 1
Properties of peat soils of the Everglades [Agricultural Area]. BD = bulk density ($Mg\,m^{-3}$); OM = organic matter content ($kg\,kg^{-1}$); OC/OM = organic carbon content/OM.

	BD	OM	OC/OM	Source
Predrainage (or analogs)	0.12			Saunders et al. (2008): 3B1, Sawgrass, 0–30 cm
	0.13			Saunders et al. (2008): 3B1, Sawgrass, 30–74 cm
	0.10			Saunders et al. (2008), SRS-3, Sawgrass, 0–30 cm
	0.12			Saunders et al. (2008), SRS-3, Sawgrass, 30–100 cm
	0.07			Corstanje et al. (2006), WCA1, 0–10 cm
	0.08			Corstanje et al. (2006), WCA1, 10–20 cm
	0.06			USEPA-REMAP (2007), WCA1, 0–10 cm (median)
	0.10–0.15			USEPA-REMAP (2007), WCA 3B, 0–10 cm
		0.92		Miller (1918); Sawgrass 1, 0–152 cm
		0.91		Miller (1918); Sawgrass 1, 152–305 cm
		0.93		Miller (1918); Sawgrass 2, 0–63 cm
		0.90		Miller (1918); Sawgrass 2, 63–208 cm
		0.92		Baldwin and Hawker (1915), 0–30 cm
		0.88		Baldwin and Hawker (1915), >30 cm
		0.93		USEPA-REMAP (2007), WCA 1, 0–10 cm
			0.47	Corstanje et al. (2006), WCA1, 0–10 cm
			0.49	Corstanje et al. (2006), WCA1, 10–20 cm
Current, top 30 cm	0.36			Weaver and Speir (1960), Everglades, 0–8 cm
	0.36			Weaver and Speir (1960), Everglades, 8–15 cm
	0.34			Weaver and Speir (1960), Everglades, 15–23 cm
	0.29			Weaver and Speir (1960), Everglades, 23–30 cm
	0.26			Zelazny and Carlisle (1974), Montverde, 0–13 cm
	0.22			Zelazny and Carlisle (1974), Montverde, 13–36 cm
	0.33			Zelazny and Carlisle (1974), Pahokee, 0–18 cm
Estimated	0.3			Smith et al. (2001), Rotenberger WMA, 2–10 cm
	0.45			Wright and Inglett (2009), Dania muck, 0–30 cm
		0.94		Volk and Schnitzer (1973), Terra Ceia, 0–20 cm
		0.93		Volk and Schnitzer (1973), Pahokee, 0–25 cm
		0.75		Janardhanan and Daroub (2010), Lauderhill, 0–20 cm
		0.83		Janardhanan and Daroub (2010), Pahokee, 0–20 cm
Estimated		0.9		Smith et al. (2001), Rotenberger WMA, 2–10 cm
		0.6		Snyder (2005) (from Talisman Property, 10 in. profile)
			0.50	Volk and Schnitzer (1973), Terra Ceia, 0–20 cm
			0.53	Volk and Schnitzer (1973), Pahokee, 0–25 cm
Current, > 30 cm	0.14			Weaver and Speir (1960), Everglades, 30–43 cm
	0.13			Weaver and Speir (1960), Everglades, 51–58 cm
	0.12			Weaver and Speir (1960), Everglades, 66–74 cm
	0.15			Weaver and Speir (1960), Everglades, 81–99 cm
	0.08			Zelazny and Carlisle (1974), Montverde, 36–81 cm
	0.18			Zelazny and Carlisle (1974), Pahokee, 18–86 cm
	0.49			Wright and Inglett (2009), Dania muck, 30–45 cm
		0.93		Volk and Schnitzer (1973), Terra Ceia, 20–122 cm
		0.94		Volk and Schnitzer (1973), Pahokee, 25–107 cm
			0.56	Volk and Schnitzer (1973), Terra Ceia, 20–122 cm
			0.48	Volk and Schnitzer (1973), Pahokee, 25–71 cm
			0.55	Volk and Schnitzer (1973), Pahokee, 71–107 cm
			0.51	Bhatti and Bauer (2002), used by Wright and Inglett

from Corstanje et al. (2006) and USEPA-REMAP (2007) because these were measured only in the upper 0–10 cm, which is of lower density than the overall profile.

A number of predrainage or near-predrainage datasets of soil organic matter content, OM_I, were available (Table 1). The spatially and numerically most extensive was that of Baldwin and Hawker (1915), with more than 400 cores samples. We used the average of their upper and lower profile values, $OM_I = 0.90\,kg\,kg^{-1}$.

The thickness of the predrainage peat profile, z_I, was calculated simply as V_I/A, that is, for the purposes of Eq. (1), the predrainage EAA peat deposit was assumed to be of equal thickness throughout.

