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Linking Hydrology, Climate and CO_2 Dynamics in Everglades Freshwater Marsh Ecosystems

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Abstract

Although wetlands have large carbon sequestering potentials that could potentially serve as a negative feedback to climate change; they are threatened globally by anthropogenic pressures. In particular, water management has greatly altered one of the largest freshwater marsh ecosystems in North America, the Florida Everglades. Here we review the links between hydrology climate and carbon dioxide (CO_2) dynamics in Everglades freshwater marsh ecosystems, which are estimated to be near CO_2-neutral (-110 to 80 g C m^{-2} yr^{-1}; negative net ecosystem exchange (NEE) values indicate ecosystem uptake of CO_2) and sensitive to shifts in climate and hydrology. As Hydroperiods are likely to change in the future with water management and climate change, it is extremely important to understand the complex relationships between hydrology, climate, CO_2, and how these interactions influence ecosystem resilience.

ABBREVIATIONS

C: Carbon; CERP: Comprehensive Everglades Restoration Plan; CO_2: Carbon Dioxide; NEE: Net Ecosystem Exchange; GEE: Gross Ecosystem Exchange; R_{eco}: Ecosystem Respiration; ENSO: El Niño Southern Oscillation

INTRODUCTION

Wetlands are one of the largest components of the terrestrial carbon (C) pool [1-3] as a result of hydric conditions that slow decomposition and allow C to accumulate in the soil over long time periods [1,4,5]. Globally wetlands are being reduced as a result of land cover change (i.e., agriculture and development) [6], creating great uncertainty in the stability of this large carbon pool. One of the largest (~700,000 ha) freshwater marsh ecosystems in North America, the Florida Everglades has been altered by water control structures and land cover change which is likely to have impacted the C sequestering capacity of this region.

The unique mosaic of wetland ecosystems of the Everglades was shaped by the historic hydrology of the south Florida region [7]. Hydroperiods were historically a function of precipitation throughout the Kissimmee-Okeechobee-Everglades ecosystems [7,8], which varied seasonally leading to a wet and dry season [7]. During the wet season, Lake Okeechobee would overflow causing surface flow to travel south through the Everglades and out to Florida Bay [7,9]. Small variations in elevation throughout the landscape determined the degree of exposure to surface flow making the position within the landscape important in understanding seasonal patterns in hydrology [7,10].

Since the early 1900s, the hydrologic regime in this subtropical system has been altered by 2500 km of spillways, levees and canals [7,11] that were designed for flood protection, to make land available for agriculture and urbanization, and to provide water to south Florida. The severe decline in water flowing into the Everglades led to a decrease of 1.2 m in the average water table depth in freshwater marsh ecosystems [12] and has changed the natural characteristics of these wetland ecosystems [7,10]. Characteristics consistent with chronically reduced water levels (i.e. peat subsidence reduced marl accretion rates, exotic species encroachment and altered fire regimes, higher abundance of woody and herbaceous species) are evident in southern sections of the Everglades. Water resources are currently being re-distributed under the Comprehensive Everglades Restoration Plan (CERP) to re-establish water levels and hydroperiods closer to natural regimes and to ameliorate areas that suffer from chronically low water levels [13].

In the Everglades region hydroperiods are likely to change in the future with CERP and climate change. To understand how these changes are likely to affect freshwater marsh ecosystems, this review explores the complex relationships between climate, hydrology and CO_2 in the Everglades freshwater marshes.

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Climate and Hydrology

The Everglades is a subtropical system with wet and dry seasons that produce variation in the hydrologic cycle that affect nutrient delivery, ecosystem primary production, and ecosystem structure [7]. Surface fluxes, sensible heat (H) and latent energy (LE) drive seasonal patterns in water level through their influence on water loss as LE (evapotranspiration: (ET)) and convective rain, the main source of wet season precipitation [9]. During the dry season, the Bermuda High pressure cell prevents convective clouds from forming thunder storms making continental fronts the main source of precipitation [14]. The switch from wet season tropical climate to dry season temperate climate causes distinct changes in the amount of precipitation in the region [14] and combined with constant water loss as LE produces seasonal fluctuations in water levels [7,9]. Hydroperiods and wet season length vary annually in the Everglades and are positively correlated with precipitation in January to March [15].

