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# Peat Soils of the Everglades of Florida, USA

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Additional information is available at the end of the chapter

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## Abstract

In this chapter, we briefly discuss the development of the Everglades over the past 5 million years, the modifications made to the Everglades over the past century and a half and the quantification of the changes that have occurred to the peat soils of the Everglades due to natural and anthropogenic causes during this most recent period. Using Geographic Information Systems and historical data sets, we have been able to calculate the original peat volumes, the remaining peat volumes and thus, the amount lost over the past approximately 150 years. From these volume calculations and peat physical and chemical characterizations by the USEPA over a large area of the Everglades, we have estimated the mass of peat and carbon lost, 900 million metric tons and 300 million metric tons, respectively. The amount of peat lost has implications for hydrological, ecological and landscape restoration and habitat recovery for the Everglades.

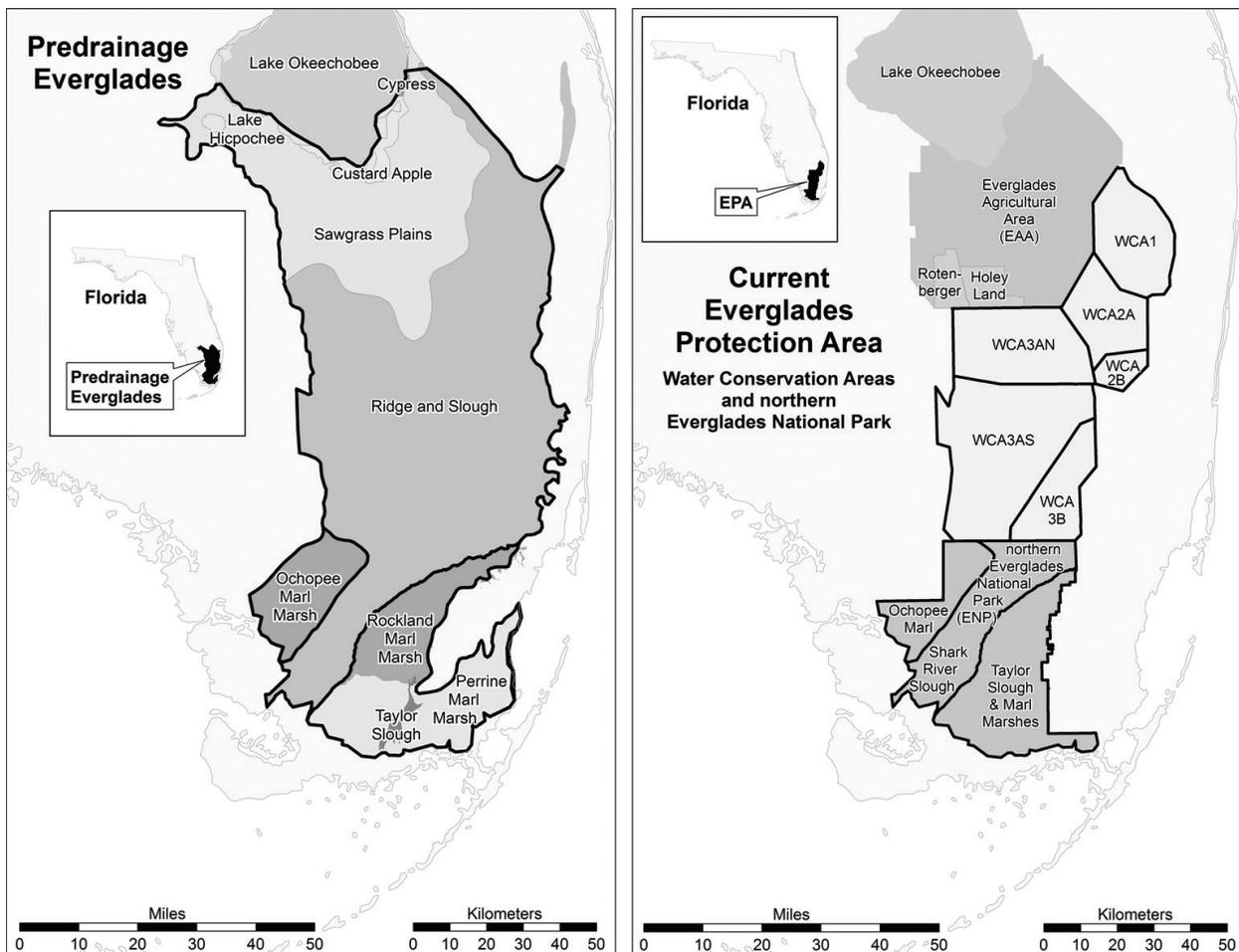
**Keywords:** Everglades peats, subsidence, drainage, peat fires, ecological restoration

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## 1. Introduction

The Everglades of the mid-1800s covered about 11,000 square kilometers (1.1 million hectares) and the basal peats have been estimated to have begun to develop approximately 5,000 years ago [1]. The historical landscape (**Figure 1**, left) is described by McVoy and colleagues [1] as having a custard apple swamp region, on the southeastern edge of Lake Okeechobee (Lake), a vast “impenetrable” sawgrass plain to the south of the Lake and a vast ridge and slough landscape which filled most of the rest of the Everglades to the south. The current Everglades is approximately 5,600 square kilometers (560,000 hectares) and is currently contained in what is known as the Everglades Protection Area (EPA) which is made up of five Water Conservation Areas (WCAs): WCA-1 or the Arthur R. Marshall Loxahatchee National Wildlife Refuge; WCA-2A; WCA-2B; WCA-3A and; WCA-3B as well as Everglades National Park (**Figure 1**, right). The EPA

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**Figure 1.** Historical predrainage Everglades landscapes, circa 1850 (left) and current Everglades footprint, including the EPA and EAA (right), modified from Hohner and Dreschel [2].

along with the Everglades Agricultural Area (EAA) are considered the current Everglades footprint (**Figure 1**, right). Geologically, south Florida, where the Everglades is located, is described as a pseudo-atoll surrounded by fossil reefs [3]. The central limestone bedrock that underlies the Everglades is relatively impermeable and formed over the past five million years [3]. A coastal ridge forms a barrier to the east which allowed the retention of water in the Everglades basin and the wet climate provided the environment for the growth of herbaceous vegetation and the consequent build-up of the peat soils, initially at a rate of about 7 cm per century with a rate of about 12 cm per century over the past millennia or so [4]. Prior to the 1800s, peat built up sufficiently to form a dam at the southern edge of the Lake which allowed water levels to rise and overflow to the south, continuously inundating the southern end of the Florida peninsula, particularly during the wet season (currently late May through mid-October). The peat that filled the Everglades basin had sufficient water-holding capacity to hold moisture during the dry season (currently mid-October through late May) during most years [1], thus allowing the preservation and accretion of the peats.

