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**Controls on ecosystem carbon dioxide exchange in short- and long-hydroperiod**

**Florida Everglades freshwater marshes**

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1 **Abstract**

2 Although freshwater wetlands are among the most productive ecosystems on Earth, little is  
3 known of carbon dioxide (CO<sub>2</sub>) exchange in low latitude wetlands. The Everglades is an  
4 extensive, oligotrophic wetland in south Florida characterized by short- and long-  
5 hydroperiod marshes. Chamber-based CO<sub>2</sub> exchange measurements were made to  
6 compare the marshes and examine the roles of primary producers, seasonality, and  
7 environmental drivers in determining exchange rates. Low rates of CO<sub>2</sub> exchange were  
8 observed in both marshes with net ecosystem production reaching maxima of 3.77 and  
9 4.28 μmol CO<sub>2</sub> m<sup>-2</sup> s<sup>-1</sup> in short- and long-hydroperiod marshes, respectively. Fluxes of CO<sub>2</sub>  
10 were affected by seasonality only in the short-hydroperiod marsh, where flux rates were  
11 significantly lower in the wet season than in the dry season. Emergent macrophytes  
12 dominated fluxes at both sites, though this was not the case for the short-hydroperiod  
13 marsh in the wet season. Water depth, a factor partly under human control, significantly  
14 affected gross ecosystem production at the short-hydroperiod marsh. As Everglades  
15 ecosystem restoration proceeds, leading to deeper water and longer hydroperiods,  
16 productivity in short-hydroperiod marshes will likely be more negatively affected than in  
17 long-hydroperiod marshes. The Everglades stand in contrast to many freshwater wetlands  
18 because of ecosystem-wide low productivity rates.

19

20 **Keywords:** carbon dioxide exchange; Everglades; productivity; water management;  
21 wetland

## 1 **Introduction**

2        Freshwater wetlands are unique ecosystems that provide important ecosystem services  
3 including regulation of biogeochemical cycling, provision of habitat for distinctive species,  
4 and flood control (Gopal et al. 2000; Zedler and Kercher 2005; Keddy et al. 2009). Globally,  
5 wetlands are threatened by human activities such as residential and urban development, as  
6 well as agricultural expansion (Dugan 1993; Dahl 2011). In the conterminous United  
7 States, approximately half of all wetlands were lost by the 1970s (Mitsch and Gosselink  
8 2007). As increased attention has focused on wetland conservation and research in recent  
9 decades, carbon cycling and storage have emerged as areas of particular interest. Wetlands  
10 are among the most productive ecosystems in the world, responsible for approximately  
11 6.3% of terrestrial net primary production (Houghton and Skole 1990; Neue et al. 1997;  
12 Keddy 2000).

13        Most knowledge of wetland carbon dioxide (CO<sub>2</sub>) exchange in non-agricultural,  
14 freshwater systems is focused on mid- and high-latitude regions of the world (e.g. Bubier et  
15 al. 1998; Hirota et al. 2006; Roulet et al. 2007; Rocha and Goulden 2008; Dusek et al. 2009).  
16 Research over the course of the past decade has begun to explore CO<sub>2</sub> exchange in the  
17 tropics and sub-tropics (e.g. Morison et al. 2000; Jones and Humphries 2002; Jauhiainen et  
18 al. 2005; Schedlbauer et al. 2010; Wright et al. 2011), but our knowledge of exchange rates  
19 and their controls remains limited. There is much to be learned about carbon dynamics in  
20 low latitude wetlands with year-round growing seasons and seasonality defined by wet and  
21 dry periods.

22        The Everglades is a large (>6,000 km<sup>2</sup>) subtropical wetland located in south Florida  
23 (Davis et al. 1994). The Everglades landscape has been subject to hydrologic management

1 for more than a century, and water flows are regulated by canals, levees, and flow control  
2 structures (USACE and SFWMD 1999). As a result of anthropogenic alterations, the  
3 Everglades now occupies half of its former spatial extent (Light and Dineen 1994). In  
4 addition, hydrologic modification has reduced water levels and hydroperiods (i.e., the  
5 duration of inundation) relative to historical levels (Light and Dineen 1994). Current  
6 construction proceeding under the Comprehensive Everglades Restoration Plan (CERP) is  
7 intended, in part, to reverse these patterns. It is likely that plant community composition  
8 and productivity will change in response to these alterations in the timing and quantity of  
9 water delivery (Armentano et al. 2006; Childers et al. 2006a).