CO_2 Dynamics in Everglades Freshwater Marsh

Hydrology is an important factor in C cycling [16-20], which directly impacts productivity [21-23], decomposition rates, CH_4 production and oxidation [18,24-27], $CaCO_3$ precipitation [7] and CO_2 sequestration [28]. Through processes tightly coupled with hydro periods, C is maintained as peat and marl in the Everglades [7]. Peat accumulates in marshes with deep water and long hydro periods, overlying permeable limestone substrate [9]. In areas with short hydroperiods and seasonal drying, marl substrate derived from algal carbonate precipitation in periphyton mats develops [29]. Prior to the last 100 years, the Everglades were a net sink for organic C as peat accreted to depths of 1–3 m. Throughout freshwater marsh ecosystems marl and peat accretion rates are lower than in the past [30,31], suggesting that changes in hydrology have altered the CO_2 sequestering capacity of these systems [29].

Annually and seasonally, precipitation and water levels vary substantially with climate patterns [7], leading to fluctuations in ecosystem CO_2 exchange rates [15,23,28,29]. Continuous measures of CO_2 fluxes show that Everglades freshwater marsh are nearly CO_2 neutral (-110 to 80 g C m^{-2} yr^{-1}; negative net ecosystem exchange (NEE) values indicate ecosystem uptake of CO_2) annually though they exhibit distinct seasonal patterns that are driven by water levels [15,29]. Hydroperiods have shaped soil conditions and species composition in Everglades's freshwater marsh ecosystems in ways that led to different seasonal patterns in CO_2 exchange rates [15,23,28]. Short hydroperiods marsh ecosystems (~ 9 months of inundation annually) are generally a small sink for CO_2annually (-110 to -6 g C m^{-2} yr^{-1}), and are often a source for CO_2 during the wet season and a sink during the dry season [15,23,28]. Long hydroperiod marsh ecosystems (~12 months of inundation annually) are normally a small source of CO_2 annually (-16 to 80 g C m^{-2} yr^{-1}) with greater rates of CO_2 uptake during the wet season [29]. As water levels decline, ecosystem respiration (R_{eco}) increases relative to CO_2 uptake (GEE) in the dry season and longer dry seasons are associated with greater CO_2 source status. In both short and long hydroperiods freshwater marsh, ecosystem respiration is the primary control on annual ecosystem CO_2 balance [15,28].

Although patterns in NEE rates differ, both short and long hydroperiods freshwater marsh exhibit higher photosynthetic capacity and a greater release of CO_2 with increasing temperature in the dry season [28]. Dry season length (and changes in dry season length) controls the CO_2 source and sink status of freshwater marsh [15]. As water levels decline, a greater response in NEE is observed [15,28]. Standing water buffers temperature effects, and reduces leaf area exposure to photosynthetically active raditation (PAR). With lower water levels the short hydroperiod's sites exhibits marked differences in seasonal response to PAR and air temperature compared to the long hydroperiod freshwater marsh [28].

Due to its effects on hydrology, extreme climate patterns also influence interannual variation in CO_2 exchange rates within the Everglades [15,32]. Phase changes in the El Niño Southern Oscillation (ENSO) co-occur with precipitation, water depth, and CO_2 flux anomalies in the Everglades [7]. El Niño phases increase dry season rainfall, resulting in higher seasonal and annual water levels [33,34] and La Niña phases reduce dry season rainfall, leading to extreme drought [33-36].In abnormally dry years that are associated with La Niña, the wet season is shortened by 15 to 34 days[15]. As a result of its effects on hydrology, ENSO phases magnify seasonal patterns in CO_2 exchange rates, and differences in season length and intensity explain inter-annual fluctuations in NEE, R_{eco}, and GEE [15].