Human alterations to the Everglades landscape began in large part with the dredging of canals to drain the Kissimmee River Valley as well as lower the water level in the Lake [5]. The

approach involved connecting the Kissimmee headwater lakes and building canals to allow water releases to the Gulf of Mexico and the Atlantic Ocean, reducing the water level in the Lake. This was to prevent overflow to the Everglades for the purpose of allowing the use of the region for agricultural and urban development. The first canal effort took place in the late 1800s with a connection from the Lake to the Caloosahatchee River. This effort was moderately successful in lowering the Lake stages, designated the Lake Okeechobee phase of Everglades drainage by McVoy and colleagues [1]. The draining of the Everglades began in earnest with the digging of four muck canals by 1917, carrying water from the Lake south to the east coast [5]. These canals (from the east clockwise to the south side of the Lake) were: The West Palm Beach Canal; the Hillsboro Canal; the North New River Canal and the Miami Canal [5]. This is considered the Muck Canal Phase [1]. The Tamiami Trail was constructed and opened in 1928 which stretched across south Florida separating what would become Everglades National Park to the south from the rest of the Everglades to the north.

Severe drying of the Everglades due to the lowering of the Lake resulted in fires which consumed large areas of the peat soil. In addition, the occurrence of several deadly hurricanes crossing south Florida resulted in the U.S. Congress authorizing the Central and Southern Florida Project for Flood Control and Other Purposes (the C & SF Project). The construction of the C & SF Project resulted in the last and current phase called the Impoundment phase [1, 5]. The Eastern Perimeter Levee was built between 1952 and 1954 to protect the urbanized eastern coastal areas. This was followed by the construction of the Everglades Agricultural Area (EAA) between 1954 and 1959, adjacent to the south end of the Lake, involving addition of levees, control structures, pumping stations and canal improvements, to allow further agricultural development of the region of the former sawgrass plains. This region contained the thickest deposit of peat within the Everglades [5]. This was followed by the impoundment of the remaining Everglades north of the Tamiami Trail. During the years 1960 through 1963, three Water Conservation Areas (WCAs) were established with the construction of perimeter levees, complete with water control structures so that water could be moved between them [5]. Southeast of the EAA, WCA-1 was constructed and was ultimately designated as the Arthur R. Marshall Loxahatchee National Wildlife Refuge. Further south and east of the EAA, WCA-2 was constructed and divided into WCA-2A and WCA-2B. The division was made to control the amount of water that would be allowed to seep into the Biscayne Aquifer, partially located under WCA-2B. Due south and west of the other two WCAs, the largest of the WCAs was constructed and designated WCA-3 which was also subdivided into WCA-3A and WCA-3B. Similar to WCA-2B, WCA-3B was located over a porous substrate which did not allow long-term water storage. Other modifications were made to deliver water to Everglades National Park [5].

### **1.1. Everglades peats**

There are four major peats associated with the Everglades: Everglades peat; Loxahatchee peat, Okeechobee muck and Okeelanta peaty muck. Everglades peat is produced from partially decomposed sawgrass leaves and roots and makes up the bulk of the peat found within the EAA. Loxahatchee peat, formed from aquatic plants such as water lilies and forms the bottoms of sloughs whereas Everglades is the substrate of ridges within the ridge and slough landscape. The other two peats, considered mucks (Okeechobee and Okeelanta) are the result

of overwash during high stages the Lake and contain a larger inorganic fraction (from 35 to 70%) than the other two peats (around 10%) [6]. The two mucks and the Everglades peats have been extensively utilized for agricultural purposes.

### 1.2. The Everglades Agricultural Area (EAA)

Most of the original Sawgrass Plains landscape (dominated by sawgrass, *Cladium jamaicense*), as well as the Custard Apple Swamp (dominated by pond apple, *Annona glabra*) was primarily converted to the Everglades Agricultural Area by the early 1960s. This region was deemed a prime agricultural region due to the thick organic soils present there [1, 6]. The custard apple mucks, about 7% of the EAA, are found adjacent to the southeastern shore of the Lake and were 2.8–3.8 m deep and about 60% organic matter [7]. These soils are now considered Typic Haplosaprists. The majority of the area (90%) is underlain with sawgrass peats which originally were highly organic, about 90% organic matter according to Baldwin and Hawker [6]. By the 1940s, these peats had decomposed, exhibiting an approximately half-meter thick surface layer of “black, finely fibrous, well decomposed organic material” [1, 6]. Subsidence over the next 30 years resulted in these soils being classified as the Montverde (sawgrass) muck series of Typic Medifibrists [8]. Currently, all the soils of the EAA are classified as Saprists which are the most decomposed suborder of Histosols [1, 9, 10]. The soils continue to subside, resulting in a continual transition from thicker to thinner soil series and ultimately may become mineral soils [11].

