Everglades peats: using historical and recent data to estimate predrainage and current volumes, masses and carbon contents

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SUMMARY

The Florida Everglades is a patterned peatland formed from sawgrass and other aquatic plant material that has accumulated over millennia. This peatland was initially drained in the late 1800s for agricultural and urban development and has been highly modified by the construction of canals and levées. Restoration plans include providing additional surface water flow which should help to prevent further peat loss by oxidation and encourage the accretion of peat that has been lost through drainage and peat fires. But how much peat has been lost? We know that about 50 % of the original surface area is gone; but what about the driver of ecological processes, the soil? Using Geographic Information Systems (GIS) technology, we compared predrainage and current peat volumes using historical and recent datasets, spatially-referenced soil bulk density values and carbon content to determine peat mass and carbon mass for each Everglades region. Given the uncertainties in the datasets, this analysis should be viewed as providing rough order-of-magnitude values. Our calculations indicate that the current Everglades contains less than 24 % of the original peat volume, 17 % of its mass and 19 % of its carbon.

KEY WORDS: aquatic plants; bulk density; restoration; sawgrass

LIST OF ACRONYMS

CEPP:	Central Everglades Planning Project
EAA:	Everglades Agricultural Area
ENP:	Everglades National Park
EPA:	Everglades Protection Area
NSRSM:	Natural Systems Regional Simulation Model
R-EMAP:	USEPA Regional Environmental Monitoring and Assessment Program
SFTP:	South Florida Topography Project
SFWMD:	South Florida Water Management District
USEPA:	United States Environmental Protection Agency
WCA:	Water Conservation Area (WCA-1, -2A, -2B, -3AN, -3AS, -3B)

INTRODUCTION

The historical Florida Everglades (Figure 1, left; Figure 2, left) was a vast patterned peatland covering much of southern Florida. McVoy *et al.* (2011) estimate the Everglades to be about five thousand years old. The patterned peatland once covered about 1.1×10^4 km^2 of South Florida (McVoy *et al.* 2011) and now covers approximately 5.6×10^3 km^2. The peat of the Everglades is formed from sawgrass (*Cladium jamaicense* Crantz) and other aquatic plant material that has accumulated over millennia, with decomposition limited by inundation (McVoy *et al.* 2011). In the late 1800s, surveys conducted in the Everglades identified deep (3 m or more) highly organic peat soils. Efforts were then focused on draining the region for agricultural development by lowering the water level of Lake Okeechobee and draining the land. These activities were successful in lowering the water table of the Everglades and facilitated farming of a large area (approximately 2.6×10^3 km^2) of sawgrass plains just south of Lake Okeechobee which was later named the Everglades Agricultural Area (EAA) and is currently dominated by sugar cane farms (Aich *et al.* 2013). A combination of dry years which

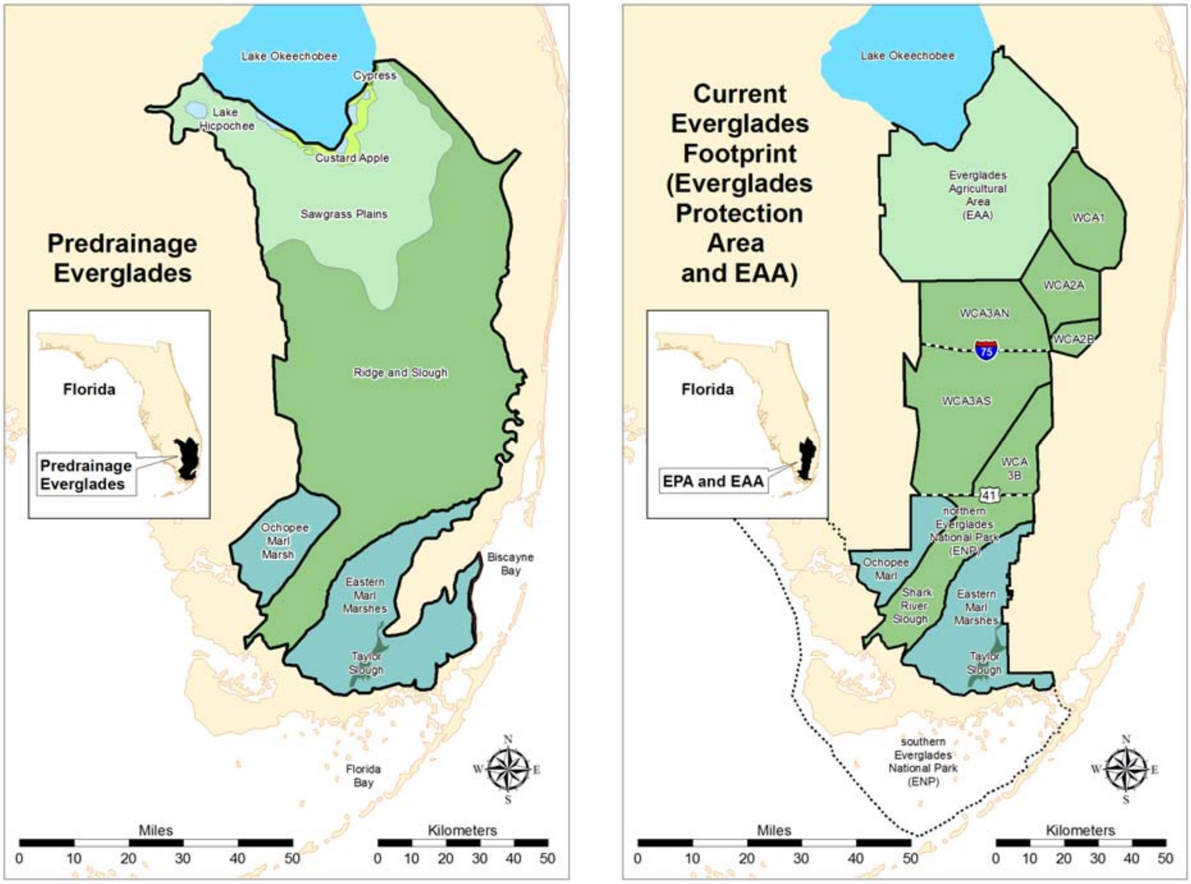

Figure 1. Two maps of South Florida, predrainage and current. The solid black borders denote the various regions used for the calculations. The map on the left is a reconstruction of the historical Everglades landscape and the image on the right is a map of the current Everglades Protection Area (EPA) and the Everglades Agricultural Area (EAA). Two highways cross the current Everglades: Alligator Alley (Interstate 75), which divides Water Conservation Area 3A (WCA-3A) into northern and southern sections; and the Tamiami Trail (Highway 41), which separates the WCAs from the ENP. After McVoy *et al.* (2011).

resulted in major peat fires in the Everglades and very wet years which flooded agricultural land and towns south of the lake led to implementation of the Central and Southern Florida Project for Flood Control and Other Purposes (C&SF Project) in 1948 (USACE & SFWMD 1999). This project built 2,300 kilometres of levées (man-made embankments of soil and rock), canals and structures to enclose large areas of the Everglades, creating the so-called Water Conservation Areas (WCAs) - shallow reservoirs in which water levels could be controlled so that water could be stored or released as required. The Everglades National Park (ENP) was established in 1947, just before the C&SF Project, to protect the southern portion of the Everglades. These activities resulted in the current landscape of what is now termed the Everglades Protection Area (EPA), which is the combination of WCAs and ENP (Figure 1, right; Figure 2, right).