The available data for current soils in the EAA appears to be more limited than might be expected (Table 1). We assumed that as the predrainage soil profile oxidized, its original mineral content was deposited onto the upper portion of the currently remaining soil, and redistributed by tillage throughout the upper 30 cm. As the mineral fraction accumulated, the soil organic matter content of the upper profile, OM_{F1}, would have correspondingly decreased. The upper profile bulk density, ρ_{bF1}, would have increased with increasing mineral content, and additionally as a result of tillage and drying of the soil. For ρ_{bF1}, we considered the Table 1 value of $0.45\,Mg\,m^{-3}$ from Wright and Inglett (2009) to be an outlier and chose $0.32\,Mg\,m^{-3}$ as a midrange among the remaining values. For OM_{F1}, we excluded the Table 1 values of 0.93 and 0.94 from Volk and Schnitzer (1973) because these values were actually greater than the predrainage soil organic matter contents. With these values excluded, we chose a midrange value of $0.80\,kg\,kg^{-1}$.

For the current soil profile below 30 cm, we assumed that this lower, untilled portion of the profile would retain some resemblance to the original predrainage soil characteristics but also that the profiles would have experienced lowered water tables and periodic drying of essentially the entire profile, leading to slight decreases in organic matter and increases in bulk density.

For the lower profile soil bulk density, ρ_{bF2}, we compared to the predrainage soil bulk density, $\rho_{bI} = 0.10\,Mg\,m^{-3}$, excluded what seemed to be an outlier value in Table 1 of $0.49\,Mg\,m^{-3}$, and chose a higher midrange value of $0.14\,Mg\,m^{-3}$ from Table 1. For the lower profile soil organic matter content, OM_{F2}, few literature values were available and they were of little guidance as they were actually greater than the predrainage value of $0.90\,kg\,kg^{-1}$

(Table 1). We chose a value of 0.86 kg kg^{-1},slightly lower than Baldwin and Hawker's (1915) measured predrainage, lower profile value of 0.88 kg kg^{-1}.

We assumed a simplified geometry for the currently remaining peat profile, that is, both layers uniformly thick, with the upper layer, z_{F1}, equal to 0.3 m and the lower layer, z_{F2}, equal to $(V_F/A) - 0.3$.

We assumed that the fraction of carbon in the soil organic matter, f_{oc}, was constant over time and depth. Given the similarity to values reported for the EAA (Table 1), we adopted the value used by Bhatti and Bauer (2002) of $f_{oc} = 0.51$ for all depths and both time periods.

The soil parameters shown in Fig. 7 reflect our best estimates of predrainage and current values, based on synthesis of the available data (Table 1), the predrainage and the current distribution of soils and landscapes (McVoy et al., 2011), and the history of Everglades drainage (McVoy et al., 2011).

Carbon loss (Mg C) calculated in Eq. (1) was converted to carbon dioxide released to the atmosphere using the stoichiometric factor of 44/12 and the assumption that all the peat carbon lost was immediately or eventually converted to carbon dioxide.

3. Results

We estimate the volume of peat lost over approximately a century of drainage as 4.5×10^9 m^3 (method 1; Table 2) and 4.9×10^9 m^3 (method 2). Using Eq. (1) to distinguish physical changes from actual oxidation gives an estimated peat mass loss of 2.50×10^8 metric tons (both methods) and a release of CO_2 to the atmosphere of 4.85×10^8 metric tons (method 1) and 4.92×10^8 metric tons (method 2). With a simplifying assumption of a constant oxidation rate, justified by relatively constant temperatures and levels of drainage, this corresponds to emission rates of 0.22 g CO_2 m^{-2} h^{-1} for method 1 and 0.16 g CO_2 m^{-2} h^{-1} for method 2. The generally small differences between the two methods, along with the uncertainties inherent in all of the datasets, suggest that the results from both methods are best combined and considered as a single estimate.

As a result of anthropogenic drainage, approximately two-thirds of the peat volume originally present within the present Everglades Agricultural Area has been lost during the last century, decreasing from about 7×10^9 m^3 to about 2.5×10^9 m^3 (Table 2). This lost volume corresponds to about 2.5×10^8 metric tons of peat.

The average vertical subsidence over the entire EAA has been almost 2 m (6 ft; Table 2). However, subsidence has not been uniform. The slope of the predrainage Everglades land surface showed a strong southward trend, ranging from about 6.4 m (21 ft) above NGVD29 near Lake Okeechobee, down to about 4.3 m (14 ft) at the southern end of the EAA (Fig. 5). The bedrock slope was more variable (Fig. 4), but generally did not decrease southward, indicating a southwardly thinning predrainage wedge of peat, thickest near Lake Okeechobee. Post-drainage subsidence has also followed this generally north–south trend, with a greater degree having occurred northward (compare Figs. 5 and 6), where the peat was originally thicker (Fig. 2; see also Figs. 4 and 5). An important consequence of this differential subsidence is that the EAA land surface, once southwardly sloped, is now essentially level (Fig. 6). Under the assumption that the peat volumes and masses shown in Table 2 were lost specifically to peat oxidation (rather than soil transport by wind or water, which also may ultimately lead to the transported carbon being oxidized), these losses correspond to release of about 5×10^8 metric tons of CO_2.