### 1.3. Everglades tree islands

Tree Islands cover a small part of the ridge and slough landscape but are unique features for maintaining biodiversity and play a significant role in the biogeochemical cycling of nutrients in the Everglades [12]. Tear-drop shaped tree islands are believed to have been shaped by flow and have a broader “head” region and with a “tail” pointed downstream. Tree island heads have the concentrations of soil phosphorus that are orders of magnitude higher than the sediments of the surrounding sloughs [13]. The peat of tree islands is called “Gandy peat” [1]. Many tree islands have been lost or severely degraded due to oxidation and fires caused by droughts and drainage due to altered hydroperiods [14, 15]. Severely degraded tree islands have lost much of their elevations such that trees are unable to grow on them because of frequent flooding. These tree islands typically have extensive areas of herbaceous plants and are now termed “ghost” tree islands, appearing similar to large ridges in the landscape. Most of the tree islands of WCA-2A are now considered ghost tree islands and their outlines can still be located on the landscape but they now host very few trees [16, 17].

## 2. Background

The basin in which the Everglades formed provided an adequate substrate while the subtropical nature of the climate of south Florida provided the appropriate environment for the formation of peat soils. This process began approximately five millennia ago and it is believed that sometime in the recent past, peat built up to create a maximum surface covering the

historical Everglades basin. Peat accretion has been estimated to have been about 12 cm per century over the last millennium or so. Since anthropogenic drainage was initiated in the late 1800s, the organic peat has shrunk and been lost by subsidence, fire and oxidation, both bacterial and chemical [1]. Rates of subsidence exceeding 2.5 cm per year have been measured in the EAA [18, 19]. The degree of subsidence due to oxidation is highly dependent upon the depth of the water table below the surface of the peat [20, 21] and has been a controlling factor in carbon emissions from the Everglades. Closed chamber studies have been conducted in an attempt to quantify the carbon emissions from peat soils in the Everglades [22] and resulted in measured emissions from 0.4 to 2.67 g/m<sup>2</sup>/h.

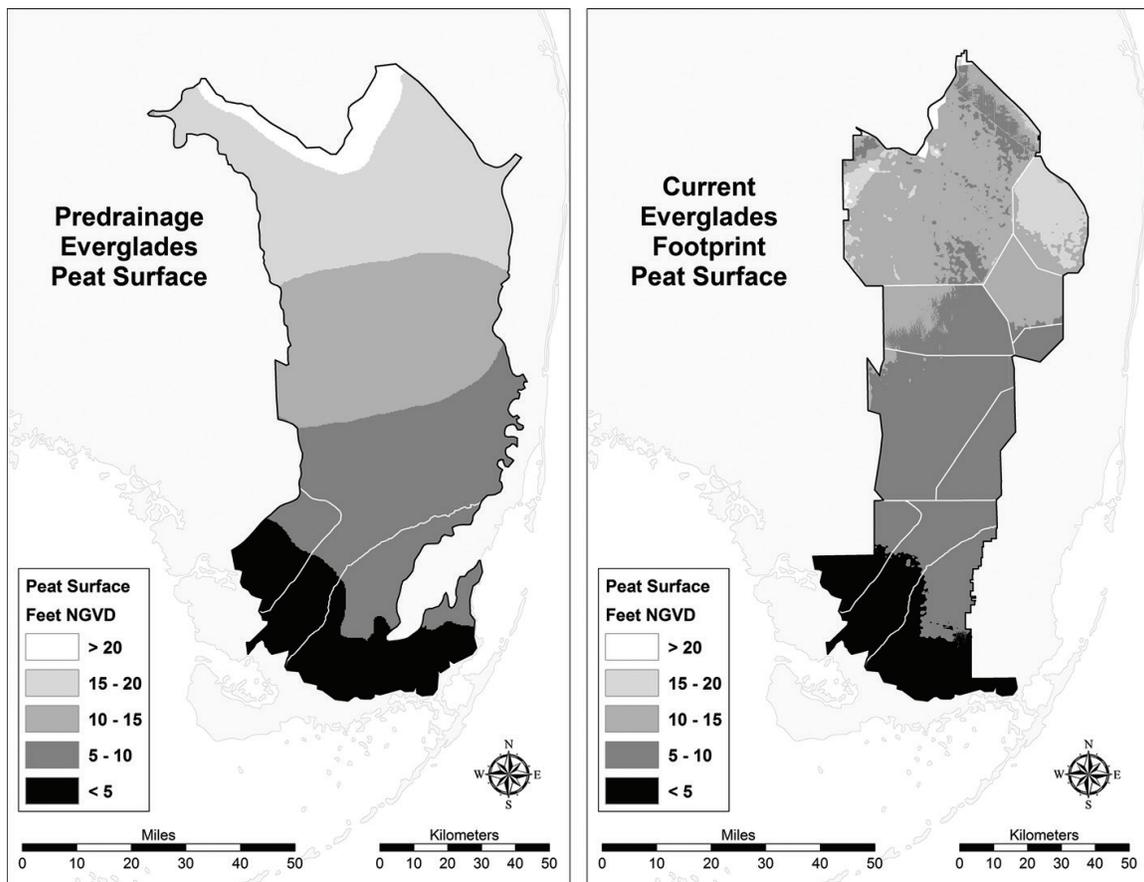
A number of studies have been conducted to determine the amount of peat remaining in the current Everglades footprint (the EAA, EPA and Everglades National Park). The USEPA's Regional Environmental Monitoring and Assessment Program or R-EMAP has measured ground depth and surface elevation [23–25]. The program has created maps that allow a comparison of the changes in elevation over the past 5 decades leading to the estimation of peat loss from the Everglades during that period. Our group has endeavored to utilize a Geographic Information System (GIS) by creating and analyzing raster grids of historical and current Everglades elevation data sets to determine the amount of peat and carbon lost within each region of the current Everglades and the EAA as well as on a tree island in WCA-2A. In addition, we have used historical data sets to determine the original peat volumes of the various predrainage landscapes of the Everglades and the existing peat volumes of the current regions of the Everglades.

The data sets used for the peat volumes analyses include: the historical surface of the predrainage Everglades determined from historical (mid-1800s through early 1900s) land and canal surveys across the landscape [26]; a current (2005) surface of the current Everglades created from a number of data sources [27]; historical surface of the predrainage EAA from historical land and canal surveys [28]; recent land surveys done specifically within the EAA [29]; a south Florida bedrock map from Parker and colleagues [30]; a tree island survey conducted in 1973 [31] and one from the same tree island conducted in 2009 [16].