Present-day planning provisions such as the Central Everglades Planning Project (CEPP) are designed to accelerate restoration of the Everglades peatland by allowing additional water to flow through it. According to the CEPP Fact Sheet (USACE & SFWMD 2014), this will be accomplished by: increasing storage, treatment and conveyance of water south of Lake Okeechobee; removing and/or plugging canals and levées within the central Everglades; and retaining water within the ENP whilst protecting urban and agricultural areas to the east from flooding. More water in the Everglades should help prevent further peat loss by oxidation, encourage the accretion of new peat to replace some of that lost since 1948 and, thus, result in the beneficial sequestration of atmospheric carbon. But how much peat has been lost? We know

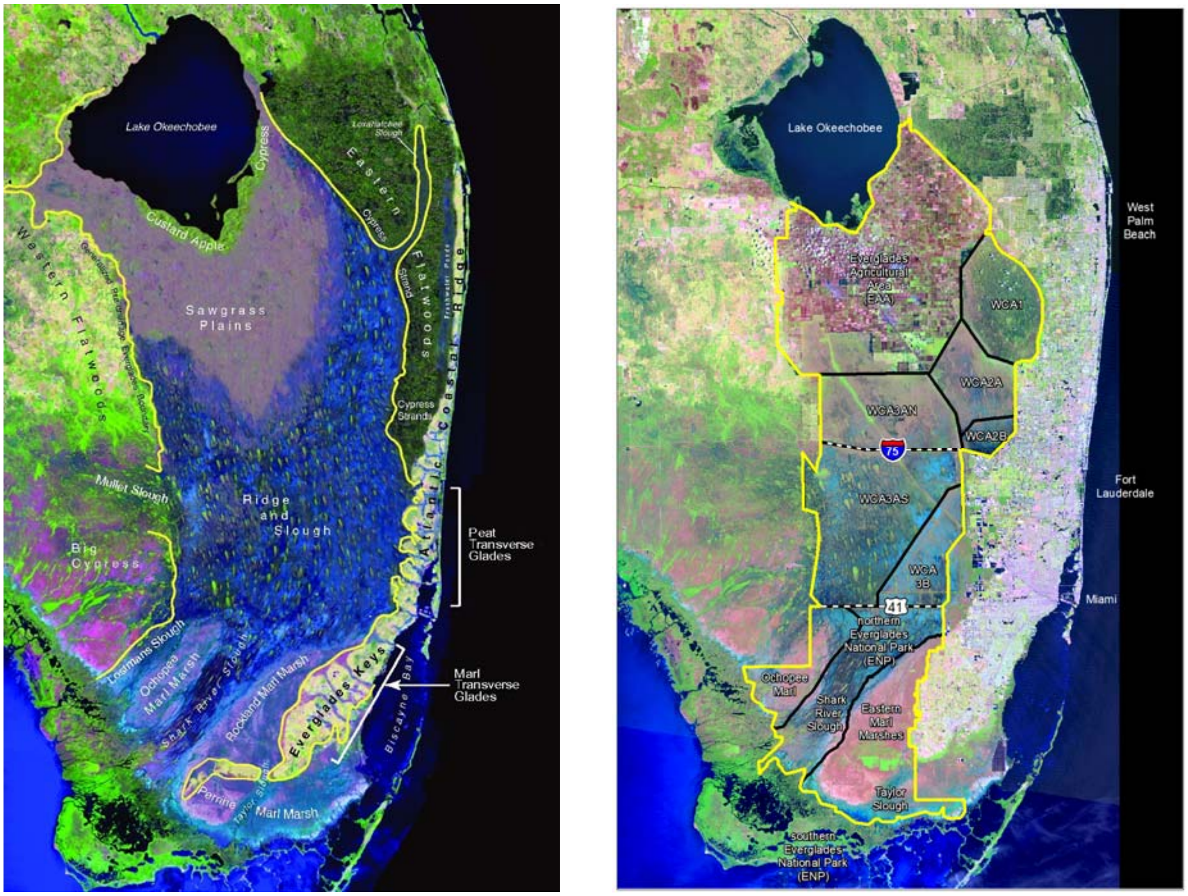

Figure 2. Two images of South Florida, a reconstructed predrainage (1880) "satellite" image from McVoy *et al.* (2011) (left) and a modern (1994) Landsat image (right). The yellow lines denote the borders of the Everglades. The Loxahatchee Slough, in the upper right part of the image on the left, was considered an ephemeral wetland and was not included in the predrainage calculations.

that about 50 % of the original surface area is gone; but it is less clear what has happened to the soil, which is the foundation and driver of ecological processes.

The soils of the WCAs are primarily Everglades peat and Loxahatchee peat (Jones 1948). Everglades peat was largely formed by the decomposition of sawgrass and dominates the central and southern Everglades. By carbon dating a single core from WCA-1, Craft & Richardson (2008) determined the age to be 530 ± 50 years BP for subsurface peat at 46 cm depth. For cores to the same depth in WCA-2A (un-enriched area), they determined an age of 830 ± 60 years BP; and for cores from WCA-3A, an age of 2060 ± 60 years BP. For a core of basal peat at 37 cm from the ENP the age was 2,550 ± 60 years BP. Everglades peat is typically less decomposed than Loxahatchee peat (plant fibres are more evident and it is lighter in colour). Loxahatchee peat is primarily the decomposition product of aquatic plants (water lilies; *Nymphea* spp.), typically forms in the bottoms of sloughs, and has higher bulk density and organic matter content than Everglades peat. It dominates the northern part of the Everglades, particularly WCA-1 and WCA-2 (Craft & Richardson 2008). A third type of peat, Gandy peat, is found on tree islands and is primarily the decomposition product of leaves of the woody vegetation found on tree islands. Tree islands may cover up to 14 % of the landscape (Willard *et al*. 2006); thus, Gandy peat represents a minor portion of the peat found in the Everglades. In comparison to the WCAs, the soils of the ENP have a lower organic content and a much higher mineral content and bulk density (Gleason & Stone 1994). Since the 1800s, anthropic modifications have significantly changed the landscape of the Everglades but these peats still dominate.

A number of recent studies have been conducted to estimate the volume of peat lost from regions of the Everglades since the initiation of drainage in the late 1800s. The USEPA Regional Environmental Monitoring and Assessment Program (R-EMAP; Stober *et al.* 1998, Scheidt *et al*. 2000, USEPA 2007) measured ground surface altitude across the EPA to create maps of surface altitude and compared them with maps created in 1946. These maps provided a range of estimates of peat loss over the ensuing five decades. Aich & Dreschel (2011) used data from the South Florida Topography Project (SFTP) (Holt *et al.* 2006) and a historical surface created for South Florida Water Management District (SFWMD) hydrological models (SFWMD 2007, McVoy *et al.* 2011, Said & Brown 2011) to estimate the loss of peat volume, mass and carbon from the current regions of the EPA since predrainage times (around 1885). Aich *et al*. (2013) used peat depths determined during historical land surveys to create a surface using kriging, as well as the other sources mentioned above, to investigate two methods (thickness *versus* topography) for determining soil subsidence and carbon loss in the EAA.

The purpose of this study is to determine the volume and mass of peat and the mass of carbon for each of the predrainage landscapes and the current Everglades regions. These characteristics have been estimated using historical and current surveys within the Everglades, a bedrock contour map of South Florida and Geographic Information Systems (GIS) technology. This information provides a rough but quantitative "first look" at the historical Everglades peatland, its current condition, and the changes in the peat soil that have occurred over more than a century.