An historical approach necessarily includes uncertainties, particularly if the historical data was collected for very different purposes. To estimate the effect of parameter uncertainties on our results, we conducted a simple perturbation analysis of Eq. (1), varying each of the parameters in combinations that would result in the highest and lowest values of carbon lost. High and low values of each parameter were chosen from the range of values shown in Table 1, combined with best professional knowledge of Everglades soils as well as of physical constraints (e.g., current organic matter values cannot exceed predrainage values; Table 3). The resultant calculations suggest that the estimate of 2.5×10^8 metric tons of peat loss could be as low as zero (calculated value actually < 0) or as high as 8.9×10^8 metric tons, and that the estimate of 5×10^8 metric tons of CO_2 lost could be as low as zero (calculated value actually < 0) or as high as 17×10^8 metric tons.

4. Discussion

Reconstruction of historical ecological conditions, particularly in an area of organic soils where the original data has been lost (literally "oxidized away") is challenging and certainly subject to uncertainties. We discuss here specific sources of uncertainty in our estimates of carbon lost, along with a simple error analysis of Eq. (1), and emergent insights into apparent constraints on the physically plausible parameter space for Eq. (1).

The sources of parameter uncertainty can be divided into uncertainties associated with the geometry of the peat deposit, which here reduces to uncertainty related to the original and current thicknesses, and uncertainties related to soil properties, specifically the bulk density and the soil organic matter content. Additional sources are the conceptualization of the peat deposit in Eq. (1), specifically the assumption that the deposit could be adequately represented as having a single, uniform thickness, z, and the assumption that the profile was and still is (aside from tillage) vertically quite uniform.

The assumption of uniform peat thickness contradicts the known north to south thinning of the original deposit. However, since Eq. (1) is linear and because the deposit was sufficiently thick that the postdrainage water table has generally been above bedrock, the soil processes north of a line of average thickness would be counterbalanced by the processes south of the same line, suggesting that an average thickness can be reasonably expected to capture the deposit behavior.

The assumption of vertical uniformity of the peat profile has strong support in the available current and predrainage data. In 1915, under nearly predrainage conditions, Baldwin and Hawker (1915) extracted more than 400 soil cores along the full length of the North New River Canal and several miles to either side. Values of loss on ignition (% organic matter) for the cores extracted within the area that later became the EAA all fell within a very narrow range: 90 ± 2%, with very little difference between the upper and lower profile (Table 1). Although no predrainage or early post-drainage data on the vertical distribution of bulk density appears to exist, present day detailed profiles of bulk density obtained by Saunders et al. (2008) from peat soil cores sectioned at 1 cm intervals showed strong uniformity with depth. While these cores were not from the EAA, they were from comparable areas with originally similar hydrology and the same sawgrass vegetation.

Uncertainties regarding the original and current average thickness of the peat deposit are somewhat harder to assess. Neither the current nor the predrainage datasets are ideal. The original thickness is likely to be an underestimate for at least three reasons. The earliest measurements of peat thickness were made more than three decades after the onset of drainage in 1882 (McVoy et al., 2011). At that time, botanists reported plant species characteristic of a drained sawgrass marsh: willow (*Salix caroliniana*), elderberry (*Sambucus canadensis*), careless weed (*Amaranthus australis*) and dog fennel (*Eupatorium capillifolium*) (Harper, 1927;

Table 2
Peat and carbon losses from the EAA.

	Method 1 (thickness)	Method 2 (elevation)	Other studies
Time period	1915–2003 (88 years)	1880–2000 (120 years)	
Original peat volume (m^3)	6.5×10^9	8.3×10^9	
Peat volume remaining, ca. 2003 (m^3)	2.0×10^9	3.4×10^9	4.7×10^9 (in 1940s)[a]
Peat volume lost by 2000/2003, (m^3)	4.5×10^9	4.9×10^9	
Ave. subsidence, m (ft)	1.6 (5.2)	1.7 (5.6)	88 yr: 1.3 (4.2)[b]; 120 yr: 1.8 (5.8)[b]
Peat mass lost (metric tons)	2.50×10^8	2.50×10^8	
Mass CO_2 lost (metric tons)	4.85×10^8	4.92×10^8	
Average emission rate (g CO_2 m^{-2} h^{-1})	0.22	0.17	0.2–6.1[c]

[a] Peat volume estimated as remaining in early 1940s. From Davis (1943a,b) for area already in agricultural use and Davis (1946) for sawgrass peat area not in agricultural use.
[b] Subsidence calculated from literature rates of 0.015 m yr^{-1} (Snyder, 2005).
[c] Emission rates from EAA soils under typical Florida temperatures (10–30 °C); soil columns and field studies (Knipling et al., 1970; Volk, 1973; Gesch et al., 2007).

Davis, 1943a,b). This shift to drier species was corroborated by the land surveyors' notations of "land dry." The botanists' and land surveyors' observations suggest that a degree of subsidence and perhaps oxidation would have reduced the peat thickness from the original predrainage wetland conditions. Additionally, the surveyors apparently used sounding rods of 10 foot length, but noted in some of the more northerly locations that the peat was thicker than this, probably in the range of 12–14 ft. Lacking other site-specific information, we necessarily set these measured lengths at 10 ft. Finally, comparison of cross sections of the EAA kriged thickness with EAA cross sections depicted in Stephens and Johnson (1951), suggests that the kriging algorithm somewhat underestimated the interior peat thickness as it attempted to fit the edges of the peat deposit (zero peat thickness). All three of these sources of error—unaccounted subsidence, sounding rod length, and artifacts of kriging—will tend to make the thicknesses mapped in Fig. 2 less than the actual predrainage thicknesses. Although difficult to quantify, we estimate that collectively these three sources of error do not cause an underestimate of the actual predrainage peat thickness by more than 20–30%.