## 2.1. Data sets

A number of sources were utilized to create the surfaces used in evaluating peat volumes:

1. The predrainage peat surface data used was created for hydrological models, specifically the Natural Systems Regional Simulation Model (NSRSM) created and used by the South Florida Water Management District to simulate the hydrologic flow of the predrainage system under various scenarios (**Figure 2**, left). The surface was created using data from more than 300 land (township) and canal survey notes from the mid-1800s through the early 1900s [26].
2. The current Everglades system data set is from the South Florida Topography Project [27] and is a combination of a number of data sets including LIDAR, Radar from the Shuttle Radar Topographic Mission, bathymetric surveys, photogrammetry, and measured spot elevations (**Figure 2**, right and **Table 1**).
3. The predrainage Everglades bedrock map is a digitized version of an Everglades bedrock contour map presented by Parker and colleagues [30] (**Figure 3**, left).



**Figure 2.** Maps of peat the peat surfaces used for the calculations reported by Hohner and Dreschel [2], derived from surface elevation data sets developed by Said and Brown [26], left and Holt and colleagues [27], right.

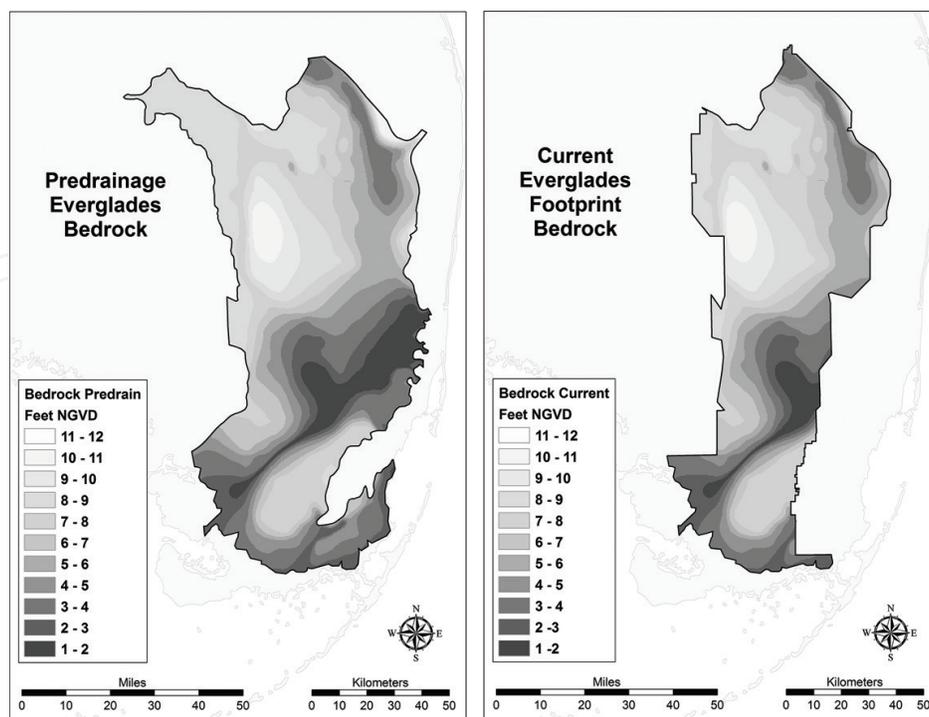
4. The current Everglades bedrock map was clipped from Data Set 3 above (**Figure 3**, right)
5. The 1973 tree island map was a digitized version of a survey map from the Central and Southern Florida Flood Control District, now known as the South Florida Water Management District [31].
6. The 2009 tree island survey was digitized from data reported by Ewe and colleagues [16].
7. One EAA predrainage map was created by clipping from the predrainage peat surface data from Data Set 1, above.
8. One EAA predrainage map was digitized using notes from a number of land surveys and canal surveys conducted in the early 1900s [28].
9. One EAA current surface was created by clipping from Data Set 2, above.
10. One EAA current surface was digitized from data presented by Snyder [29].
11. The EAA bedrock surface was created by clipping from Data Set 3, above.

In addition, spatially measured bulk density and peat carbon content point data sets from the USEPA R-EMAP were interpolated to create raster surfaces for the calculations of peat mass and carbon [23–25].

Data source	Data type
U.S. Army Corps of Engineers (USACE)	Terrestrial Light Detection and Ranging (LIDAR) Surveys Hydrographic, Structural and Channel Cross-section Surveys of the Okeechobee and the Atlantic Intercoastal Waterways Hydrographic Surveys of the St. Lucie Estuary, the Caloosahatchee Estuary and the Lake Okeechobee
Collier County	LIDAR Survey
International Hurricane Research Center (IHRS), Florida International University	LIDAR Survey
National Ocean Service (NOS), National Oceanic and Atmospheric Administration (NOAA)	Bathymetric Surveys of the Loxahatchee Estuary, the St. Lucie Estuary and the Lake Okeechobee Coastal Relief Model (CRM) Bathymetry of the Collier Shore, and the Charlotte Harbor to the Key West
Lee County	Photogrammetry
U.S. Geological Survey (USGS)	Measured Spot Elevations High Accuracy Elevation Dataset (HAED) National Elevation Dataset (NED)
South Florida Water Management District (SFWMD)	Coastal Bathymetry of the Naples Bay, and the southwest Florida to the Florida Bay
Shuttle Radar Topographic Mission (SRTM)	Radio Detection and Ranging (RADAR) of the Everglades Agricultural Area

After [33].

**Table 1.** Sources of data combined for the South Florida Topography Project (Current Elevation Data Set).



**Figure 3.** Maps of Everglades bedrock used for the calculations reported by Hohner and Dreschel [2], derived from a map presented by Parker and colleagues [30], left and the same surface clipped to the current Everglades footprint, right.

