# Late Holocene vegetation, climate, and land-use impacts on carbon dynamics in the Florida Everglades

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ABSTRACT

Tropical and subtropical peatlands are considered a significant carbon sink. The Florida Everglades includes 6000-km$^2$ of peat-accumulating wetland; however, detailed carbon dynamics from different environments within the Everglades have not been extensively studied or compared. Here we present carbon accumulation rates from 13 cores and 4 different environments, including sawgrass ridges and sloughs, tree islands, and marl prairies, whose hydroperiods and vegetation communities differ. We find that the lowest rates of C accumulation occur in sloughs in the southern Everglades. The highest rates are found where hydroperiods are generally shorter, including near-tails of tree islands and drier ridges. Long-term average rates of 100 to >200 g C m$^{-2}$ yr$^{-1}$ are as high, and in some cases, higher than rates recorded from the tropics and 10—20 times higher than boreal averages. C accumulation rates were impacted by both the Medieval Climate Anomaly and the Little Ice Age, but the largest impacts to C accumulation rates over the Holocene record have been the anthropogenic changes associated with expansion of agriculture and construction of canals and levees to control movement of surface water. Water management practices in the 20th century have altered the natural hydroperiods and fire regimes of the Everglades. The Florida Everglades as a whole has acted as a significant carbon sink over the mid- to late-Holocene, but reduction of the spatial extent of the original wetland area, as well as the alteration of natural hydrology in the late 19th and 20th centuries, have significantly reduced the carbon sink capacity of this subtropical wetland.

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## 1. Introduction

Global peatlands are the largest reservoir of soil carbon, covering only 3% of the Earth's surface but storing roughly 450—500 Gt, or one-third of the terrestrial soil carbon (Gorham, 1991; Yu et al., 2010). The waterlogged nature of these wetland soils slows decomposition, which has allowed carbon to accumulate slowly over thousands of years. Boreal and arctic peatlands cover the largest land area and have been the most extensively studied (i.e., Turunen et al., 2002; Gorham et al., 2003; Smith et al., 2004; MacDonald et al., 2006; Yu et al., 2009; Jones and Yu, 2010). Several studies have advanced understanding of long-term carbon dynamics in tropical peatlands in Indonesia (Neuzil, 1997; Page et al., 2004; Dommain et al., 2011; Page et al., 2011), Africa (Kivinen and Pakarinen, 1981; Joosten and Clarke, 2002; Page et al., 2011), and South America (Lähteenoja et al., 2009, 2013), which collectively comprise 11% of the global peatland area (Page et al.,

2011). The Florida Everglades is an expansive low-latitude peat accumulating system, but information on the long-term carbon dynamics, especially as it relates to climate, hydrology, and vegetation, is sparse. Here we examine long-term rates of carbon accumulation from four different types of wetland communities distributed throughout the Everglades to understand the role of vegetation and hydrology on carbon dynamics, and to assess how past climatic perturbations and the more recent land-use changes have impacted the ability of the Everglades to act as carbon sinks.

### 1.1. Regional setting

The Everglades ecosystem today occupies roughly 6000 km$^2$ in southern Florida, although the original extent was ~12,000 km$^2$ (Lodge, 2005). The wetland consists of a matrix of tree islands, mangrove swamps, cypress domes, marl prairies, sawgrass marshes, sawgrass ridges, and sloughs. Pliocene and Pleistocene limestone bedrock underlies the Holocene peat and marls that have accumulated on the surface (Gleason and Stone, 1994). Peat began accumulating in the Everglades ~7000 years ago in topographic low

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spots (Gleason and Stone, 1994), and hydrologic fluctuations related to global- to regional- scale changes in sea level and climate have influenced vegetation patterns. The mid-Holocene expansion of the Everglades is coeval with the establishment of many peatlands and swamps on the southeastern Atlantic and Gulf Coastal plains and can be attributed to the combined consequences of sea-level rise, orbitally driven changes in atmospheric circulation, and a stabilization of higher water tables (Willard and Bernhardt, 2011). Land-use change since the late 19th century, primarily through the installation of canals, levees, and other water-control structures, has altered the hydrology and impacted distribution of native plant communities as well as the frequency and severity of wildfires (McAvoy et al., 2011). Nearly half of the original Everglades land area has been lost to agriculture and development that began in the late 19th century, and the drainage of these areas has caused land subsidence of more than 1.5 m in some areas (Snyder and Davidson, 1994). An effort is underway to restore the natural hydrologic patterns in the Everglades by removing many of the canals and levees (CERP, 2012). Understanding past long-term carbon dynamics of the Everglades is important to anticipating the consequences of implementing the Comprehensive Everglades Restoration Plan (CERP, 2012) on the Everglades carbon storage capacity.