The estimation of current peat thickness (Fig. 3) used in Method 1 is also likely to be a source of uncertainty due to the sparseness of the supporting data set. That said, the uncertainty may not be as large as the sparseness might suggest. The extreme flatness of the current EAA ground surface appears to reduce the uncertainty. We compared Fig. 3 with an older, much more detailed soil map (Cox et al., 1988), which included five classes of soil thickness (>51; 36–51; 20–36; 8–20; <8 in.). We assumed that all thicknesses estimated for 2003 (i.e., Fig. 3) should be less than or equal to those mapped by Cox et al. in 1988, due to ongoing subsidence between 1988 and 2003. We found only minor areas (< 5%) that contradicted this criterion, suggesting that Fig. 3 may in fact be a reasonable estimate of current peat thickness.

For the topography-based calculations of peat loss (Method 2), both the predrainage and the current estimated topography contain potential sources of error. Surprisingly, the current land surface may include more uncertainty than the predrainage surface. If so, the greater accuracy of the predrainage surface would be due to the physical constraints that shaped the predrainage system - a peat surface leveled by the presence of surface water, with water depths controlled by the elevations of the slightly higher uplands bordering the Everglades.

While it is difficult to assess the overall effect of thickness-related uncertainty, we do note the close similarity of the peat volumes estimated by the two methods. Although not conclusive, the similarity suggests the possibility that both may in fact capture the actual change in volume (and thickness).

The perturbation analysis discussed in the Results section varied the parameter values (Table 3) of Eq. (1) in combinations that would produce the largest and smallest values of carbon lost. We estimated the high and low values for each parameter based on values from the literature (Table 1), field knowledge of the soils and their drainage history, and logical constraints. For example, physically, the post drainage organic matter content cannot exceed the predrainage content and the post drainage bulk density must be greater than or equal to the predrainage value. The analysis clarified that Eq. (1) is highly sensitive to the estimated value of the predrainage bulk density. The analysis also suggested that the range of physically plausible parameter values may in fact be narrow; even the quite narrow ranges shown in Table 3 resulted in negative values for the estimated minimum value of carbon released. This is of course not realistic, suggesting that the Table 3 values of one or more parameters, or combinations of parameters, had been varied too widely, at least for the low extreme.

The CO_2 losses found in this study can be compared with emission rates found in other studies, provided that it can be assumed that emission rates were constant over the century of peat loss. While it is known that rate of subsidence of peat soils is closer to exponential than linear, this is primarily due to the initial physical changes related to dewatering and compaction. Assuming that the oxidation rate was approximately constant (stationary temperature and depth of drained water table), we calculated a CO_2 emission rate of about 0.2 g CO_2 m^{-2} h^{-1} (Table 2). This rate is similar to but lower than field-measured values of 0.4–2.7 g m^{-2} h^{-1} for tilled and untilled EAA soils (Gesch et al., 2007) and also to values of 0.3 and 0.8 g m^{-2} h^{-1} measured in an peatland of similar area

Table 3
Values of current and predrainage soil parameters for the Everglades Agricultural Area (EAA) used in this study.

Parameter	Time period	Depth	Symbol	Units	Low	Mid	High
Peat thickness	Predrainage	All	z_I	m	2.33[a]	2.63	3.23[a]
Peat thickness	Current	>30 cm	z_{F2}	m	0.50	0.65	0.80
Bulk density	Predrainage	All	ρ_{bI}	Mg m^{-3}	0.08	0.10	0.12
Bulk density	Current	0–30 cm	ρ_{bF1}	Mg m^{-3}	0.28	0.32	0.36
Bulk density	Current	>30 cm	ρ_{bF2}	Mg m^{-3}	0.10	0.14	0.18
Organic matter	Predrainage	All	OM_I	kg kg^{-1}	0.88	0.90	0.92
Organic matter	Current	0–30 cm	OM_{F1}	kg kg^{-1}	0.75	0.80	0.85
Organic matter	Current	>30	OM_{F2}	kg kg^{-1}	0.84	0.86	0.88

[a] High and low estimates are intentionally asymmetric to reflect the likelihood that predrainage sources underestimated peat thickness.

and drainage history in Central Kalimantan, Indonesia (Jauhiainen et al., 2008).

If consistent with past history, CO_2 releases from the EAA appear to be approximately 5×10^6 metric tons per year (Table 2). This is similar to the annual carbon emissions of approximately 1×10^5 American households, assuming emissions of 48 metric tons per year per household (Jones, 2011). If the remaining approximately 30% of the original peat (Table 2) is also oxidized, an additional 1.7×10^8 metric tons of CO_2 will be released.

According to Bridgham et al. (2006), North American wetlands form a large carbon pool and serve as a small to moderate carbon sink. They estimate that Florida wetlands emit up to about $30\,g\,m^{-2}\,yr^{-1}$ of methane but that these emissions are likely offset by the positive benefits of carbon sequestration in the soils and plants. They contend that carbon sequestration in wetlands cannot be used as a rationale for preserving them, although the other ecosystem services they provide justifies their recovery. They do indicate that protecting and restoring peatlands will contribute to net carbon sequestration even given the amount of methane emitted.