### 3. Approach and results

The availability of both the predrainage surface elevations and the current surface elevations made it possible to create GIS raster grids (305 × 305 m pixel size) from which the differences could be calculated, thus providing a means for calculating volume differences. Thus, for the initial calculations of peat loss, ArcGIS software's Raster Calculator function of the Spatial Analyst Tool [32] and a raster layer subtraction technique was used to determine the change in volume from predrainage to the present. This was the process used by Aich and Dreschel [33] following the correcting of the two surfaces to a common vertical datum (NAVD88). These volumes were converted to SI units and then used to calculate the mass of peat loss from each region by multiplying by a bulk density of 0.26 g cm<sup>-3</sup> [34]. The mass of each region was then calculated using a carbon content of 51.8% [34] and the carbon dioxide released by multiplying the carbon by the molecular weight of carbon dioxide divided by the atomic mass of carbon (44/12). The results of these calculations are presented in **Table 2**.

For the calculation of peat volumes and loss in the EAA, two methods using different data sets were used in an attempt to confirm the numbers. See [28] for greater detail. For the first method, an early EAA (1915) surface elevation map (Data Set #4) was created using a subset of the data described for Data Set #1 and ordinary kriging and the current (2005) peat thickness map was created from measurements at 15 locations made by Snyder [29] and ordinary kriging. For the second method, the predrainage EAA surface was clipped from the map created by Said and Brown [26] which provided Data Set #1 and the current surface was clipped from the map created from the South Florida Topography Project [27] as well as the bedrock surface map from Parker et al. [30] which provided data set #3. All surfaces not in NAVD88 were corrected to that datum. For both methods, ArcGIS software's Map Calculator function of the Spatial Analysis Tool [32] and a raster layer subtraction technique was used to determine the differences between the surfaces. All values were converted to SI units for the calculation of peat volume (m<sup>3</sup>), peat mass (MT = metric ton) and carbon mass from the past, present and the amount lost (**Table 3**).

For the calculation of peat loss from Dineen Island, a ghost tree island in WCA-2A, two data sources were available. A survey map from 1973 (Data Set #9) [31] was used to create a surface elevation map and for the most current surface, a survey conducted in 2009 (Data Set #10) [16] was used to create the surface elevation maps (**Figures 4 and 5**). Both surface elevation maps were created using ordinary kriging and elevation points collected during a number of transects made across the island [17] (**Figures 4 and 5**, [17]). The difference between the surfaces

Everglades region	WCA-1	WCA-2A	WCA-2B	WCA-3A	WCA-3B	ENP	EAA	Total
Volume of peat lost (m <sup>3</sup> )	2.2 × 10 <sup>8</sup>	2.1 × 10 <sup>8</sup>	1.1 × 10 <sup>8</sup>	1.3 × 10 <sup>9</sup>	2.5 × 10 <sup>8</sup>	1.2 × 10 <sup>8</sup>	4.9 × 10 <sup>9</sup>	7.1 × 10 <sup>9</sup>
Average subsidence (m)	0.4	0.5	0.9	0.6	0.6	0.01	1.7	–

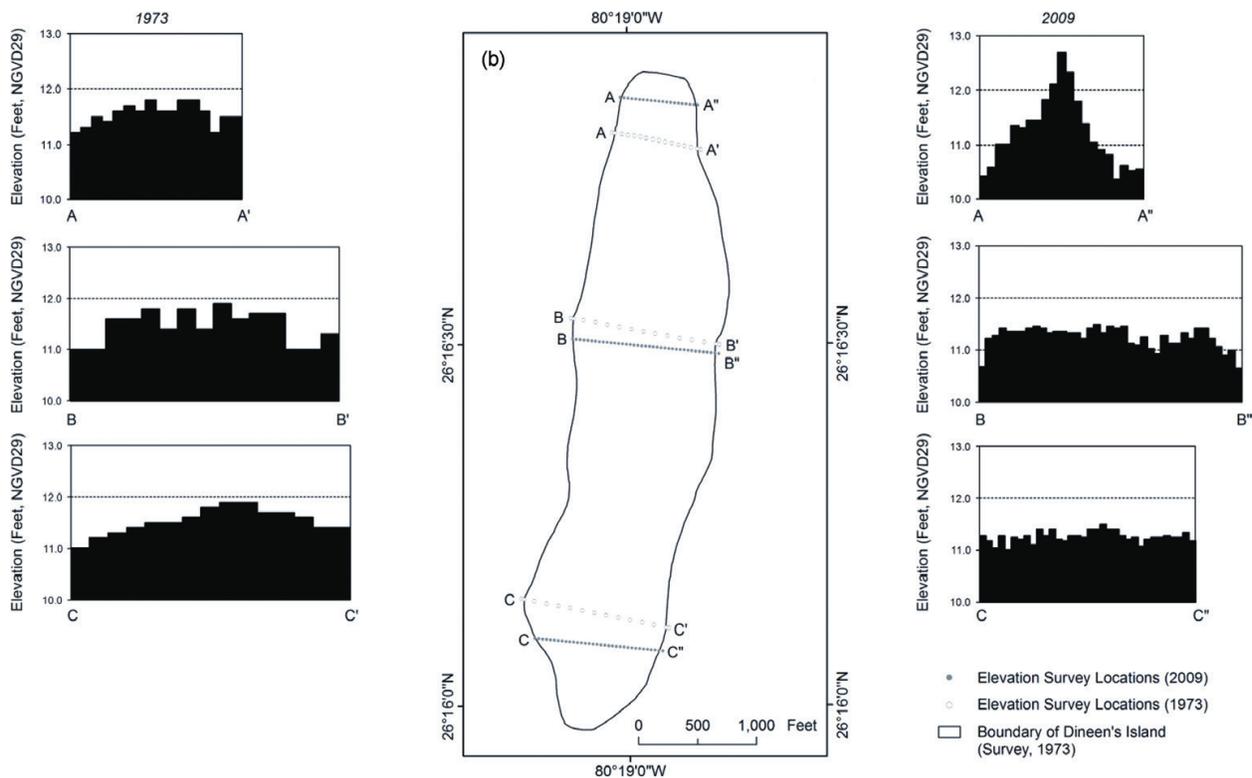
**Table 2.** Everglades peat loss and subsidence since the mid-1800s from [33].