Low-temperature episodes (<5°C) have also been shown to impact CO_2 dynamics in Everglades freshwater marsh ecosystems, where both water levels and distance from the coast influence exposure and response to low-temperature episodes. Photo synthetically active radiation increases on days where temperatures fall below 5°C leading to an enhanced photosynthetic capacity [32]. With higher water levels buffering extreme temperatures, the long hydroperiods freshwater marsh generally has a lower frequency of low temperature episodes and gaines 1.59 g C m^{-2} per low-temperature episode, while the short Hydroperiods freshwater gains just 0.06 g C m^{-2} per low-temperature episode^{-1} [32]. As climate change projections suggest that the frequency of low-temperature episodes will decline in the Everglades region, it is likely that old-sensitive species will increase in density, reducing landscape heterogeneity and increasing ecosystem sensitivity to low-temperature events.

Climate Change

Climate change could be particularly severe in freshwater marsh ecosystems [37,38], where exchanges of energy and mass are tightly coupled. As a result of its effects on hydrology, freshwater marsh are among the most vulnerable ecosystems when faced with climate change [37,38]. Changes in precipitation, air temperature, atmospheric CO_2 concentrations and sea level rise have the potential to alter CO_2 dynamics, which feedback to global climate change. Patterns in precipitation have important influences on the hydrology of freshwater marsh [15], while air temperature affects hydrology, gas exchange, and metabolic rates. Higher atmospheric concentrations of CO_2 are likely to enhance productivity rates [38], though the extent and duration of this enrichment effect would vary with species and nutrient concentrations. In freshwater systems with a close proximity to the coast, sealevel rise is of great concern and increase saltwater