Approaches to restoration of the remaining Everglades have included the option of purchasing substantial portions of the EAA and their conversion to either water quality treatment marshes or water storage areas (Grunwald, 2008). Both options would re-inundate remaining peats, preventing further oxidation of peat, and reducing carbon emissions. Additionally, in some cases, carbon sequestration as marsh peat would also be expected. This could lead to the region again becoming a significant carbon sink, providing an important ecosystem service. Under the assumptions that (a) 40% of the EAA would be inundated and (b) that the past emission rate of approximately $0.2\,g\,CO_2\,m^{-2}\,h^{-1}$ would be reduced to zero, this would eliminate carbon releases from that area.

Assuming a carbon credit price of \$10–100 per metric ton (Mathews, 2008), the eliminated annual carbon releases would be worth \$50 million to \$500 million per year, with a total value of approximately \$2 billion to \$20 billion for preserving the remaining approximately 1×10^8 metric tons of peat. This could offset the loss in sugar production revenues of approximately \$749 million calculated for the proposed restoration (Hodges et al., 2008). Given the world-wide interest in mitigating climate change through the reduction of carbon emissions, the proposed purchase and its conversion to either water storage or water treatment wetlands would appear to be a beneficial choice, both environmentally and economically.

5. Conclusions

Anthropogenic drainage of the Everglades Agricultural Area implemented to make use of the organic (peat) soils of the Everglades, has resulted in subsidence and soil loss. Using historic and recent surveys, we mapped the historic and recent peat thickness and the soil surfaces. The loss of peat was calculated as the difference between these different thicknesses and surfaces. Our calculations suggest that over 4 billion m^3 of peat soil has been lost from the area. Corresponding bulk emission rates of $0.2\,g\,CO_2\,m^{-2}\,h^{-1}$ were similar to field measurements from other studies. As soil transport losses are essentially zero in this area, we assumed that this soil carbon has all been released to the atmosphere through oxidation, translating into about 0.5 billion metric tons of carbon dioxide released, contributing to global climate change. Restoring this area to a wetland would preserve the remaining peat and could ultimately lead to the area again becoming a net sink for carbon. Depending upon future developments in the carbon credit market, restoration of the area as a carbon sink could also reap economic benefits.

References

Allison, R.V., Baker, J.R., Bender, G., Bestor, H.A., Davis, C.K., Emery, N.S., Elliott, F.C., Ferguson, G.E., Glass, W.A., Gunter, H., Herr, B. Neller, J.R., Parker, G.C., Silver, J., Vinten, C.R., Wallis, W.T., 1944. Report by Advisory Committee on the present drainage system in relation to water control requirements of Everglades Drainage District, May 1, Everglades Drainage District, Miami, 1944, 41 pp.

Baldwin, M., Hawker, H.W., 1915. Soil survey of the Fort Lauderdale Area, Florida In: Whitney, M. (Ed.), Field Operations of the Bureau of Soils, U.S. Department of Agriculture, Washington, DC.

Bhatti, J.S., Bauer, I.E., 2002. Comparing loss-on-ignition with dry combustion method for determination of organic matter for upland and lowland forest ecosystems. Commun. Soil Sci. Plant Anal. 33, 3419–3430.

Bonham-Carter, G.F., 1994. Geographic Information Systems for Geoscientists: Modeling with GIS. Pergamon/Elsevier Science, Tarrytown, NY.

Bridgham, S.D., Megonigal, J.P., Keller, J.K., Bliss, N.B., Trettin, C., 2006. The carbon balance of North American wetlands. Wetlands 26 (4), 889–916.

Clayton, B.S., Neller, J.R., Allison, R.V., 1942. Water control in the peat and muck soils of the Florida Everglades. Fla. Agr. Exp. Sta. Bull. 378, 1–74.

Corstanje, R., Grunwald, S., Reddy, K.R., Osborne, T.Z., Newman, S., 2006. Assessment of the spatial distribution of soil properties in a Northern Everglades Marsh. J. Environ. Qual. 35, 938–949.

Cox, S., Lewis, D., McCollum, S., Bledsoe, M., Marrotte, R., 1988. Subsidence Study of the Everglades Agricultural Area. USDA, Soil Conservation Service, Green Acres Field Office, Green Acres, FL.

Davis, C.K., 1943a. Summary of three years of conservation work in the Everglades, and plans for the future. Soil Sci. Soc. Fla. Proc., 116–117.

Davis, J.H., 1943b. The Natural Features of Southern Florida: Especially the Vegetation, and the Everglades. Geological Bulletin #25. Florida Geological Survey, Tallahassee, FL, 311 pp.

Davis Jr., J.R., 1946. The peat deposits of Florida. Florida Geological Survey Bulletin #30. Florida Geological Survey, Tallahassee, FL, 247pp.

Elliot, F.C., 1911-T44 R34. Field Notes for State Survey.

Elliot, F.C., 1911-T46 R34. Field Notes for State Survey.