10 Short- and long-hydroperiod marshes are the two principal freshwater wetlands found  
11 in the Everglades, and both are oligotrophic (Noe et al. 2001; Lodge 2005; Childers et al.  
12 2006b). Short-hydroperiod marshes experience annual dry periods during which the  
13 water table falls below the soil surface, while long-hydroperiod marshes are typically  
14 inundated year-round. As such, the soils and communities of primary producers in these  
15 marshes are quite different. Short-hydroperiod marshes are characterized by marl  
16 (calcium carbonate) soils, and the plant community is dominated by a relatively uniform  
17 grass-sedge canopy (Davis et al. 2005). In contrast, long-hydroperiod marshes have peat  
18 soils and topography typified by sparsely vegetated sloughs and densely vegetated ridges  
19 (Ogden 2005). Both types of marshes contain an additional group of primary producers,  
20 periphyton, though biomass is much higher in short-hydroperiod marshes than in long-  
21 hydroperiod marshes (Gottlieb et al. 2006).

22 Despite ecosystem oligotrophy, high rates of ecosystem productivity have been  
23 reported in both short- and long-hydroperiod Everglades freshwater marshes (Ewe et al.

1 2006). However, prior studies have not directly compared rates of CO<sub>2</sub> exchange between  
2 these contrasting ecosystems, nor have they evaluated the roles of primary producers and  
3 climatic factors in driving rates of CO<sub>2</sub> exchange. It is essential to understand these factors,  
4 particularly in light of Everglades ecosystem restoration activities currently underway.  
5 Three principal research questions were addressed in the present study: (1) How are net  
6 ecosystem production (NEP), ecosystem respiration (ER), and gross ecosystem production  
7 (GEP) affected by both seasonality and the experimental removal of a primary producer  
8 group (i.e., macrophytes or periphyton) in short- and long-hydroperiod marshes? (2) How  
9 do ecosystem CO<sub>2</sub> exchange rates vary between short- and long-hydroperiod marshes? (3)  
10 What environmental factors are the key drivers of NEP, ER, and GEP, and do these factors  
11 vary between short- and long-hydroperiod marshes?

12

## 13 **Methods**

### 14 *Study Sites*

15 This research was conducted at two study sites (Fig. 1), a short-hydroperiod marsh  
16 located within Taylor Slough at 25°26'16.50"N 80°35'40.68"W (a site hereafter referred to  
17 as TS) and a long-hydroperiod marsh located within Shark River Slough at 25°33'6.72"N  
18 80°46'57.36"W (a site hereafter referred to as SRS). Taylor and Shark River Sloughs are  
19 the two major drainages of Everglades National Park, and the research described in the  
20 present study was conducted prior to the initiation of any CERP-related restoration  
21 activities. Mean annual temperature is 23.9°C and average rainfall is 143 cm per year  
22 (NCDC 2009). Climate in south Florida is best characterized by wet and dry seasons (Beck  
23 et al. 2006; Kottek et al. 2006) with the majority of the annual precipitation falling between

1 May and October. Wet season precipitation is delivered via convectively formed clouds or  
2 during the passage of tropical storms and hurricanes (Duever et al. 1994). Dry season  
3 precipitation typically coincides with the passage of cold fronts over the Florida peninsula.

4 The TS site is a seasonally inundated freshwater marsh with a typical hydroperiod of  
5 ~5 months per year (Schedlbauer et al. 2010). This site is characterized by shallow (0.14  
6 m), marl soils, and the vegetation is dominated by sawgrass (*Cladium jamaicense*) and  
7 muhly grass (*Muhlenbergia capillaris*). Vegetation is short-statured, reaching only 0.73 m  
8 above the soil surface. There is no seasonal variation in leaf area index ( $1.8 \text{ m}^2 \text{ m}^{-2}$ ), or in  
9 the aboveground biomass of one of the co-dominant plant species, *C. jamaicense*  
10 (Schedlbauer et al. 2010). Periphyton is present at the site, and mats of periphyton begin  
11 to grow substantially ~2 months into the wet season, forming dense “sweaters” around  
12 submerged vegetation. When the site is dry, the periphyton exists as a desiccated mat,  
13 often suspended in strands between individual plants and sometimes covering the soil  
14 surface. Together, periphyton and submerged macrophytes contribute to the geochemical  
15 fixation of CO<sub>2</sub> as calcium carbonate during periods when the site is inundated. Seasonality  
16 at TS is best defined by whether or not the site is inundated rather than climatic seasonality  
17 because the two do not always coincide (Schedlbauer et al. 2010).

18 The SRS site is also a freshwater marsh, but is usually inundated year-round and is  
19 characterized by ridge and slough topography (Ogden 2005). Soils are composed of peat  
20 deposits that are 0.73 m deep within ridges and 0.66 m deep within sloughs. The  
21 vegetation at SRS is different from that found at TS. *C. jamaicense* is dominant in ridge  
22 areas, and a mixture of emergent spikerush (*Eleocharis* sp.), emergent panic grass  
23 (*Panicum* sp.), and submerged bladderwort (*Utricularia* sp.) species dominate the sloughs.