METHODS

Site descriptions and division into sub-regions

The predrainage Everglades was roughly 60 km wide and 200 km long, starting at the south shore of Lake Okeechobee and delivering water southward into Florida Bay and Biscayne Bay (McVoy *et al.* 2011; Figure 1, left; Figure 2, left). The current EPA is 30–50 km wide and about 160 km long, divided into WCA-1, WCA-2A, WCA-2B, WCA-3A, WCA-3B and the ENP (Figure 1, right; Figure 2, right). Two highways cross the Everglades, namely: Alligator Alley (Interstate 75), which divides WCA-3A into northern and southern sections; and the Tamiami Trail (Highway 41), which separates the WCAs from the ENP. The EAA, set aside for farming, is immediately south of Lake Okeechobee.

For the mapping and calculations described here, the predrainage Everglades was subdivided into peat-dominated regions (the sawgrass plains plus the ridge and slough) and the bordering marl-soil landscapes (marl marshes) of the northern ENP (McVoy, *et al.* 2011; Figure 1, left; Figure 2, left). The "current Everglades footprint" was taken to be the combined area of the EAA and the EPA, and was subdivided into the EAA, WCAs, Shark River Slough and the bordering landscapes of the northern ENP (Figure 1, right; Figure 2, right). For the purpose of examining changes, we also divided the predrainage Everglades into the current regions so that we could directly compare the predrainage and current conditions for each region. The period of record for the changes was defined as 1885 to 2005 (120 years).

Data sources

We used the predrainage surface created for the Natural Systems Regional Simulation Model (NSRSM), which was an interpolation of one-foot contour lines based on information contained in more than 300 land and canal surveys and survey notes from the mid- and late 1800s and early 1900s (SFWMD 2007, McVoy *et al.* 2011, Said & Brown 2011; Figure 3, left). The current surface was created using data from the SFTP, which is a mosaic of: a space-borne RADAR survey (Shuttle Radar Topographic Mission); LIDAR surveys conducted by the local, state and federal governments; photogrammetry; and measured spot heights (High Accuracy Elevation Dataset and National Elevation Dataset) (Holt *et al.* 2006; Figure 4, left). These data were clipped at the southern boundary to match the extent of the NSRSM predrainage surface. The same datasets were described and utilised by Aich & Dreschel (2011) and Aich *et al.* (2013). Key to the present study was a bedrock contour map of the Everglades region (Parker *et al.* 1955), which was digitised and interpolated to generate the bedrock surface (Figure 3, right; Figure 4, right) needed to calculate the original and current peat volumes. All altitude data have been converted to National Geodetic Vertical Datum of 1929 (NGVD).

We used the bulk density and carbon content of peat samples (10 cm deep) taken across the Everglades landscape during a recent USEPA R-EMAP sampling program that collected 228 spatially referenced soil samples described by Stober *et al.* (1998), Scheidt *et al*. (2000) and USEPA (2007) to provide a dataset in which the locations of the samples were known. The value that was used to convert organic matter (loss on ignition) to carbon content (kg carbon *per* kg organic matter) was 0.51 (Bhatti & Bauer 2002). This value was

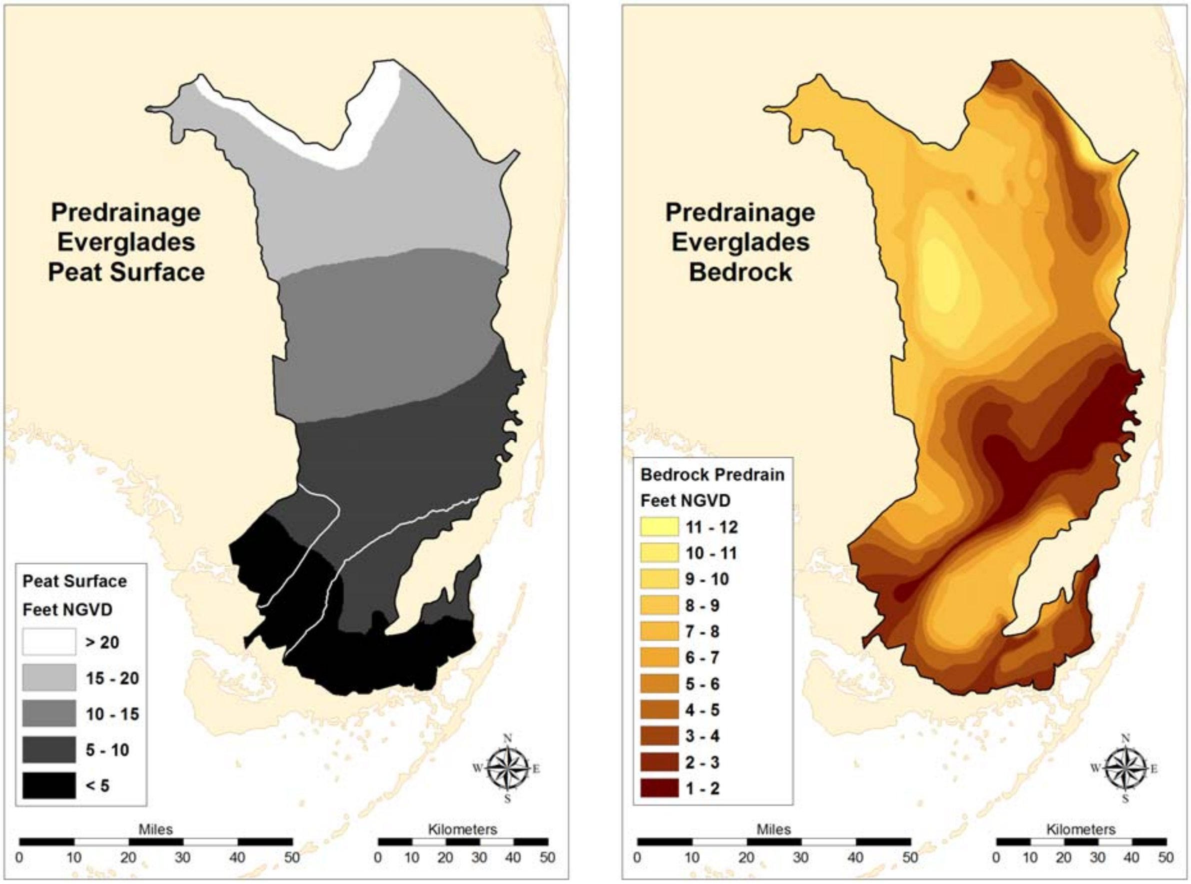

Figure 3. Left: map of the historical Everglades peat surface (derived from McVoy *et al.* 2011 and Said & Brown 2011); right: map of the Everglades bedrock surface (derived from Parker *et al.* 1955). Altitudes are in feet above the National Geodetic Vertical Datum of 1929 (NGVD).

adopted by Aich *et al*. (2013), on the basis that they found values ranging from 0.47 to 0.56 reported in the scientific literature. Their literature review also indicated that the peat of typical sawgrass ridges is relatively uniform in terms of bulk density from the surface to 100 cm depth (Saunders *et al*. 2008) and in terms of organic matter content (per unit volume) to 305 cm depth (Miller 1918). Uniform bulk density was also observed in all but one of the cores (from the surface to 36 cm depth) collected in WCA-3AS by Arfstrom *et al*. (2000).