Elliot, F.C., 1911-T47 R34. Field Notes for State Survey.

Elliot, F.C., 1912-T43 R34. Field Notes for State Survey.

Elliot, F.C., 1912-T45 R34. Field Notes for State Survey.

Ensey, R.F., Elliot, F.C., 1911. Map of Everglades Drainage District. The Trustees of the Internal Improvement Fund. Government Printing Office, Washington, DC.

ESRI, 2004. ArcGIS 9: Using ArcGIS™ Geostatistical Analyst. ESRI, Inc., Redlands, CA.

FDEP (Florida Department of Environmental Protection) and Florida Resources and Environmental Analysis Center, 1984. Land Boundary Information System.

FEEC (Florida Everglades Engineering Commission), 1913. Florida Everglades. The Trustees of the Internal Improvement Fund. Government Printing Office, Washington, DC.

Franklin, L.D., 1914-T43 R35. Field Notes and Plat Map for State Survey, vol. FCEv01: 0.5-13.

Franklin, L.D., 1914-T44 R35. Field Notes and Plat Map for State Survey, vol. FCEv01: 1e-2e.

Frederick, T.E., 1914-T44 R35. Field Notes for State Survey, vol. W.

Frederick, T.E., 1914-T44 R36. Field Notes for State Survey, vol. Y.

Frederick, T.E., 1914-T45 R35. Field Notes for State Survey, vol. X.

Frederick, T.E., 1914-T45 R36. Field Notes for State Survey, vol. V.

Gesch, R.W., Reicosky, D.C., Gilbert, R.A., Morris, D.R., 2007. Influence of tillage and plant residue management on respiration of a Florida Everglades Histosol. Soil Tillage Res. 92, 156–166.

Gleason, P.J., Stone, P., 1994. Age, origin and landscape evolution of the Everglades peatland. In: Davis, S.M., Ogden, J.C., Park, W.A. (Eds.), Everglades: The Ecosystem and Its Restoration. St. Lucie Press, Delray Beach, pp. 149–197.

Grunwald, M., 2008. Booting US Sugar from the Everglades. Time.com for Tuesday, June 24, 2008. http://www.time.com/time/nation/article/0,8599,1817390,00.html

Hardin, O.A., 1915-T44 R35. Field Notes and Plat Map for State Survey, vol. N.

Hardin, O.A., 1915-T44 R36. Field Notes and Plat Map for State Survey, vol. N.

Hardin, O.A., 1915-T45 R35. Field notes for State Survey, vol. L.

Hardin, O.A., 1915-T45 R36. Field Notes for State Survey, vol. K.

Hardin, O.A., 1915-T46 R35. Field Notes for State Survey, vol. J.

Hardin, O.A., 1915-T46 R36. Field Notes for State Survey, vol. I.

Hardin, O.A., 1915-T47 R35. Field Notes for State Survey, vol. S.

Hardin, O.A., 1916-T42 R36. Field Notes and Plat Map for State Survey, vol. U.

Hardin, O.A., 1916-T42 R37. Field Notes and Plat Map for State Survey, vol. D.

Hardin, O.A., 1916-T42 R38. Field Notes and Plat Map for State Survey, vol. E: 4E-5E, 11E-14E; FCEv02, pp. 421–436.

Hardin, O.A., 1916-T42 R39. Field Notes and Plat Map for State Survey, vol. R.

Hardin, O.A., 1916-T43 R34. Field Notes and Plat Map for State Survey, vol. M.

Hardin, O.A., 1916-T43 R36. Field Notes and Plat Map for State Survey, vol. A.

Hardin, O.A., 1916-T43 R37. Field Notes and Plat Map for State Survey, vol. B/C/E/F/Z.

Hardin, O.A., 1916-T43 R38. Field Notes and Plat Map for State Survey, vol. E; FCEv02, pp. 457–473.

Hardin, O.A., 1916-T43 R39. Field Notes and Plat Map for State Survey, vol. E: 6E, 9E; O: 1–2; FCEv02, pp. 437–456.

Hardin, O.A., 1916-T44 R34. Field notes for State Survey, vol. T.

Hardin, O.A., 1916-T45 R34. Field Notes and Plat Map for State Survey, vol. I.

Hardin, O.A., 1916-T46 R34. Field Notes and Plat Map for State Survey, vol. G.

Hardin, O.A., 1916-T47 R34. Field Notes and Plat Map for State Survey, vol. Q.

Harper, R.M., 1927. Natural resources of southern Florida. Florida Geol. Survey, Tallahassee. 18th Annual Report.

Hodges, A.W., Mulkey, W.D., Spreen, T.H., Clouser, R.L., 2008. Economic Impacts of the U.S. Sugar Corporation in Florida: Implications of the Purchase by the State of Florida. EDIS document FE754, Food and Resource Economics Department, Florida Cooperative Extension Service. Institute of Food and Agricultural Sciences, University of Florida, Gainesville, FL.

Holt, P.R., Sutton, R.J., Vogler, D., 2006. South Florida Digital Elevation Model. Draft Report to the South Florida Water Management District, CESAJ/IM-I, 54 pp.

Horne, C.R., 1914-T44 R37. Field Notes and Plat Map for State Survey, vol. FCEv02, pp. 306–308, 311–334, 392–406.