1 Vegetation height on ridges averages 1.34 m above the soil surface, while slough vegetation  
2 is approximately 0.70 m above the soil. Periphyton is also present at SRS, floating at or  
3 beneath the water surface, often in association with submerged vegetation. Seasonality at  
4 this long-hydroperiod marsh is best defined by south Florida's climatic seasonality because  
5 the site is typically inundated year-round. As such, there are slight mismatches in  
6 seasonality between TS and SRS (Fig. 2A).

7 The TS and SRS sites are the locations of eddy covariance towers that are part of the  
8 AmeriFlux network. At the towers, measurements of air temperature ( $T_{\text{air}}$ ), relative  
9 humidity (HMP45C, Vaisala, Helsinki, Finland), and photosynthetically active radiation  
10 (PAR, PAR Lite, Kipp and Zonen, Delft, Netherlands) were made every 15 s and averaged at  
11 30 min intervals. Measurements were logged using both CR1000 and CR10X data loggers  
12 (Campbell Scientific, Logan, UT). Measurements of water depth were made at both sites  
13 with water level recorders installed in PVC wells (HOBO U20-001-01).

#### 14 *Field Measurements*

15 Monthly chamber measurements of ecosystem  $\text{CO}_2$  exchange were made at both sites  
16 for a period of approximately one year. Measurements of NEP and ER were made with  
17 custom-made polycarbonate chambers. The chamber used at TS was  $0.208 \text{ m}^3$  (50.8 cm  $\times$   
18 50.8 cm  $\times$  80.6 cm), while that used at SRS was  $0.310 \text{ m}^3$  (50.8 cm  $\times$  50.8 cm  $\times$  120.0 cm).  
19 Chamber height varied to accommodate differences in vegetation height at the two sites.  
20 Each chamber was fitted with a 4+ m vent tube, a capped vent to aid in pressure  
21 equilibration while seating the chamber, and an aluminum angle bar base covered with  
22 closed-cell foam. Two box fans were affixed to the inside top of each chamber and were

1 run constantly during measurement periods to ensure that air within the chambers was  
2 well mixed. Chambers were configured for non-steady state, flow-through measurements.

3 During measurement periods, the chamber was coupled to a custom-made system to  
4 measure chamber CO<sub>2</sub> concentration. This system included a LI-840 CO<sub>2</sub>/H<sub>2</sub>O infrared gas  
5 analyzer (LI-COR, Inc., Lincoln, NE) coupled to a CR10X datalogger (Campbell Scientific,  
6 Logan, UT) that recorded CO<sub>2</sub> concentration every second. Air was drawn into the LI-840  
7 with a pump (UNMP 105B, KNF Neuberger, Trenton, NJ) located downstream from the  
8 analyzer. The flow rate was maintained at slightly <1 liter per minute with a rotameter  
9 (VFA-22-SSV, Dwyer Instruments, Inc.) located upstream from the LI-840. Air was  
10 circulated between the chamber and LI-840 through tubing (Bev-A-Line IV, Thermoplastic  
11 Processes, Stirling, NJ). Measurements of PAR (LI-210, LI-COR, Inc., Lincoln, NE) were also  
12 recorded by the datalogger at 1 s intervals during measurement periods.

13 When measurements were made, the chamber was placed over the measurement  
14 location and checked to ensure that there was a leak-free seal at the base of the chamber.  
15 After a 1 min equilibration period, a 1 min measurement period commenced.  
16 Measurements of NEP were made under full-sun conditions and ER was measured with a  
17 black nylon cloth placed over the chamber. Chamber measurements were typically made  
18 between 10 AM and 1 PM. The chamber was always vented between measurements to  
19 ensure that CO<sub>2</sub> concentration, T<sub>air</sub>, and humidity remained as close to ambient conditions  
20 as possible. When water was present at the study sites, water depth was measured at each  
21 measurement location so that chamber volume could be adjusted accordingly.

22 The chamber measurement technique and experimental design varied between study  
23 sites. In particular, different manipulative treatments were applied at each site to evaluate



1 the roles of primary producers (i.e., macrophytes and periphyton) in determining CO<sub>2</sub>  
2 exchange rates. At TS, a periphyton removal treatment was carried out in the dry season.  
3 This treatment did not substantially disturb macrophytes and facilitated repeated  
4 measurements over time (see below). However, at SRS the site was continually inundated  
5 during measurement periods, and it was not possible to remove submerged periphyton  
6 growing in close association with macrophytes. As a result, an above-water macrophyte  
7 removal treatment was applied to plots that were first measured in an undisturbed state  
8 (see below).

9 At TS, ten polyethylene bases (50.8 cm × 50.8 cm × 15.2 cm) were constructed and  
10 seated in marl soil at the outset of the experiment. Bases were inserted an average of 3.8  
11 cm into the soil and were allowed to settle for at least two weeks prior to the start of the  
12 experiment. Five bases served as controls and were not manipulated in any way. Five  
13 additional bases were the treatment bases, subjected to the periphyton removal treatment.  
14 During the dry season, periphyton was carefully removed from plants and the soil surface  
15 by hand. Periphyton was removed only to the extent that it did not disturb the soil surface  
16 or vegetation within each base. As such, a small amount of periphyton remained within  
17 each of the treatment bases. No attempt was made to remove periphyton from within the  
18 bases during periods of inundation or immediately after the water level dropped below the  
19 soil surface. Periphyton grew in such close association with the vegetation and soil that  
20 removal would have led to a high degree of disturbance.