Geospatial procedures

The raster maps of peat and bedrock surfaces and peat depths were produced in ArcGIS (ESRI Inc., Redlands, CA) using a standard (US customary units) 1000 × 1000 foot (ft) (305 × 305 m) grid resolution. To minimise unknown statistical assumptions, we used the Inverse-Distance Weighted (IDW) technique in ArcGIS to create the surfaces used in the calculations of volume and mass. We used surfaces interpolated from the NSRSM (Said & Brown 2011), the SFTP (Holt *et al.* 2006) and the bedrock map (Parker *et al.* 1955) to calculate the original and current volumes of peat in the respective regions of the Everglades.

We also interpolated the R-EMAP soil bulk density values using IDW, and created a raster to determine the spatial distribution of peat mass in Mg (1000 kg; i.e. US metric tons or SI tonnes) *per* 1000 × 1000 foot (305 × 305 m) pixel. We then used the spatial distribution of mass with a projected raster of carbon content (kg carbon *per* kg peat), again created using IDW, to determine the spatial distribution of bulk peat carbon. The bulk mass and carbon values were converted to Mg m^{-2} (1 m^2 = 10.764 ft^2, i.e. the area of one pixel was 92,902.267 m^2) prior to creation of the final maps (and for the final calculations).

To inform hindcasting of the predrainage bulk densities and carbon contents of the soils, we compared values from the R-EMAP dataset with

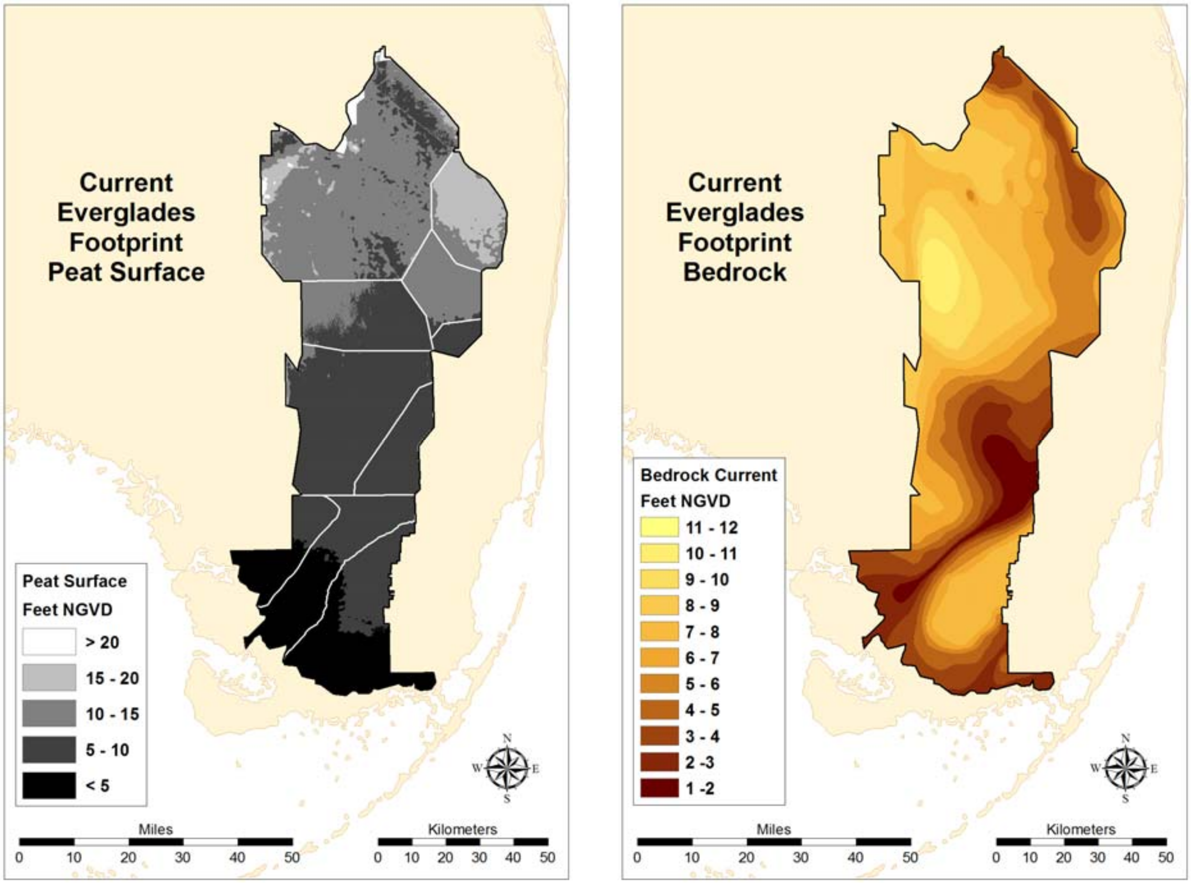

Figure 4. Left: map of the current Everglades peat surface (derived from Holt *et al.* 2006); right: map of the bedrock surface cropped to the current footprint of the Everglades (derived from Parker *et al.* 1955). Altitudes are in feet above the National Geodetic Vertical Datum of 1929 (NGVD).

values presented by Aich *et al.* (2013) for proxy predrainage soils (minimally impacted soils from WCA-1) and determined that the current values could reasonably be used to represent the predrainage peats as well. Moreover, the relative uniformity of bulk density and organic matter profiles noted above (Miller 1918, Saunders *et al.* 2008) indicates that these characteristics change little over time. Therefore, we used the R-EMAP values in both the predrainage calculations and the current calculations. We calculated statistics for each region using the Map Algebra tool in ArcGIS.

RESULTS

The peat depth maps are presented in Figure 5. Our calculations indicate that predrainage peat depths north of the present route of Highway 41 were mostly more than 5 ft (1.5 m) increasing northwards to more than 10 ft (3 m) and reaching 15 ft (4.6 m) or more near Lake Okeechobee. Current peat depths are less than 5 ft throughout the EPA except in WCA-1 (< 15 ft), WCA-2 (< 10 ft) and a small remnant of deeper (< 10 ft) peat near the centre of WCA-3. Peat depth across most of the EAA is also < 5 ft and exceeds 10 ft only at the extreme north end. The 228 R-EMAP peat bulk density locations and values, together with the interpolated peat mass values, are shown in Figure 6. The R-EMAP percent carbon and interpolated carbon mass values are presented similarly in Figure 7. Typically, the bulk density increases and the organic content of peat decreases from north to south across the Everglades. When this information is combined with the peat depth data shown in Figure 5, a reduction in bulk mass (Mg m^{-2}) of both peat and carbon is indicated over most of the area north of Highway 41.

The areas of regions together with the peat volume, mass, carbon content and carbon accretion rate results are presented for the predrainage Everglades in Table 1 and (apart from accretion