EAA analysis	Time period	Original peat volume (m <sup>3</sup> )	Peat volume remaining (m <sup>3</sup> )	Peat volume lost (m <sup>3</sup> )	Average subsidence (m)	Peat mass lost (MT)	CO <sub>2</sub> lost (MT)	Average emission rate (g CO <sub>2</sub> m <sup>-2</sup> h <sup>-1</sup> )
Method 1	1915–2003	6.5 × 10 <sup>9</sup>	2.0 × 10 <sup>9</sup>	4.5 × 10 <sup>9</sup>	1.6	2.5 × 10 <sup>8</sup>	4.9 × 10 <sup>8</sup>	0.22
Method 2	1880–2000	8.3 × 10 <sup>9</sup>	3.4 × 10 <sup>9</sup>	4.9 × 10 <sup>9</sup>	1.7	2.5 × 10 <sup>8</sup>	4.9 × 10 <sup>8</sup>	0.17

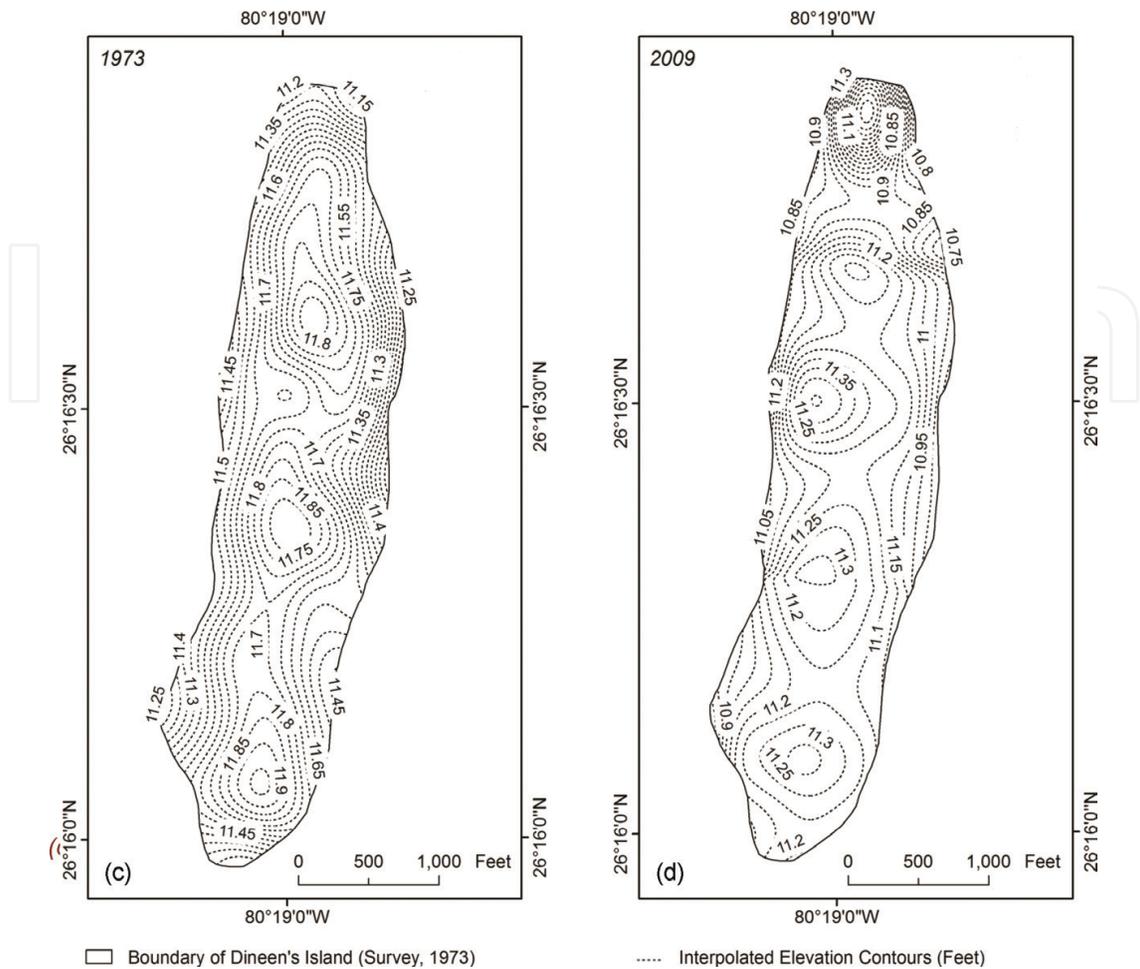
MT = metric ton.

**Table 3.** Results of the GIS analysis of the peats of the Everglades Agricultural Area [28].

were used to calculate the volume change in the head and near tail plus far tail of the tree island. The volumes were converted to SI units. Then, in combination with physical data from peat cores taken along the same transects in 2009, the calculation of the changes in peat mass, peat carbon and peat nutrients were performed (**Table 4**). Two possible explanations for why there was an increase in elevation on the small head are: 1. The two surveys did not overlay each other exactly and that the second survey captured the bedrock high or 2. Peat accretion due to the dominance of an exotic tree, Brazilian Pepper (*Schinus terebinthifolius*) accounted for an increase in soil elevation [17].



**Figure 4.** Topographic profiles of Dineen Island in 1973 and 2009 showing the change in the peat surface over 36 years. Modified from [17].