21 During measurements at SRS, the site was constantly inundated with water, often  
22 reaching 40+ cm above the soil surface (Fig. 2A). As a result, no bases were seated in the  
23 soil. Instead, a float was constructed from a piece of foamboard and the chamber was

1 placed over a 50.8 cm × 50.8 cm hole in the board. This allowed the chamber to float above  
2 the area of marsh that was to be measured. Chamber measurement plots were randomly  
3 selected on each visit to the site and control (i.e., unmanipulated) measurements of NEP  
4 and ER were made at each plot. Subsequent to these measurements, all emergent  
5 macrophytes within the plot were clipped just beneath the water surface so that NEP and  
6 ER could then be measured in treated plots. Clipped macrophytes were returned to the lab,  
7 dried at 70°C for 48 hours, and weighed.

8 Chamber measurements were made regularly at TS over the period from April 2008  
9 through August 2009. Measurements at SRS began later and occurred on fewer dates  
10 because of limited site access during periods with low water levels. The SRS site is remote  
11 and chamber measurements could be made only when the site was accessible by airboat.

#### 12 *Data Processing and Statistical Analyses*

13 Measurements of CO<sub>2</sub> concentration within the chamber during a measurement period  
14 were plotted as a function of time, and linear regression was used to determine the rate of  
15 change in CO<sub>2</sub> concentration over each 1 min measurement period (i.e., the slope of the  
16 relationship). These data were then used to determine CO<sub>2</sub> flux rates in μmol m<sup>-2</sup> s<sup>-1</sup> as,

$$17 \text{ CO}_2 \text{ flux} = (dC/dt) \times ((p_a V)/(T R A))$$

18 where dC/dt is the slope described above, p<sub>a</sub> is atmospheric pressure (Pa), V is chamber  
19 volume (m<sup>3</sup>), T is temperature (K), R is the gas constant (8.3143 J mol<sup>-1</sup> K<sup>-1</sup>), and A is  
20 chamber area (m<sup>2</sup>). Chamber volume was allowed to vary with water level at each  
21 measurement location.

22 Individual measurements of NEP and ER at each base or plot location were used to  
23 determine gross ecosystem production (GEP) as,

1  $GEP = NEP - ER$

2 where positive values indicate CO<sub>2</sub> uptake by the ecosystem and negative values indicate  
3 CO<sub>2</sub> release from the ecosystem.

4 The statistical analyses described below were performed with R (version 2.13.0, The R  
5 Foundation for Statistical Computing, 2011). The effects of the experimental treatments  
6 and seasonality on NEP, ER, and GEP at both sites were examined with linear mixed-effects  
7 models (Schabenberger and Pierce 2002). The fixed effects at both sites were treatment  
8 (at TS: periphyton removal and control, at SRS: macrophyte removal and control), season  
9 (wet and dry), and the treatment by season interaction term. The random effect at both  
10 sites was measurement location (at TS: base location, at SRS: measurement plot). At TS,  
11 periphyton removal treatment measurements were eliminated from the dataset for all  
12 dates more than two months into the wet season. As described above, it was not possible  
13 to remove periphyton from within the bases after this time. Therefore, the analysis of the  
14 experimental treatment at TS was only for the mid to late dry season and early wet season.  
15 The mixed-effects statistical design accommodated an unbalanced study design. In  
16 addition to the late-wet season and early dry season data that were eliminated at TS, the  
17 weather occasionally made it impossible to complete a full set of chamber measurements.

18 Analysis of variance (ANOVA) was used to examine whether NEP, ER, and GEP varied  
19 between the short- and long-hydroperiod marshes. Specifically, dry and wet season data  
20 from the control treatments at TS were compared with seasonally-pooled control  
21 treatment data from SRS. Data were analyzed in this manner because of the findings from  
22 the mixed effects model analysis, as discussed below. To meet the ANOVA assumptions of  
23 normality and equal variances, it was necessary to apply a square root transformation to

1 the GEP data in the TS wet season vs. SRS comparison and to remove three outliers  
2 (residuals >2 standard deviations from the mean) from the ER TS dry season vs. SRS  
3 comparison.