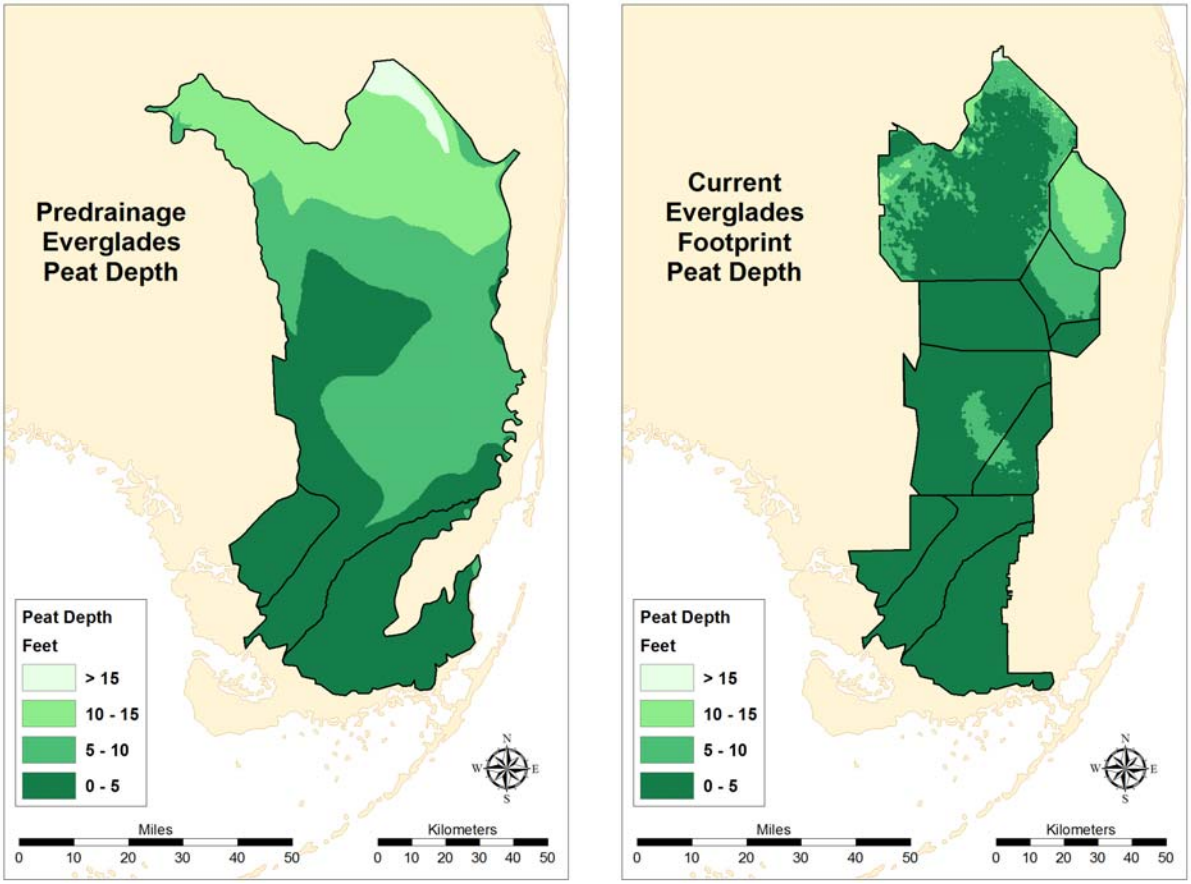

Figure 5. Left: map of peat depth in the predrainage Everglades, derived from the NSRSM predrainage surface and the bedrock map (Figure 3); right: map of peat depth in the current Everglades, derived from the SFTP current surface and the relevant part of the same bedrock map (Figure 4).

rates) for the current Everglades in Table 2. The total predrainage and current Everglades area, peat volume, peat mass and peat carbon and the loss of each are presented in Table 3. These results indicate that three-quarters of the peat has been lost, along with the associated carbon content.

Original and recent peat volumes for the current Everglades regions, the percent remaining volume for each region, the original mass and carbon for each of the current regions and their estimated carbon accretion rates, are presented in Table 4. These results indicate that peat has not been lost uniformly across the Everglades, with some regions losing greater percentages than others. The carbon accretion rates are calculated assuming that the age of the Everglades peats is approximately 5000 years (Gleason & Stone 1994, Craft & Richardson 1998, McVoy *et al*. 2011). The volume results from this and other studies are compared in Table 5. Our calculations agree closely with the other studies cited, given the uncertainties in the data sources.

DISCUSSION

Within the EPA, the northern section of WCA-3A is the most impacted region with approximately 25 % of the original peat still in existence (Table 4). This result is consistent with the findings of Bruland *et al.* (2006) and the fact that this region has been subject to greater drying than other regions as a result of drainage and impoundment (McVoy *et al.* 2011). The other WCAs show better preservation of peat volume, ranging from 53 % remaining in WCA-2B to the best preserved region (WCA-1) retaining 89 %. The latter is currently managed as part of the Loxahatchee National Wildlife Refuge, which is a deep peat region (3–4 m; Brandt *et al.* 2000). The EAA, where the water table is controlled for agricultural purposes (Aich *et al.* 2013), contains about 42 % of its original peat. Oleszczuk *et al*. (2008) give a median emissions (loss) value of 41.1 Mg CO_2 ha^{-1} yr^{-1} for ploughed fens (arable land), with a high range of variation. Multiplied by

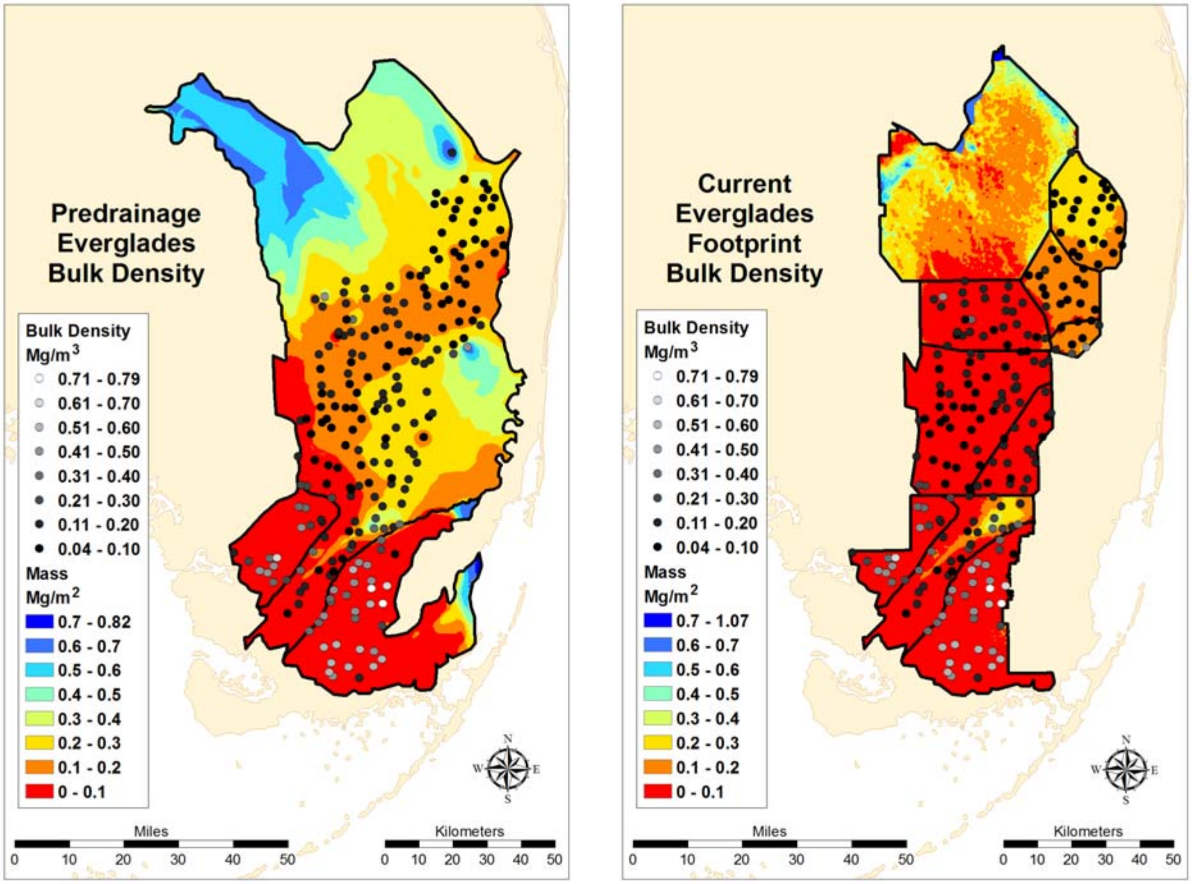

Figure 6. Maps of bulk peat mass for the predrainage (left) and current (right) Everglades with the point locations of the USEPA R-EMAP soil samples from which the bulk density values were obtained.