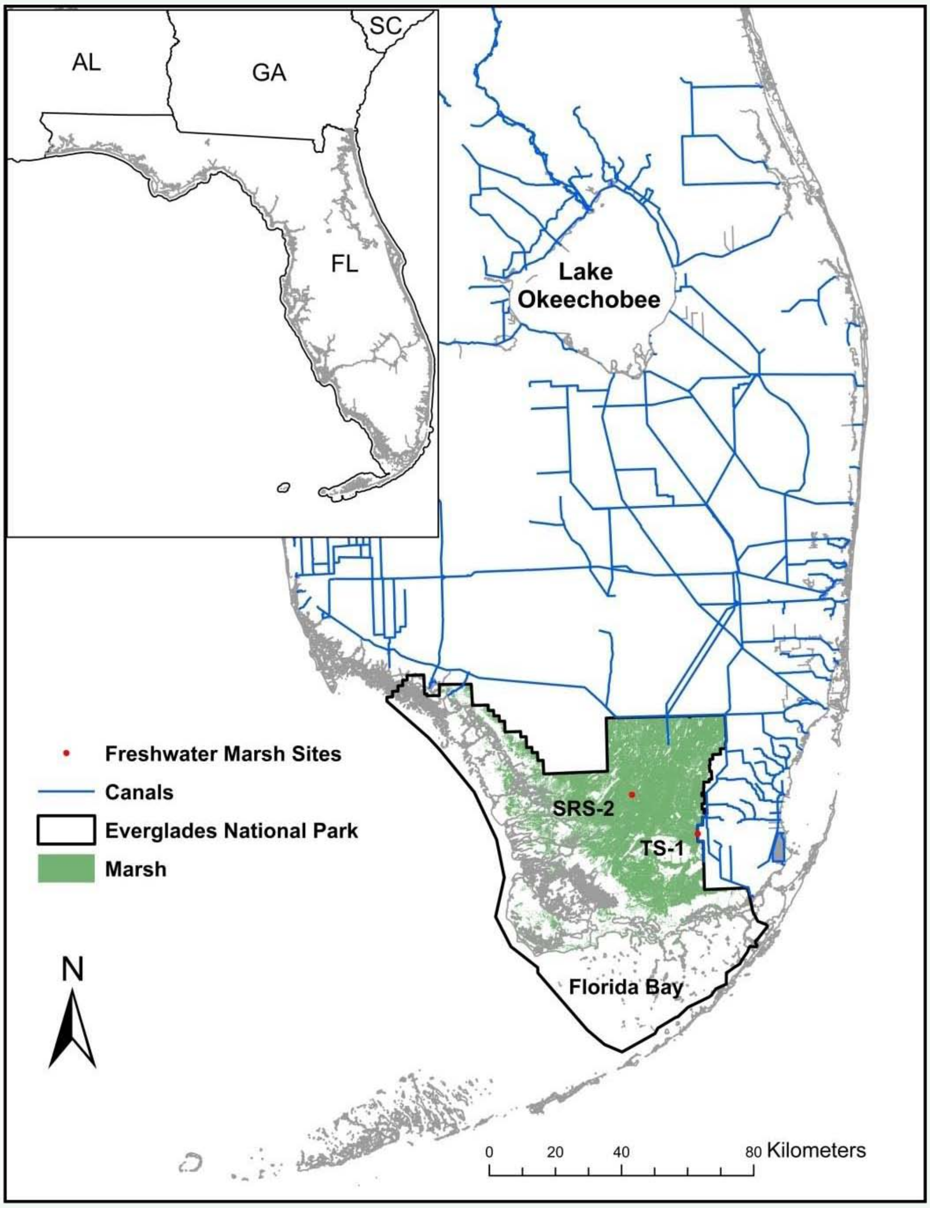

Figure 1 Marsh ecosystems (green) in Everglades National Park, Florida, USA. Canals (blue) show the flow of water from Lake Okeechobee in central Florida to Everglades National Park. Eddy covariance tower sites (red) measure CO_2 flux continuously, within long (Shark River Slough; SRS-2) and short (Taylor Slough; TS-2) hydroperiod freshwater marsh ecosystems. GIS layers were obtained from the Florida Coastal Everglades Long Term Ecological Research data portal (http://fcelter.fiu.edu/data/FCE/).

intrusion and could lead to wetland type conversions [39].

Changes in seasonal precipitation patterns and temperature are expected with climate change in the Everglades region [40,41]. Although annual precipitation is expected to rise, wet season precipitation is projected to decline by 5 to 10% [42], and summer months in the Everglades region will become drier [40,41]. Greater annual precipitation is predicted to occur with warming (+1 to +4.2°C by 2100) [41], and is associated with larger convective storms and higher intensity hurricanes [34,41]. Shifts in wet season length (-1 to 7 days) [30] and intensity as a result of climate change will likely become one of the most important factors affecting CO_2 dynamics in the Everglades region [15]. However the hydrologic regime and oligotrophic condition of Everglades freshwater marsh are thought to lower the ecosystem sensitivity to climate change, reducing the exposure and vulnerability to change and protecting soil C pools [30]. Longer dry periods in between heavier precipitation events are also projected for the Everglades region [40,41,43] where increased drought frequency stands to have a significant effect on the greenhouse warming potential of Everglades ecosystems [44]. The increase in drought frequency and intensity in the future could potentially turn subtropical wetland ecosystems into sources of carbon as ecosystem productivity is reduced by water stress and C stored in the soil becomes oxic for longer periods of time [44].

Using simulation models, the results of projected climate

Table 1: Seasonal and annual NEE, GEE, and R_{eco} (g C m^{-2} yr^{-1}) at long (Shark River Slough; SRS-2) and short (Taylor Slough; TS-1) hydro period freshwater marsh ecosystems. Seasons with a La Niña or El Niño phase are marked with an * and ω, respectively.