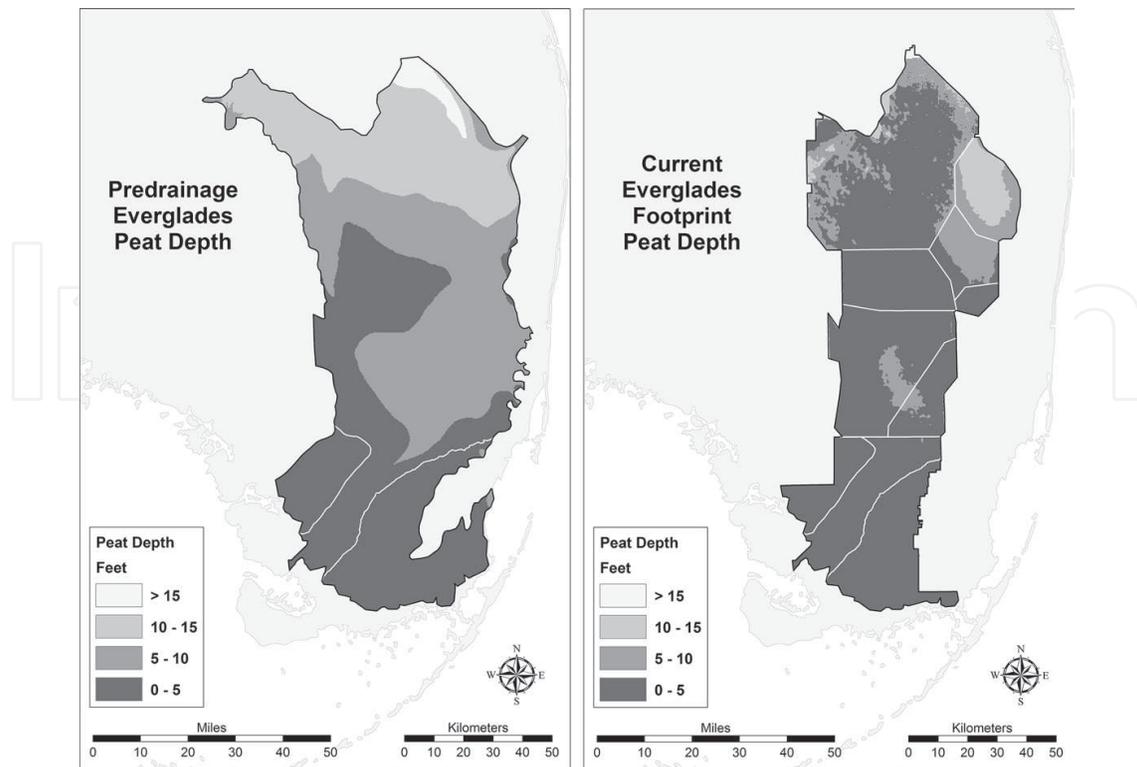


**Figure 5.** Interpolated contour maps of the peat surface of Dineen Island in 1973 (left) and 2009 (right). Modified from [17].

Hohner and Dreschel [2] utilized Data Sets #1, #2, and #3 to determine the volumes of the pre-drainage landscapes (**Figure 6**, left) and current regions (**Figure 6**, right) and the volume lost. These pre-drainage and current volumes were then combined with bulk density data from the USEPA R-EMAP [24] to calculate the corresponding masses and loss on ignition. The loss on ignition values were converted to bulk percent carbon using a conversion value of 0.51 [35] which was reported as the carbon content of the organic matter of typical peats. The results of those calculations are presented in **Table 5**. The current volumes were then compared to recent R-EMAP results [36] where 228 spatially-referenced peat depth measurements were

Dineen island analysis	Volume change (m <sup>3</sup> )	Peat mass change (MT)	Carbon change (MT)	Total phosphorus change (MT)	Total nitrogen change (MT)
Head	$5.6 \times 10^2$	57	25	0.8	1.6
Near and far tails	$-7.3 \times 10^4$	$-8.0 \times 10^3$	$-3.6 \times 10^3$	-3.1	$-2.1 \times 10^2$

**Table 4.** Results of the GIS analysis of the changes in peat on an Everglades tree island of WCA-2A between 1973 and 2009 [17].



**Figure 6.** Maps of peat depth, derived from surface elevation data sets and the bedrock map from Parker and colleagues [30]. Left: predrainage peat depths using the predrainage surface developed by Said and Brown [26]. Right: current peat depths using the current surface from the South Florida Topography Project [27].

Region	Total area (km <sup>2</sup> )	Predrainage peat volume (m <sup>3</sup> )	Current peat volume (m <sup>3</sup> )	Predrainage peat mass (MT)	Current peat mass (MT)	Predrainage peat carbon (MT)	Current peat carbon (MT)
WCA-1	$5.6 \times 10^2$	$2.0 \times 10^9$	$1.8 \times 10^9$	$1.4 \times 10^8$	$1.2 \times 10^8$	$6.5 \times 10^7$	$5.6 \times 10^7$
WCA-2A	$4.2 \times 10^2$	$9.1 \times 10^8$	$6.9 \times 10^8$	$7.7 \times 10^7$	$5.9 \times 10^7$	$3.4 \times 10^7$	$2.6 \times 10^7$
WCA-2B	$1.1 \times 10^2$	$2.2 \times 10^8$	$1.1 \times 10^8$	$3.0 \times 10^7$	$1.6 \times 10^7$	$1.0 \times 10^7$	$5.5 \times 10^6$
WCA-3AN	$7.2 \times 10^2$	$8.5 \times 10^8$	$2.2 \times 10^8$	$1.3 \times 10^8$	$3.0 \times 10^7$	$4.5 \times 10^7$	$1.1 \times 10^7$
WCA-3AS	$1.3 \times 10^3$	$1.8 \times 10^9$	$1.1 \times 10^9$	$2.5 \times 10^8$	$1.1 \times 10^8$	$7.8 \times 10^7$	$4.7 \times 10^7$
WCA-3B	$4.0 \times 10^2$	$7.2 \times 10^8$	$4.6 \times 10^8$	$1.3 \times 10^8$	$5.7 \times 10^7$	$3.2 \times 10^7$	$2.0 \times 10^7$
ENP Ochopee Marl Marsh	$3.8 \times 10^2$	$6.9 \times 10^6$	$9.2 \times 10^6$	$1.9 \times 10^6$	$2.7 \times 10^6$	$3.6 \times 10^5$	$4.8 \times 10^5$
ENP Shark River Slough	$7.7 \times 10^2$	$3.5 \times 10^8$	$2.8 \times 10^8$	$6.3 \times 10^7$	$5.2 \times 10^7$	$1.8 \times 10^7$	$1.4 \times 10^7$
ENP Eastern Marls & Taylor Slough	$9.9 \times 10^2$	$1.4 \times 10^7$	$1.2 \times 10^7$	$4.3 \times 10^6$	$4.1 \times 10^6$	$6.5 \times 10^6$	$5.0 \times 10^6$
<b>Total EPA</b>	$5.6 \times 10^3$	$6.9 \times 10^9$	$4.7 \times 10^9$	$8.2 \times 10^8$	$4.5 \times 10^8$	$2.9 \times 10^8$	$1.8 \times 10^8$