2.6×10^5 ha and by 120 years, this translates to 3.5×10^8 Mg of carbon as an estimated loss for the EAA. Our spatial calculations yield a value of 2.4×10^8 Mg of carbon as the estimated 120-year loss for the EAA. As the water table in the EAA is controlled to maximise yield and yet reduce peat oxidation, the values are consistent.

When the predrainage (NSRSM) peat surface developed by McVoy *et al.* (2011) was used here to calculate the change in peat volume from predrainage to current conditions, the Ochopee Marl Marsh (part of the southernmost region of the current Everglades footprint) showed a slight net increase in peat volume, translating to about 0.6 cm change in surface altitude. The volumes of this and the other marl marshes of ENP show much smaller changes (up to three orders of magnitude less) than those of the northern regions and Shark River Slough. The small increase in peat volume is within the margin of error, and should be considered an artefact of the analysis process.

Aich & Dreschel (2011), using single values for bulk density (0.26 Mg m^{-3}) and carbon content (51.8 %) determined that in the last *ca.* 120 years, 7.1×10^9 m^3 of peat were lost from the Everglades (including the EPA and EAA) which resulted in the evolution of 3.4×10^9 Mg of carbon dioxide from 9.2×10^8 Mg of carbon. In their calculations, 4.9×10^9 m^3 of peat and 2.3×10^9 Mg of carbon dioxide, equivalent to 6.3×10^8 Mg of carbon, were lost from the EAA. These values are somewhat larger than the results of the current study, mainly due to the single bulk density value that was used. This translates to a change in peat depth at an average rate of 15.6 mm yr^{-1} for the EAA; 3.2 mm yr^{-1} for WCA-1; 4.3 mm yr^{-1} for WCA-2A; 7.5 mm yr^{-1} for WCA-2B; 7.3 mm yr^{-1} for WCA-3A north; 4.4 mm yr^{-1} for WCA-3A south; 5.4 mm yr^{-1} for WCA-3B; 0.75 mm yr^{-1} for ENP Shark River Slough; and less than 0.1 mm yr^{-1} for the marl marshes. In this study, our calculations allow us to compare the predrainage and current volumes for each of the current Everglades regions. Aich & Dreschel (2011) used the same sources for the

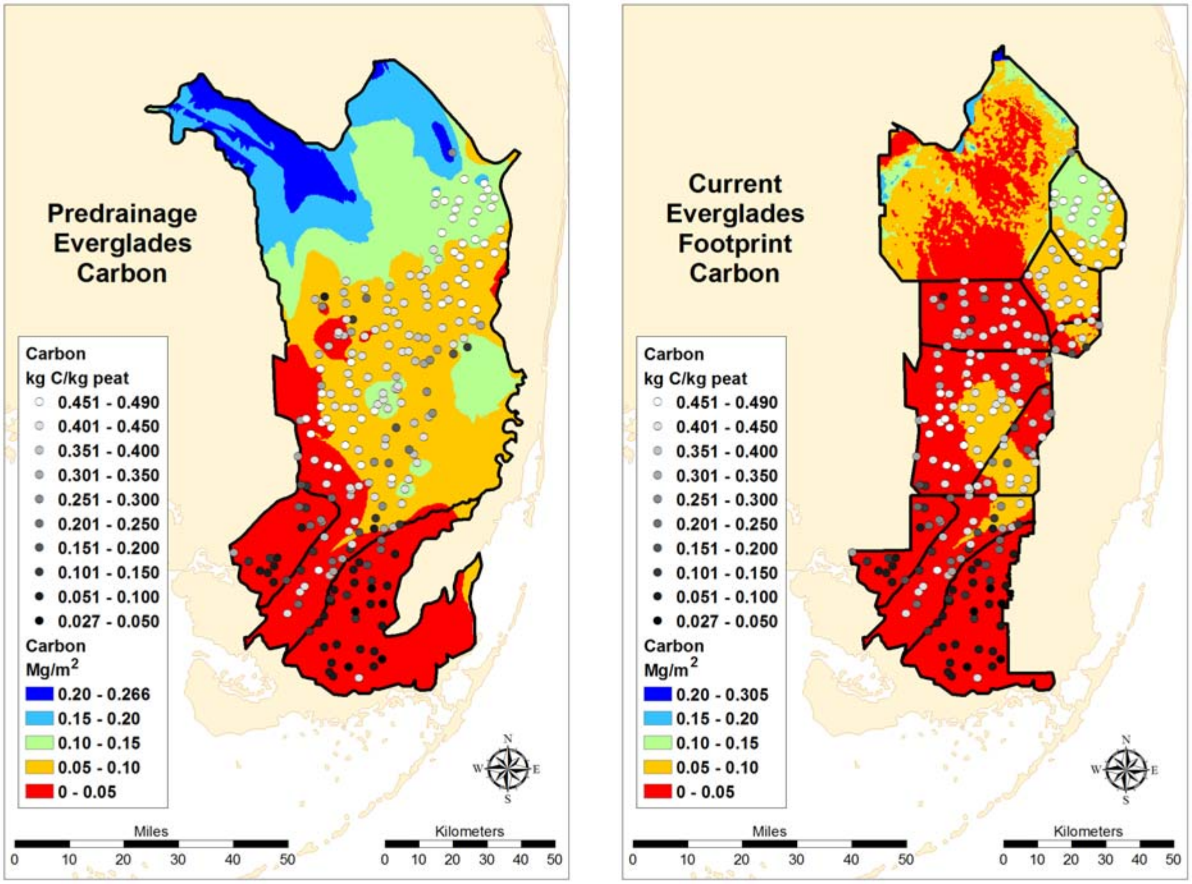

Figure 7. Maps of bulk peat carbon for the predrainage (left) and current (right) Everglades including the point locations of the USEPA R-EMAP soil samples from which the carbon content values were obtained.

surface altitude maps as were used in this study, and estimated the peat and carbon loss from each of the current Everglades regions using kriging interpolation. Their loss of volume calculations for the EPA and EAA compare very well with the current study using IDW interpolation. They compare their calculated carbon dioxide emissions with those determined by Gesch *et al.* (2007) from closed chamber tests for two different soil treatments (till and no-till) in the EAA and found them to be within a similar range of 0.4–2.67 g CO_2 m^{-2} hr^{-2}. Converting our carbon values to carbon dioxide emissions, we find a rate of 0.33 g CO_2 m^{-2} hr^{-2} for the EAA; 0.05 g CO_2 m^{-2} hr^{-2} for WCA-1; 0.06 g CO_2 m^{-2} hr^{-2} for WCA-2A; 0.14 g CO_2 m^{-2} hr^{-2} for WCA-2B; 0.16 g CO_2 m^{-2} hr^{-2} for WCA-3AN; 0.08 g CO_2 m^{-2} hr^{-2} for WCA-3AS; 0.1g CO_2 m^{-2} hr^{-2} for WCA-3B; 0.02 g CO_2 m^{-2} hr^{-2} for Shark River Slough; and less than 0.001 g CO_2 m^{-2} hr^{-2} for the marl marshes. Since the closed chamber tests were short-term, it is expected that the emission rates would have been somewhat greater than our calculated rates over more than a century. Jauhiainen *et al*. (2008) observed carbon dioxide emission rates of 0.3–0.8 g CO_2 m^{-2} hr^{-2} from an extensive tropical peatland in south-east Asia that was undergoing similar drainage by canalisation. Their values are similar to those we calculated for the EAA, which is a deep-peat highly impacted former region of the Everglades.