Horne, C.R., 1914-T44 R38. Field Notes and Plat Map for State Survey, vol. FCEv02, pp. 303–305, 335–338, 380–391.

Horne, C.R., 1914-T44 R39. Field Notes and Plat Map for State Survey, vol. FCEv02, pp. 300–302, 339–347, 369–371.

Ingebritsen, S.E., McVoy, C., Glaz, B., Park, W., 1999. Florida Everglades: subsidence threatens agriculture and complicates ecosystem restoration. In: Galloway, D. (Ed.), Land Subsidence in the United States. Circ. 1182. U.S. Geol. Survey, Reston, VA, pp. 95–106.

Janardhanan, L., Daroub, S.H., 2010. Phosphorus sorption in organic soils in south Florida. Soil Sci. Soc. Am. J. 74 (5), 1597–1606.

Jauhiainen, J., Limin, S., Silvennoinen, H., Vasander, H., 2008. Carbon dioxide and methane fluxes in drained tropical peat before and after hydrological restoration. Ecology 89 (12), 3503–3514.

Jones, K., 2011. Quantifying carbon footprint reduction opportunities for U.S. households and communities. Environ. Sci. Technol. 45 (9), 4088–4095, http://dx.doi.org/10.1021/es102221h.

Jones, L.A., Allison, R.V., Ruehle, C.D., Neller, G.D., Henderson, J.R., Marsden, R.D., Steele, G.G., Davis, C.K., Clayton, B.S., Stephens, J.C., Gallatin, M.H., Stephens, A.R., 1948. Soils, Geology and Water Control in the Everglades Region. Bulletin 442. Agricultural Experiment Station, University of Florida, Gainesville, FL.

Knipling, E.B., Schroder, V.N., Duncan, W.G., 1970. CO_2 evolution from Florida organic soils. Crop Sci. Soc. Fla. Proc. 30, 320–326.

Kreamer, J.M., 1892. Map of Hic-po-chee and Okeechobee Sugar Lands. In: Lee and De Soto Counties. Atlantic and Gulf Coast Canal and Okeechobee Land Company, Florida.

Light, S., Dineen, W., 1994. Water control in the Everglades: a historical perspective. In: Davis, S.M., Ogden, J.C., Park, W.A. (Eds.), Everglades: The Ecosystem and Its Restoration. St. Lucie Press, Delray Beach, FL.

Lo, C.P., Yeung, A.K.W., 2002. Concepts and Techniques of Geographic Information Systems. Prentice-Hall, Upper Saddle River, NJ.

Loveless, C.M., 1959. A study of the vegetation in the Florida Everglades. Ecology 40, 1–9.

Mathews, J.A., 2008. How carbon credits could drive the emergence of renewable energies. Energy Policy 36, 3633–3639.

Mayo, N., 1940. Possibilities of the Everglades (Revised). Bulletin #61 New Series. Florida Dept. of Agriculture, Tallahassee, FL, 91 pp.

McDowell, L.L., Stephens, J.C., Stewart, E.H., 1969. Radiocarbon chronology of the Florida Everglades peat. Soil Sci. Soc. Am. Proc. 33, 743– 745.

McVoy, C.W., Said, W.P., Obeysekera, J., VanArman, J., Dreschel, T.W., 2011. Landscapes and Hydrology of the Predrainage Everglades. University Press of Florida, Gainesville, FL.

Miller, C.F., 1918. Inorganic composition of a peat and of the plant from which it was formed. J. Agric. Res. 13, 605–609.

Neller, J.R., 1944. Oxidation loss of lowmoor peat in fields with different water tables. Soil Sci. 58, 195–204.

Parker, G.G., Ferguson, G.E., Love, S.K., 1955. Water Resources of Southeastern Florida. Geological Survey Water-Supply Paper 1255. United States Government Printing Office, Washington, DC.

Rice, R.W., Gilbert, R.A., Daroub, S.H., 2005. Application of the Soil Taxonomy Key to the Organic Soils of the Everglades Agricultural Area. SS-AGR-246. Agronomy Dept., Fla. Coop. Ext. Serv., Inst. Food Agric. Sci., Univ. of Fla, Gainesville, FL.

Robertson, W.B., 1953. A Survey of the Effects of Fire in Everglades National Park. U.S. Department of Interior, National Park Service, Everglades National Park, Homestead, FL, 169 pp.

Said, W.P., Brown, M.C., Newton, T., 2006. Natural System Regional Simulation Model (NSRSM) v2.0 Implementation Report. 2006. Draft Report to the South Florida Water Management District, West Palm Beach, FL.

Saunders, C.J., Jaffe, R., Gao, M., Anderson, W., Lynch, J.A., Childers, D.L., 2008. Decadal to millennial dynamics of ridge-and-slough wetlands in Shark Slough. In: Everglades National Park: Integrating Paleoecological Data and Simulation Modeling. National Park Service, Miami.

Schothorst, C.J., 1977. Subsidence of low moor peat soils in the western Netherlands. Geoderma 17, 265–291.

Shih, S.F., Mishoe, J.W., Jones, J.W., Myhre, D.L., 1978. Modeling the subsidence of Everglades organic soil. Trans. Am. Soc. Agric. Eng. 21, 1151–1156.