4 Multiple linear regressions were used to determine the effect of various environmental  
5 factors on rates of CO<sub>2</sub> exchange at each study site. Regressions were performed on control  
6 treatment NEP, ER, and GEP values expressed as means for each measurement date.  
7 Forward and backward stepwise multiple regressions were performed using the Akaike  
8 Information Criterion (AIC) to select predictor variables for the final models (R Package  
9 MASS, stepAIC function). Full models for NEP and GEP included water depth relative to the  
10 soil surface, T<sub>air</sub>, vapor pressure deficit (D, as the vapor pressure difference between  
11 saturated and ambient air at T<sub>air</sub>), and PAR as predictor variables. In the ER analysis, PAR  
12 was not used as a predictor variable because measurements were made in the dark.  
13 Potential predictor variables such as soil temperature, water temperature, and soil  
14 volumetric water content were excluded from the analysis because of multicollinearity  
15 with the selected variables. Most environmental data used in the models were drawn from  
16 the half-hourly micrometeorological dataset and were averaged across the time period  
17 during which chamber measurements were made (i.e., from 10 AM to 1 PM). The one  
18 exception was the PAR data, which was calculated as a mean of the PAR measurements  
19 made during each 1 min chamber measurement period.

20

## 21 **Results**

### 22 *Micrometeorological site comparison*

1 Water levels varied seasonally at both TS and SRS with the highest water levels in the  
2 wet season and the lowest levels in the dry season (Fig. 2A). Climatically-defined  
3 seasonality did not coincide well with site-specific seasonality at TS in 2008, though it  
4 matched well in 2009 (Fig. 2A). Measurements of  $T_{\text{air}}$ , D, and maximum daily PAR ( $\text{PAR}_{\text{max}}$ )  
5 were similar between study sites and exhibited expected seasonal patterns (Fig. 2B, C, D).

#### 6 *Treatment and seasonal effects on NEP, ER, and GEP*

7 At the short-hydroperiod TS marsh, the periphyton removal treatment had no  
8 significant effect on NEP, ER, or GEP ( $p > 0.05$ , Table 1, Fig. 3). It should be noted that this  
9 treatment was effectually applied only during the mid to late dry season and early wet  
10 season. Seasonality did have an effect on all three parameters, with significantly higher  
11 rates of NEP, ER, and GEP observed in the dry season ( $p < 0.001$ , Table 1, Fig. 3). For all  
12 analyses at TS, the treatment by season interaction was not significant ( $p > 0.05$ ).

13 At the long-hydroperiod SRS marsh, the macrophyte removal treatment had a  
14 significant effect on both NEP and GEP ( $p < 0.0001$ ), but not on ER ( $p > 0.05$ , Table 1).  
15 Significantly higher rates of NEP and GEP were observed for measurements made prior to  
16 macrophyte removal (Fig. 4). In contrast to TS, there was no significant effect of  
17 seasonality on any of the  $\text{CO}_2$  exchange parameters at SRS. As such, all data from SRS were  
18 pooled across seasons for subsequent analyses. The treatment by season interaction was  
19 not significant for any of these analyses at SRS ( $p > 0.05$ , Table 1, Fig. 4).

#### 20 *Short- vs. long-hydroperiod comparisons of $\text{CO}_2$ exchange*

21 Net ecosystem production did not differ significantly between TS in the dry season and  
22 SRS ( $p > 0.05$ ), though ER and GEP did differ significantly ( $p < 0.001$ , Table 2). Both ER and  
23 GEP were significantly greater at TS during the dry season than they were at SRS. These

1 relationships changed when the TS wet season data were compared to the seasonally-  
2 pooled data from SRS. In this case, NEP, ER, and GEP were all significantly different ( $p <$   
3  $0.001$ ) between sites with NEP and GEP greater at SRS, while ER remained greater at TS  
4 (Table 2).

### 5 *Environmental drivers of NEP, ER, and GEP*

6 Multiple regression analyses indicated that  $T_{\text{air}}$  and D best predicted rates of NEP at TS,  
7 while at SRS,  $T_{\text{air}}$  and PAR were the most important predictor variables for NEP. However,  
8 neither of these regression equations accounted for much of the variation in the data ( $R^2_{\text{adj}}$   
9 of 0.26 and 0.24 for TS and SRS, respectively) and neither equation was significant ( $p >$   
10  $0.05$ , Table 3). The regression equations used to predict ER were significant at both sites ( $p$   
11  $< 0.05$ ) and included the variables water depth and D at TS and  $T_{\text{air}}$  and D at SRS (Table 3).  
12 These equations explained 62% of the variation in ER rates at TS and 59% at SRS.  
13 Equations for GEP were also significant at both sites ( $p < 0.05$ ) and included water depth,  
14  $T_{\text{air}}$ , and D at TS, but only  $T_{\text{air}}$  at SRS (Table 3). The explanatory power of the GEP equation  
15 was higher at TS than at SRS ( $R^2_{\text{adj}}$  of 0.65 and 0.34, respectively).