Region	Total area (km <sup>2</sup> )	Predrainage peat volume (m <sup>3</sup> )	Current peat volume (m <sup>3</sup> )	Predrainage peat mass (MT)	Current peat mass (MT)	Predrainage peat carbon (MT)	Current peat carbon (MT)
Total EAA	$2.6 \times 10^3$	$8.3 \times 10^9$	$3.5 \times 10^9$	$1.0 \times 10^9$	$5.6 \times 10^8$	$4.0 \times 10^8$	$1.6 \times 10^8$
Total EPA + EAA	$8.2 \times 10^3$	$1.5 \times 10^{10}$	$8.2 \times 10^9$	$1.9 \times 10^9$	$1.0 \times 10^9$	$6.8 \times 10^8$	$3.4 \times 10^8$

**Table 5.** Results of the GIS analysis of the original and current volumes, masses and carbon of the peats of the current Everglades footprint [2].

made across the Everglades to calculate the regional volumes remaining. The results of the comparison showed that although regionally, current volumes differed somewhat between the two, the total volume of the current EPA was the same for both methods,  $4.7 \times 10^9$  m<sup>3</sup> (see [36] and **Table 5**).

## 4. Discussion

The Everglades is one of the largest peatlands in the world, recognized internationally by being designated as a Wetland of International Importance (Ramsar Convention), an International Biosphere Reserve (UNESCO) and a World Heritage Site in Danger (UNESCO) [37]. However, for the past century and a quarter, anthropogenic modifications to the region have resulted in changes in the hydrology, chemistry and biology of the Everglades.

In particular, the Everglades experienced drying as a result of being hydrologically cut off from Lake Okeechobee in the late 1800s and early 1900s. This led to years of excessive drying of the peatland resulting in biological peat oxidation and the occurrence of peat fires. Because of this drying, the Everglades has experienced wide-spread soil loss. The amount of peat oxidation is directly related to the depth of the water table below the peat. By far, the greatest amount of peat loss has occurred in the Everglades Agricultural Area due to controlling ground water levels to enable the growth of food crops.

The loss of the peat soils in the EPA is an impact that has affected aspects of hydrology, landscapes, habitats and atmospheric chemistry, namely the increase in carbon dioxide and other greenhouse gases. Thus, the quantification of peat soil loss is important in the evaluation of the ecological and societal impacts such as water storage and climate change.

Quantification of peat soil loss has been pursued in a number of studies [6, 8, 17–22, 24, 29, 36], but current GIS technologies have only been available recently to conduct the investigation of changes in surface elevation provided by data mining historical spatial data sets. The use of GIS in combination with spatial data sets for the determination of peat loss was demonstrated by the current study for several landscapes within the Everglades of Florida. Where spatial data sets are available, this technique appears to be a viable method of estimating the changes in soil

surface and/or the underlying soil depth, even though there are many uncertainties in using historical data sets and limited point data in creating the surface elevation maps and raster grids. These limitations are discussed in detail in [2, 17, 28, 33].

The key findings from the analyses described here are:

1. Since the mid-1800s, the EPA and the EAA have experienced peat subsidence from much less than a meter to greater than 1.7 m depending upon the primary substrate of the region;
2. This subsidence has resulted in the loss of more than 10 billion cubic meters of peat from these regions;
3. Individual (ghost) tree islands have also experienced quantitatively similar peat subsidence in WCA-2A. We extrapolated this loss to all the ghost islands (total area about 22 times that of Dineen Island) [17];
4. The historical Everglades contained about 20 billion cubic meters of peat, massing approximately 2.6 billion metric tons;
5. The current EPA covers approximately half the area but has less than a quarter of the peat remaining (4.7 billion cubic meters) massing about 450 million metric tons.

We estimated that at least 1.3 billion metric tons of carbon dioxide have been emitted from the Everglades region since predrainage (1880) due to peat loss (**Table 6**). This is roughly one-quarter of the carbon dioxide emitted by the entire U.S. in 2015 (5,172,338,000 metric tons) [38]. Thus, the loss of peat carbon from the Everglades has had a significant impact on the global carbon balance.

The Central Everglades Planning Project (CEPP) [39] is a restoration project intended to fill canals and remove levees with the purpose of returning flows to specific regions of the Everglades. Although portions of the Everglades may be restored, the Everglades has lost half of the area and thus, it is impossible to fully restore it to predrainage conditions. If future restoration activities such as the CEPP are successful in keeping the remaining Everglades hydrated, further peat oxidation will be prevented and peat accretion may again be greater than loss.

Everglades region	Ghost tree islands of WCA-2A (1973–2009)	EAA (1880–2000)	WCA-1 (1885–2005)	WCA-2 (1885–2005)	WCA-3 (1885–2005)	ENP (1885–2005)	Total
Estimated carbon lost (MT)	$7.9 \times 10^4$	$2.4 \times 10^8$	$9.0 \times 10^6$	$1.3 \times 10^7$	$7.7 \times 10^7$	$4.0 \times 10^6$	$3.4 \times 10^8$
Estimated CO <sub>2</sub> emitted (MT)	$2.9 \times 10^5$	$8.8 \times 10^8$	$3.3 \times 10^7$	$4.6 \times 10^7$	$2.8 \times 10^8$	$1.5 \times 10^7$	$1.3 \times 10^9$

**Table 6.** Summary table of the estimated peat carbon lost from the current Everglades footprint and the estimated resulting carbon dioxide emissions.

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