Aich *et al.* (2013) calculated the predrainage and current volumes of the EAA using two methods. The first method calculated differences between two surfaces created by kriging, one using values from predrainage and early post-drainage surveys (McVoy *et al.* 2011) and the other using recent values from Snyder (2005). The second method calculated differences from the two peat surfaces used in this study. The results again compare well with those of the current study. In an analysis of an Everglades tree island in WCA-2A, Aich *et al*. (2014) found that peat had been lost at an average rate of 4.0 mm yr^{-1}, which is similar to the average rates for the entire WCA of 4.2 mm yr^{-1} determined

Table 1. Areas, volumes, peat mass and peat carbon of the Everglades sub-regions determined from the predrainage (NSRSM) surface datasets and R-EMAP soils data.

region	total area (km^2)	peat volume (m^3)	mass (Mg)	carbon (Mg)	carbon accretion rate ($g\ m^{-2}\ yr^{-1}$)*
Ochopee Marl Marsh	5.7×10^2	8.2×10^6	2.3×10^6	4.4×10^5	0.2
Ridge and slough	8.9×10^3	2.0×10^{10}	2.5×10^9	9.3×10^8	20.9
Eastern Marl Marshes & Taylor Slough	1.6×10^3	1.9×10^8	8.5×10^7	8.4×10^6	1.0
Totals	1.1×10^4	2.0×10^{10}	2.6×10^9	9.4×10^8	

*The carbon accretion rate is calculated from the carbon content for each region, divided by the area in m^2 and 5000 years (McVoy *et al*. 2011) and multiplied by 1,000,000 $g\ Mg^{-1}$.

Table 2. Areas, volumes, peat mass and peat carbon of the Everglades sub-regions determined from the current (SFTP) surface datasets and R-EMAP soils data.

region	total area (km^2)	peat volume (m^3)	mass (Mg)	carbon (Mg)
EAA	2.6×10^3	3.5×10^9	5.6×10^8	1.6×10^8
WCA-1	5.6×10^2	1.8×10^9	1.2×10^8	5.6×10^7
WCA-2A	4.2×10^2	6.9×10^8	5.9×10^7	2.6×10^7
WCA-2B	1.1×10^2	1.1×10^8	1.6×10^7	5.5×10^6
WCA-3AN	7.2×10^2	2.2×10^8	3.0×10^7	1.1×10^7
WCA-3AS	1.3×10^3	1.1×10^9	1.1×10^8	4.7×10^7
WCA-3B	4.0×10^2	4.6×10^8	5.7×10^7	2.0×10^7
ENP-Ochopee Marl Marsh	3.8×10^2	9.2×10^6	2.7×10^6	4.8×10^5
ENP-Shark River Slough	7.7×10^2	2.8×10^8	5.2×10^7	1.4×10^7
ENP-Eastern Marl Marshes & Taylor Slough	9.9×10^2	1.2×10^7	4.1×10^6	5.0×10^5
Totals for EPA plus EAA	8.2×10^3	8.2×10^9	1.0×10^9	3.4×10^8
Totals for EPA	5.6×10^3	4.7×10^9	4.5×10^8	1.8×10^8

Table 3. Peat volume, peat mass and peat carbon mass for the predrainage and current Everglades and the loss of each.

time period	total area (km^2)	peat volume (m^3)	mass (Mg)	carbon (Mg)
predrainage Everglades totals	1.1×10^4	2.0×10^{10}	2.6×10^9	9.4×10^8
current EPA totals	5.6×10^3	4.7×10^9	4.5×10^8	1.8×10^8
change (loss)	5.4×10^3	1.5×10^{10}	2.2×10^9	7.6×10^8

Table 4. Estimated volume changes since drainage and predrainage carbon accretion rates for the current Everglades footprint, by region.

region	total area (km^2)	original volume (m^3)	current volume (m^3)	percent of original volume remaining	original mass (Mg)	original carbon (Mg)	carbon accretion rate* ($g\ m^{-2}\ yr^{-1}$)
EAA	2.6×10^3	8.3×10^9	3.5×10^9	42	1.0×10^9	4.0×10^8	30.8
WCA-1	5.6×10^2	2.0×10^9	1.8×10^9	89	1.4×10^8	6.5×10^7	22.9
WCA-2A	4.2×10^2	9.1×10^8	6.9×10^8	76	7.7×10^7	3.4×10^7	16.2
WCA-2B	1.1×10^2	2.2×10^8	1.1×10^8	53	3.0×10^7	1.0×10^7	18.2
WCA-3AN	7.2×10^2	8.5×10^8	2.2×10^8	25	1.3×10^8	4.5×10^7	12.5
WCA-3AS	1.3×10^3	1.8×10^9	1.1×10^9	62	2.5×10^8	7.8×10^7	12.0
WCA-3B	4.0×10^2	7.2×10^8	4.6×10^8	64	1.3×10^8	3.2×10^7	16.0
ENP-Ochopee Marl Marsh	3.8×10^2	6.9×10^6	9.2×10^6	134	1.9×10^6	3.6×10^5	0.2
ENP-Shark River Slough	7.7×10^2	3.5×10^8	2.8×10^8	80	6.3×10^7	1.8×10^7	4.6
ENP-Eastern Marl Marshes & Taylor Slough	9.9×10^2	1.4×10^7	1.2×10^7	90	4.3×10^6	6.5×10^5	0.2
Total EPA + EAA	8.2×10^3	1.5×10^{10}	8.2×10^9	54	1.9×10^9	6.8×10^8	16.6
Total EPA	5.6×10^3	6.9×10^9	4.7×10^9	68	8.2×10^8	1.0×10^8	3.6

*The carbon accretion rate is calculated from the predrainage carbon content for each region divided by the area and 5000 years (McVoy *et al*. 2011) and multiplied by 1,000,000 $g\ Mg^{-1}$.

Table 5. Comparison of values between the current study [1] and various prior studies, namely: [2] Stephens *et al.* (1984); [3] Aich & Dreschel (2011); [4] Aich *et al.* (2013), Method 1; [5] Aich *et al.* (2013), Method 2.

region	volume (m^3)				volume lost (m^3)			
	Original [1]	Current [1]	1924 [2][abc]	1978 [2][abc]	[1]	[3][c]	[4][b]	[5][c]
EAA	8.3×10^9	3.5×10^9	6.8×10^9	3.1×10^9	4.8×10^9	4.9×10^9	4.5×10^9	4.9×10^9
total EPA+EAA	1.5×10^{10}	8.2×10^9			7.0×10^9	7.1×10^9		
total EPA	6.9×10^9	4.7×10^9			2.2×10^9	2.2×10^9		

[a]estimated using peat depth at a concrete marker in Belle Glade, Florida (8.6 ft = 2.6 m in 1924; 4.1 ft = 1.2 m in 1978), multiplied by the area of the EAA; [b]calculations made from datasets that are independent of the ones used in this study; [c]calculations made using a different geospatial technique from the one used in this study.

by Aich & Dreschel (2011) and 4.3 mm yr^{-1} from this study. Stephens *et al.* (1984), in a discussion of organic soil subsidence, showed the changes in surface altitude as indicated by a concrete monument marked with graduations at 0.25-ft (76 mm) intervals at the Everglades Experiment Station in Belle Glade, Florida (located in the EAA), where the surface was approximately 4.5 ft (1.4 m) higher in 1924 than it was in 1978. Multiplying the peat depths at the monument by the area of the EAA indicated 6.8×10^9 m^3 present in 1924 and 3.1×10^9 m^3 present in 1978. Even though the monument measurements were taken at a single location within the EAA, these peat volumes compare reasonably well with those derived in the present work (8.3×10^9 m^3 predrainage and 3.5×10^9 m^3 currently). For a comparison of values among these various studies, see Table 5.