16 Although PAR is an important driver of  $\text{CO}_2$  exchange, it was only incorporated as a  
17 variable in the multiple regression analyses to account for seasonal variation (Fig. 2b).  
18 Measurements of NEP were made under full-sun conditions and were assumed to  
19 represent maximum daily rates of NEP. An analysis of PAR recorded during the 1 minute  
20 NEP measurement intervals revealed that on all but two days (at SRS on 10/30/08 and  
21 7/17/09) PAR was greater than or equal to (i.e., within one standard error) mean PAR  
22 values recorded by the nearby micrometeorological stations during the measurement  
23 period (data not shown).

1 In addition to environmental drivers, it was possible to explore the relationship  
2 between plant biomass and CO<sub>2</sub> exchange at SRS because of the nature of the macrophyte  
3 removal treatment. Linear regression analyses indicated that plant dry biomass exhibited  
4 a significant positive relationship with both NEP and GEP at SRS ( $R^2_{adj} = 0.71$  and  $0.58$ ,  
5 respectively,  $p < 0.0001$ , data not shown). There was no significant relationship between  
6 ER and plant biomass ( $p > 0.05$ , data not shown).

7

## 8 **Discussion**

### 9 *Treatment and seasonal effects on NEP, ER, and GEP*

10 Contrasting patterns of CO<sub>2</sub> flux responses to experimental treatments and seasons  
11 were observed between the short- and long-hydroperiod Everglades marshes. At the  
12 short-hydroperiod TS marsh, no significant differences in CO<sub>2</sub> exchange rates were  
13 observed in the control vs. periphyton removal treatments. This indicated that during the  
14 period in which the treatment was effectively applied (i.e., the mid-dry to early wet  
15 season), periphyton did not significantly contribute to CO<sub>2</sub> fluxes at the site. Although  
16 periphyton exhibits an immediate metabolic response to rewetting in the wet season  
17 (Thomas et al. 2006a), the contribution of periphyton to ecosystem CO<sub>2</sub> exchange was not  
18 strong enough to be detected.

19 Seasonality played a key role in influencing rates of CO<sub>2</sub> exchange at TS, such that  
20 exchange rates were significantly lower during periods of inundation. The seasonal  
21 patterns of NEP, ER, and GEP mirrored those reported at the nearby eddy covariance tower  
22 (Schedlbauer et al. 2010). Flux rates were highest in the dry season, declined through the  
23 early part of the wet season, and then increased again as the wet season proceeded.

1 Similarity between the two measurement methods was reflected in a linear regression  
2 analysis of mean control chamber derived NEP vs. eddy covariance derived NEP (mean  
3 values from 10 AM to 1 PM on the chamber measurement dates). This analysis yielded a  
4 significant, positive relationship between the two methods ( $y = 1.10x - 0.58$ ,  $R^2_{\text{adj}} = 0.70$ ,  $p$   
5  $< 0.001$ , data not shown). Chamber measurements indicated that dry season fluxes were  
6 clearly dominated by contributions from macrophytes, though heterotrophic contributions  
7 from the well-aerated soil also played a role in determining ER. In the daytime hours of the  
8 dry season, the TS marsh was a net sink for  $\text{CO}_2$ , and maximum rates of NEP reached  $3.77$   
9  $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ .

10 Following the onset of the wet season, the TS ecosystem became a net source of  $\text{CO}_2$  to  
11 the atmosphere during the daytime with NEP rates reaching a minimum of  $-1.36 \mu\text{mol CO}_2$   
12  $\text{m}^{-2} \text{ s}^{-1}$ . The wet season shift from  $\text{CO}_2$  sink to source principally reflected the seasonal  
13 suppression of photosynthesis by macrophytes following flooding of the site (Schedlbauer  
14 et al. 2010). The subsequent transition from low to moderate flux rates during the wet  
15 season can be attributed to the growth and development of dense periphyton mats  $\sim 2$   
16 months into the season (Thomas et al. 2006b; Schedlbauer et al. 2010). It appears that  
17 large, metabolically active periphyton mats shifted the ecosystem from net  $\text{CO}_2$  source to  
18 sink as the wet season proceeded. The contribution of periphyton to primary production at  
19 TS was principally confined to the mid to late wet season. Although a prior study indicated  
20 that periphyton was responsible for  $>50\%$  of aboveground net primary production (ANPP)  
21 at TS (Ewe et al. 2006), the present data set suggests a smaller role for periphyton in  
22 determining site productivity. Scaling errors in the previous study may have contributed to  
23 this discrepancy (Schedlbauer et al. 2010). The depressed NEP rates in the wet season also



1 indicate that geochemical fixation of CO<sub>2</sub> and subsequent marl accretion at TS was  
2 proceeding slowly.