Shih, S.F., Stewart, E.H., Allen, L.H., Hilliard, J.W., 1979a. An investigation of subsidence lines in 1978. Belle Glade Agric. Res. Educ. Center, Belle Glade, Florida. Belle Glade AREC Research Report EV-1979-1.

Shih, S.F., Mishoe, J.W., Jones, J.W., Myhre, D.L., 1979b. Subsidence related to land use in Everglades agricultural area. Trans. Am. Soc. Agric. Eng. 22, 568, 560–563.

Shih, S.F., Stewart, E.H., Allen Jr., L.H., Hilliard, J.W., 1979c. Variability of depth to bedrock in Everglades organic soil. Soil Crop Sci. Soc. Fla. 38, 6671.

Shih, S.F., Glaz, B., Barnes, R.E., 1997. Subsidence lines revisited in the Everglades Agricultural Area, 1997. Agric. Exp. Stat., Univ. Fla., Bull. Tech., 902.

Simpson, C.T., 1920. In Lower Florida Wilds. G. P. Putnam's Sons, New York and London404.

Sklar, F., McVoy, C., VanZee, R., Gawlik, D.E., Tarboton, K., Rudnick, D., Miao, S., Armentano, T., 2002. The effects of altered hydrology on the ecology of the Everglades 2002. In: Porter, J.W., Porter, K.G. (Eds.), The Everglades, Florida Bay, And Coral Reefs Of The Florida Keys: An Ecosystem Sourcebook. CRC Press, Boca Raton, FL, pp. 39–82.

Smith, B. Esq., 1848. Report on Reconnaissance of the Everglades. In: U.S. Congress. 1911.

Smith, S.M., Newman, S., Garrett, P.B., Leeds, J.A., 2001. Differential effects of surface and peat fire on soil constituents in a degraded wetland of the Northern Florida Everglades. J. Environ. Qual. 30 (6), 1998–2005.

Snyder, G.H., 2005. Everglades agricultural area soil subsidence and land use projections. Soil Crop Sci. Soc. Fla. Proc. 64, 44–51.

Snyder, G.H., Davidson, J., 1994. Everglades agricultural area; past, present and future. In: Davis, S.M., Ogden, J.C. (Eds.), Everglades: The Ecosystem and its Restoration. St. Lucie Press, Delray Beach, FL, pp. 85–116.

Soil Survey Staff, 1998. Keys to Soil Taxonomy, 8th ed. USDA Natural Resource Conservation Service, U.S. Government Printing Office, Washington, DC.

Soil Survey Staff, 1999. Soil Taxonomy: A Basic System of Soil Classification for Making and Interpreting Soil Surveys. USDA Natural Resource Conservation Service Agriculture Handbook #436. U.S. Government Printing Office, Washington, DC.

Stephens, J.C., Johnson, L., 1951. Subsidence of organic soils in the upper Everglades region of Florida. Soil Crop Sci. Soc. Fla. Proc. 11, 191–237.

Stephens, J.C., Speir, W.H., Subsidence of organic soils in the U.S.A. Extrait de la Publication No. 89. Assoc. Intern. D'Hydrologie Scientifique, 1969, pp. 523–534.

Stephens, J.C., Allen, L.H., Chen, E., 1984. Organic soil subsidence. GSA Rev. Eng. Geol. VI, 107–122.

U.S. Army Corps of Engineers, 1978. Report on rule curves and key operating criteria. In: Central and Southern Florida Project for Flood Control and Other Purposes. Master Regulation Manual, vol. 2, Appendix D, U.S. Army Corps of Engineers, Jacksonville, FL, pp. 37A–37B.

U.S. Army Corps of Engineers, 2009. CORPSCON, Geospatial Applications Software Fact Sheet. U.S. Army Corps of Engineers, Army Geospatial Center, Alexandria, VA.

USEPA-REMAP, 2007. Everglades Ecosystem Assessment: Water Management and Quality, Eutrophication, Mercury Contamination, Soils and Habitat; Monitoring for Adaptive Management. A R-EMAP Status Report, EPA 904-R-07-001, August 2007.

Volk, B.G., 1973. Everglades histosol subsidence: 1. CO_2 evolution as affected by soil type, temperature and moisture. Soil Crop Sci. Soc. Fla. Proc. 32, 132–135.

Volk, B.G., Schnitzer, M., 1973. Chemical and spectroscopic methods for assessing subsidence in Florida histosols. Soil Crop Sci. Soc. Fla. Proc. 37, 886–888.

Weaver, H.A., Speir, W.H., 1960. Applying basic soil water data to water control problems in Everglades peaty muck. USDA Agric. Res. Serv., ARS, 40–41.

Wright, A.L., Inglett, P.W., 2009. Soil organic C and N and distribution of ^{13}C and ^{15}N in aggregates of Everglades Histosols. Soil Sci. Soc. Am. J. 73, 427–433.

Zelazny, L.W., Carlisle, V.W., 1974. Physical, chemical, elemental and oxygen-containing functional group analysis of selected Florida histosols. In: Histosols, Chapter 6, Special Publication No. 6, Soil Science Society of America, Madison, WI.