In their evaluation of carbon accumulation using cores from various regions of the EPA, Jones *et al.* (2014) found average accumulation rates ranging from 8.4 to over 200 g m^{-2} yr^{-1}. They indicated that the rates from their southernmost ridge and slough cores (8.4–8.9 g m^{-2} yr^{-1}) compared well with the outcome of a previous study by Glaser *et al.* (2012) which had determined a rate of 12.1 g m^{-2} yr^{-1} for Shark River Slough from a single core. These rates and ours (Table 1) are generally lower than those calculated by Craft & Richardson (1998) using a single core from the middle of each region of the Everglades (37 g m^{-2} yr^{-1}). The differences between the referenced values and ours may be due to the fact that we calculated a landscape-scale average for each region instead of relying on a single core. Our regional carbon values yielded an average accretion rate of 20.9 g m^{-2} yr^{-1} for the peat-dominated predrainage ridge and slough region (Table 1), and a regional range of 4.6 g m^{-2} yr^{-1} for Shark River Slough to 30.8 g m^{-2} yr^{-1} for the historical sawgrass plains (now the EAA; Table 4).

Our results should not be viewed as precise, as a number of uncertainties must be taken into account. First, the datasets used to develop the predrainage and current surfaces have inconsistent variance because they were assembled from various sources. For the predrainage surface, peat depth values from land and canal surveys were extracted and interpolated to create the surface altitude. These various surveys were conducted over the course of decades and by a number of different surveyors (McVoy *et al.* 2011). The sounding rods used by the land surveyors were ten feet in length. In the northern regions of the Everglades, peat depths exceeded this amount and were reported as "greater than ten feet". However, in regions where canals were dug, the greater depths to bedrock were determined. This uncertainty in the northern predrainage Everglades data is described in greater detail by Aich *et al.* (2013). The current Everglades surface was assembled from a number of data sources which are presented in Holt *et al.* (2006). The bedrock map from Parker *et al.* (1955) is the sole source of extensive bedrock altitude data for South Florida. This map was based on extensive probing across the region at intervals of 660 feet (201 m) as described by Jones (1948). In addition, as the soil properties (bulk density and carbon content) were not measured on the predrainage peats, we used the current characteristics of Everglades soils for the current peat calculations and as proxies for the predrainage peats. The sampling was conducted primarily within the current footprint of the WCAs and ENP; thus, regions within the historical footprint but outside these current regions had limited data for interpolation, particularly in the EAA and the eastern urbanised regions.

The change in the soils over the past century varies by region but it is likely that they have lost some carbon and increased in bulk density. However, these soils still generally retain a large organic fraction, particularly in the northern ridge and slough regions (particularly for WCA-1 and WCA-3AS). A more detailed discussion of Everglades peats, comparing the current and predrainage situations, can be found in Aich *et al.* (2013). Also, as with any interpolation, the original surfaces were estimated from point data which have spatial and topographical limitations depending on whether surfaces were measured on ridges or in sloughs. Where it could be calculated, Root Mean Square Error (RMSE) for IDW interpolations of bulk density ranges from 0.061 to 0.137 for predrainage regions (Figure 6, left) and from 0.014 to 0.137 for current regions (Figure 6, right); and RMSE of carbon ranges from 0.083 to 0.088 for predrainage regions (Figure 7, left) and from 0.010 to 0.156 for current regions (Figure 7, right).

Finally, we assumed that the volume change was entirely due to loss of organic matter, primarily to oxidation. This may add additional uncertainty to the subsequent calculations of mass and carbon. Compaction may occur when peat soils are initially drained. Couwenberg & Hooijer (2013) found that physical compaction could account for up to 20–30 % of the volume loss observed in their study of oil palm plantations created on former peat-based wetlands. Drexler *et al*. (2009) discuss peat loss related to wetland drainage in California and indicate that the farming practice of continuously artificially lowering the water table is the primary cause of settling and compaction. It is likely that the EAA has experienced the same phenomenon. On the other hand, Stephens *et al.* (1984) found that oxidation is a long-term process in the Everglades. Over the period that we examined, it seems probable that the subsidence due to compaction has been less than 20 % of the total volume lost, and thus within the margin of error of our calculations. Despite the uncertainties, we believe that there are sufficient historical records to indicate that the datasets used in this study contain reasonable order-of-magnitude values for estimating the total peat volumes, masses and changes (see Table 5).

The Central Everglades Planning Project (CEPP) will accelerate restoration by allowing an additional 2.6×10^8 m^3 of water per year to flow through the Everglades (USACE 2014). South Florida has been strongly impacted by the presence of seven million residents, and salt water intrusion into the freshwater aquifer is a major problem due to canal drainage and aquifer pumping. Water retained in the Everglades (whether as surface water or in water-saturated peat) will provide the head pressure of fresh water that is needed to prevent salt water intrusion into local well fields as projected in the context of sea level rise. The water is also needed to prevent further peat loss by oxidation. A quote from Barlow (2003) sums up this aspect: "Future changes in the region's water-management operations that have been proposed in the Everglades restoration plan are likely to have consequences for the coastal ground-water system, including movement of the freshwater-saltwater interface". A series of stormwater treatment areas (currently at 2.3×10^2 km^2; Entry & Gottlieb 2014) and other water conveyance and treatment features have been and are being constructed and operated to provide the low-nutrient water needed for this restoration. The ultimate benefit of providing greater volumes of water to the remaining Everglades footprint will be the prevention of further peat oxidation and the encouragement of atmospheric carbon sequestration leading to accretion of peat that has been lost from the region for more than a century.

CONCLUSIONS

The historical Everglades had an area of about 1.1×10^4 km^2, with a peat volume of 2.0×10^{10} m^3 and a peat mass of 2.6×10^9 Mg containing 9.4×10^8 Mg of carbon. The Everglades is now about 5.6×10^3 km^2 in area with peat volume 4.7×10^9 m^3, peat mass 4.5×10^8 Mg, and 1.8×10^8 Mg of carbon. Thus, the current Everglades covers approximately half the original area (50.9 %) but has less than a quarter of the predrainage peat volume (23.5 %), mass (17.3 %) and carbon (19.1 %).

Our spatial interpolations of bedrock and peat depths indicate that 1.5×10^{10} m^3 of peat with a mass of 2.2×10^9 Mg have been lost from the Everglades since predrainage, containing 7.6×10^8 Mg of carbon, 1.6×10^8 Mg of which still remains in the peat soils of the EAA. The current footprint of the EPA has retained about 68 % of the peat originally found within that footprint, which ranges in the peat-dominated regions from 89 % in WCA-1 to 25 % in northern WCA-3A.

Calculations such as these are important for evaluation of the contribution of Everglades peats to the global changes in atmospheric CO_2 concentrations and their impact on climate change. With restoration, the rate of peat accretion may increase sufficiently to enable the Everglades again to become a net sink for CO_2.

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