		Taylor Slough (TS-1)								**Shark River Slough (SRS-2)**						
Year	**Season**	**NEE (S.E)**		**GEE (S.E)**		**R_{eco} (S.E)**		**Days Below <5 °C**	**ENSO**	**NEE (S.E)**		**GEE (S.E)**		**R_{eco} (S.E)**		**Days Below <5 °C**
2009	Dry	-30	6	-262	6	232	7	5	*	66	11	-163	12	229	5	2
	Wet	19	8	-194	7	213	9		ω	14	4	-198	5	212	5	
	Annual	-11	14	-456	13	445	16			80	15	-361	17	441	10	
2010	Dry	-19	6	-199	4	180	5	20	ω	-11	3	-249	3	238	2	15
	Wet	14	7	-219	6	233	7		*	-5	8	-92	7	88	6	
	Annual	-5	13	-419	10	413	12			-16	12	-342	11	326	8	
2011	Dry	-56	13	-303	14	247	12	2	*	17	13	-231	7	248	11	1
	Wet	-55	15	-309	12.8)	254	15		*	60	7	-152	7	211	7	
	Annual	-111	28	-611	27	501	27			76	20	-383	14	459	18	
2012	Dry	-75	8	-250	8	175	8	4	*	56	5	-116	3	172	3	0
	Wet	32	8	-123	8	155	8			9	7	-137	5	146	5	
	Annual	-44	16	-373	16	329	16			65	12	-253	8	317	8	
2013	Dry	-1	5	-119	4	119	5	5		-4	2	-98	2	93	3	1
	Wet	-30	7	-147	5	117	6			6	5	-138	4	144	4	
	Annual	-31	11	-266	8	236	10			2	8	-236	6	238	7	

Abbreviations: NEE: Net Ecosystem Exchange; GEE: Gross Ecosystem Exchange; R_{eco}: Ecosystem Respiration; ENSO: El Niño Southern Oscillation

change (precipitation, temperature, and atmospheric CO_2) indicates that there may be slight shifts in the start and length of the wet season (-1 to +7 days) and a small enhancement in the sink capacity (by -169 to -573 g C m^{-2} $century^{-1}$) of both short and long hydroperiods ecosystems compared to CO_2 dynamics under the current climate regime. Over 100 years, rising temperatures increase net CO_2 exchange rates (+1 to 13 g C m^{-2} $century^{-1}$) and shifts in precipitation patterns alter cumulative net carbon uptake by -46 to +13 to g C m^{-2} $century^{-1}$.

In the Florida Everglades sea levels are projected to rise from 0.25 to 0.35 m between 2006 and 2080 [45,46]. With over half of the Everglades less than 1 m above sea level, sea level rise could have a profound influence on the future structure and function of wetlands in this region [47,48]. Declines in productivity have been shown to occur with increases in salinity in Everglades sawgrass (*Cladium mariscus*subsp. *jamaicense* (Crantz) Kük*)* dominated systems, suggesting that an increase in saltwater intrusion could impact freshwater marsh productivity and is likely to initiate shits in species composition [21].

Vulnerability of freshwater marsh to climate change varies across marsh types and depends on how sensitive the vegetation and hydrology are to shifts in the climate regime. Climate change simulations for temperature, precipitation and atmospheric CO_2 concentrations in Everglades freshwater marsh show that the hydrologic regime and oligotrophic condition lowers the ecosystem sensitivity [30]. Although the Everglades are resilient to shifts in climate, sea level rise and changes in the disturbance regime may be the driving force of change in the Florida Everglades.

CONCLUSION

Hydroperiods are likely to change in the future with the implementation of CERP and climate change, making it extremely important to understand the complex relationships between hydrology, climate, CO_2, and how these relationships influence ecosystem resilience. An important feature of wetland resilience is recovery following disturbance events or the successful shift from one wetland type to another. Studies have shown that wetland resilience is a function of good flushing by either fresh or saline waters [49]. Where flow and flushing diminish, communities collapse [49,50], which is true for the long-term maintenance of freshwater marsh communities in the Everglades. Improved freshwater flow, through CERP, is expected to aid in the recovery of freshwater marsh from catastrophic setbacks (from hurricanes, fire, freeze, and salinity changes). The CERP could re-establish the seasonal patterns in water depth closer to natural levels, decreasing the system's sensitivity to climate fluctuations, and securing hydric conditions required to maintain soil C pools.

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