The subtropical climate of the Florida Everglades is characterized by hot, humid summers and mild winters. Much like tropical environments, the wet/dry cycle is more important than winter/summer temperature in controlling Everglades vegetation patterns (Richardson, 2010). The majority (70%) of the rain falls during the warmest portion of the year, from mid-May to November (average 86 cm; range 58–135 cm) (Duever et al., 1994). This seasonality is largely responsible for Everglades peat accumulation, because 81% of the Everglades water budget was historically derived from rainfall, with 8% from lake overflow and 10% from marginal overflow, and only 1% from groundwater (Harvey and McCormick, 2009). Recent changes to the hydrology have resulted in an increase to 33% of total inputs coming from surface-water inflow (Harvey and McCormick, 2009). This pattern of precipitation is driven by the movement of the Bermuda High from its location over Bermuda during the wet season to the Azores during the dry season (Stahle and Cleaveland, 1994). The El Niño Southern Oscillation (ENSO) can significantly impact rainfall patterns in South Florida. El Niño results in greater than average rainfall, while La Niña increases the prevalence of droughts across South Florida (Abtew et al., 2006). The hydrology of the region also is impacted by the multidecadal variability associated with Atlantic Multidecadal Oscillation (AMO) (Enfield et al., 2001) and the North Atlantic Oscillation (NAO). Average temperatures are greater than 27 °C from April to October in the northern Everglades and March to November in the southern Everglades, while winter temperatures average above 10 °C (Richardson, 2010).

Prior to impoundment, overland and sheet flow from Lake Okeechobee and the Kissimmee River created a mosaic of habitats, including sloughs, sawgrass ridges, tree islands, and marl prairie. Sloughs are dominated by *Nymphaea* (waterlily), *Nymphoides* (floating heart), and *Nuphar* (spatterdock) in relatively deep water and >10 months of inundation (Gunderson, 1994), while ridges (.1–.2 m higher than sloughs) are dominated by *Cladium jamaicense* (sawgrass) and are only inundated 6–9 months. Tree islands occupy the highest ground and are scattered throughout the ridge and slough landscape, comprising 14% of the Everglades today (Sklar and van der Valk, 2002). Tree islands are teardrop-shaped and oriented parallel to flow. Tree island heads are the most elevated and provide refuge for subtropical hardwood trees and shrubs (e.g., *Bursera simaruba, Rivina humilis, Eugenia axillaris, Annona glabra, Chrysobalanus icaco, Persea borbonia, Ilex* sp., *Salix carolina, Myrsine floridana,* and *Morella cerifera*) and ferns (*Acrostichum danaeifolium,*

*Blechnum serrulatum, Thelypteris kunthii*), while the near-tails (downstream from the heads) experience longer hydroperiods and the vegetation is dominated by water-tolerant hardwoods (*Morella* and *Cephalanthus*), ferns (*Osmunda regalis*), sedges, and other marsh taxa (*Sagittaria* and *Pontederia)* (Heisler et al., 2002). The strand islands of the Loxahatchee National Wildlife Refuge have a hydroperiod up to 9 months and today are largely dominated by dahoon holly (*Ilex cassine*) (Lodge, 2010), although communities historically have included ferns (*Osmunda regalis, B. serrulatum*), and shrubs and herbs (*M. cerifera, Ilex,* Amaranthaceae, Asteraceae) (Bernhardt et al., 2013).

Marl prairies have the shortest hydroperiods of all Everglades ecosystems, ranging from 2 to 9 months. The shorter hydroperiod and shallow water allow marl to precipitate, whereas the longer hydroperiods result in peat accumulation. Marl prairies have high species diversity despite being sparsely vegetated (Lodge, 2005). Those locations with 1–2 month hydroperiods are dominated by grasses such as *Schizachyrium rhizomatum,* those with 3–5 month hydroperiods are dominated by *Muhlenbergia,* and those with 6–8 month hydroperiods are dominated by *C. jamaicense* (Olmsted and Loope, 1984; Davis et al., 2005). Periphyton assemblages are dominated by filamentous cyanobacteria such as *Scytonema* and *Schizothrix* (Davis et al., 2005).

## 2. Methods

### 2.1. Core collection and sampling

Analyses were performed on 13 cores that were collected from a range of wetland communities within the Everglades, including near tails of tree islands and at least one tree island head, ridges and sloughs, and the marl prairie from 1998 to 2008 (Fig. 1). A piston corer with a 10-cm diameter barrel was used for collecting the cores. All cores were taken to bedrock, except for the one strand island core from the Loxahatchee National Wildlife Refuge, 00-3-7-1, for which basal peat was not reached. For all cores, sediment lithology was described and sediment was sampled for pollen and microscopic charcoal in 1-cm increments for the top 20 cm and 2-cm increments from 20 cm to the base of the core. All samples were oven dried at 50 °C and the dried samples were stored at room temperature.

### 2.2. Geochronology

The chronologies of these cores are based on radiocarbon dates ($^{14}$C), lead-210 ($^{210}$Pb), and pollen biostratigraphy. Radiocarbon dates were obtained from bulk sediments picked clean of roots by Beta Analytic and converted to calendar years using Calib 6.0 using the IntCal09 calibration curve (Reimer et al., 2011). Bulk samples were used for radiometric dating because identifiable plant macros, like seeds, could not be found, as the peat was very decomposed. Using bulk dates in such a setting does invite the potential that the peat could incorporate older carbon and consequentially yield an anomalously older date. For most records, the chronology for the last 100 years is based on the first occurrence of the pollen of the invasive species *Casuarina equisetifolia,* which was introduced to South Florida at about AD 1900 (Langeland, 1990). Where possible based on the amount of available material, we also used $^{210}$Pb (lead-210) to constrain the last century of deposition. Lead-210 accumulation rates were calculated making the assumption of a constant initial excess $^{210}$Pb concentration (CIC model).

### 2.3. Pollen

Most pollen records associated with the cores analyzed for carbon analysis have been previously published. The tree island