3 In contrast to TS, treatment effects were strong and seasonal effects were non-existent  
4 at the long-hydroperiod SRS marsh. Rates of CO<sub>2</sub> exchange were strongly driven by  
5 contributions from the emergent macrophyte community. In the absence of emergent  
6 macrophytes, NEP, ER, and GEP rates significantly decreased and were often close to zero.  
7 The effect of macrophyte removal was most dramatic for NEP and GEP, given that rates of  
8 ER were low year-round, regardless of treatment. These data indicate that the contribution  
9 of periphyton to ecosystem CO<sub>2</sub> exchange was minor in this long-hydroperiod marsh. This  
10 finding supports data reported by Ewe et al. (2006) indicating that periphyton contributes  
11 only 10% of the average ANPP at this study site.

12 As a peat marsh, it was expected that the long-hydroperiod SRS ecosystem would act as  
13 a CO<sub>2</sub> sink and, on each measurement date under mid-day, full sun conditions, this was  
14 found to be the case. Rates of NEP varied from 1.36 to 4.28  $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ . Despite data  
15 showing the site as a CO<sub>2</sub> sink during daytime hours, the unusually dry conditions recorded  
16 at the site in spring 2009 exposed peat soil at the site (J.L. Schedlbauer, personal  
17 observation), and the exposure of these carbon-rich soils likely switched the site from CO<sub>2</sub>  
18 sink to source. Unfortunately, chamber measurements were logistically impossible during  
19 this time period. The historical occurrence of site dry-downs is unknown, but likely to be  
20 rare given the presence of >0.65 m deep peat deposits at the site.

21 In comparison with other subtropical and tropical freshwater wetlands where CO<sub>2</sub>  
22 exchange rates have been measured, the findings reported for these Everglades marshes  
23 are notably different. Typically, net rates of CO<sub>2</sub> uptake by tropical wetlands are highest in

1 the wet season and lowest in the dry season (Morison et al. 2000; Jones and Humphries  
2 2002). This pattern was not found in either short- or long-hydroperiod Everglades  
3 marshes; the pattern was opposite at TS and there was no pattern at SRS. The seasonal  
4 stimulation of primary productivity in many low-latitude wetlands is absent in these  
5 oligotrophic Everglades marshes.

#### 6 *Short- vs. long-hydroperiod comparisons of CO<sub>2</sub> exchange*

7 Both TS and SRS exhibited statistically similar rates of NEP when compared during the  
8 TS dry season. This was unexpected given the contrasting primary producer communities  
9 and hydroperiods at these sites. However, both GEP and ER were significantly higher at TS,  
10 likely reflecting the contributions of the well-aerated soil microbial community to CO<sub>2</sub>  
11 fluxes from the site. During the wet season at TS, macrophyte leaf area was submerged and  
12 photosynthetic rates declined (Schedlbauer et al. 2010), and this led to rates of NEP and  
13 GEP that were significantly lower than at SRS. Despite the fact that both sites share *C.*  
14 *jamaicense* as a dominant plant species, inundation had contrasting effects on site  
15 productivity. These data suggest that the *C. jamaicense* population at SRS is better adapted  
16 to flooded conditions, an idea supported by ANPP data for the species. *C. jamaicense* ANPP  
17 at SRS is nearly double the value reported for TS (606 vs. 304 g C m<sup>-2</sup> year<sup>-1</sup>, Ewe et al.  
18 2006).

19 The seasonal and year-round mean values for NEP, ER, and GEP compared favorably  
20 with data collected at the eddy covariance towers at each site (Schedlbauer et al. 2010; K.L.  
21 Jimenez, unpublished manuscript). Carbon dioxide fluxes determined using chamber  
22 measurement methods clearly captured representative data at both sites. However, it  
23 should be noted that measurements of ER during inundated periods at both study sites may

1 have underestimated true ER. Although the chamber was darkened for ~1 min before a  
2 measurement was recorded, it is probable that lags were present in the system. In sunlight,  
3 aquatic photosynthesis will decrease the dissolved CO<sub>2</sub> concentration in the water column  
4 and cause a net flux of CO<sub>2</sub> into the water. This flux likely continued following chamber  
5 darkening because equilibration of CO<sub>2</sub> in a large volume of water proceeds relatively  
6 slowly. Further, because the chamber was placed on a float at SRS, it is possible that water  
7 upstream from the darkened chamber flowed under the float during ER measurements.  
8 Although water flow at SRS is slow (1.5 – 4.5 cm s<sup>-1</sup>, Riscassi and Schaffranek 2002), the  
9 introduction of recently sunlit water depleted in dissolved CO<sub>2</sub> may have affected ER  
10 measurements. Because of these possibilities, ER may have been underestimated at TS in  
11 the wet season and at SRS year-round.

12 The data collected from these Everglades marshes contrast with other studies of CO<sub>2</sub>  
13 exchange in wetlands at low latitudes. Carbon dioxide flux rates in both short- and long-  
14 hydroperiod marshes were much lower than values reported elsewhere. For instance, the  
15 maximum rates of net CO<sub>2</sub> uptake in a papyrus (*Cyperus papyrus*) wetland were reported to  
16 reach 24 μmol CO<sub>2</sub> m<sup>-2</sup> s<sup>-1</sup> (Jones and Humphries 2002), while maximum values in an  
17 Amazonian floodplain were >40 μmol CO<sub>2</sub> m<sup>-2</sup> s<sup>-1</sup> (Morison et al. 2000). Also, in  
18 comparison with growing season data from freshwater wetlands at mid to high latitude,  
19 these Everglades CO<sub>2</sub> exchange rates were low (Bonneville et al. 2008; Rocha and Goulden  
20 2008; Dusek et al. 2009). The present data strongly reflect the oligotrophic nature of  
21 Everglades wetlands, where phosphorous availability is known to limit the productivity of  
22 periphyton and macrophytes including *C. jamaicense* and *Eleocharis* sp. (Daoust and  
23 Childers 1999; Noe et al. 2001; Iwaniec et al. 2006).

1 *Environmental drivers of NEP, ER, and GEP*

2 Environmental drivers of CO<sub>2</sub> exchange varied between the short- and long-  
3 hydroperiod study sites. Considering the significant multiple regression equations for ER  
4 and GEP, the most notable finding is that water level influenced both terms at TS, but had  
5 no effect at SRS. This supports the findings reported above showing a significant seasonal  
6 effect on CO<sub>2</sub> exchange at TS, but not at SRS. This relationship is important in light of  
7 impending changes in Everglades water management as the Comprehensive Everglades  
8 Restoration Plan (CERP) proceeds. These data indicate that increased water depths and  
9 longer hydroperiods will have a substantial effect on CO<sub>2</sub> exchange in short-hydroperiod  
10 marshes, but a limited effect within long-hydroperiod marshes. While other environmental  
11 drivers (i.e., T<sub>air</sub>, D, PAR) influence NEP, ER, and GEP, these factors are largely beyond  
12 human control.

13 The weakness of the relationship between environmental drivers and the NEP and GEP  
14 terms at SRS was likely related to heterogeneity in the site's plant community. Both terms  
15 were significantly related to plant biomass, a metric that varies substantially from ridge to  
16 slough. It seems that variation in the amount of plant material enclosed by the  
17 measurement chamber was more important than any environmental variable in  
18 determining CO<sub>2</sub> exchange rates. However, the same cannot be said for the weak  
19 relationship between environmental drivers and NEP at TS where vegetation is relatively  
20 heterogeneous. A longer-term dataset may help to resolve the role of environmental  
21 drivers in determining NEP.

22 *Conclusions*

1        Although wetlands are among the world's most productive ecosystems, the freshwater  
2 marshes of the Everglades are atypical. In contrast to previous research (Ewe et al. 2006),  
3 the data reported here reflect that the Everglades is an oligotrophic ecosystem with low  
4 productivity in both short- and long-hydroperiod marshes. Everglades wetlands are also  
5 distinguished because seasonal cues, specifically the transition from dry to wet season, do  
6 not yield pulses in productivity, as reported in other low-latitude wetland ecosystems.

7        Despite contrasting plant communities, net ecosystem production was surprisingly  
8 similar between short-hydroperiod marshes in the dry season and long-hydroperiod  
9 marshes year-round. Further, it is clear that (emergent) macrophytes were the dominant  
10 contributors to CO<sub>2</sub> exchange rates during these periods. Whether these similarities will  
11 persist in the future, as Everglades restoration under CERP proceeds, is uncertain.

12        It is likely that productivity in short-hydroperiod marshes, rather than long-  
13 hydroperiod marshes, will be most affected by alterations in the timing and quantity of  
14 water delivery to the Everglades. The current study shows that rates of CO<sub>2</sub> exchange in  
15 short-hydroperiod marshes like TS are highly sensitive to seasonality and water levels.  
16 Deeper water and longer hydroperiods are likely to decrease the amount of carbon stored  
17 by these ecosystems on an annual basis. Additionally, past research indicates that plant  
18 communities in short-hydroperiod Everglades marshes can change rapidly (i.e., within 3-4  
19 years) in response to altered hydrologic regimes (Armentano et al. 2006). As a result, these  
20 ecosystems may shift toward more hydrophytic plant communities. The net effect of  
21 Everglades restoration activities on productivity in short-hydroperiod marshes is, as yet,  
22 unclear, but any alterations will have wide-ranging effects given that these marshes occupy  
23 approximately one-third of the Everglades' spatial extent (Davis et al. 2005).

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1 **Table 1.** F-values from mixed-effects ANOVA analyses of net ecosystem production (NEP),  
 2 ecosystem respiration (ER), and gross ecosystem production (GEP) measured at Taylor  
 3 Slough (TS) and Shark River Slough (SRS). All models had the fixed effects treatment,  
 4 season, and treatment by season interaction. Treatment at TS was the periphyton removal,  
 5 while at SRS it was the macrophyte removal, and both treatments were compared with  
 6 control measurements. Season refers to dry or wet season. Asterisks indicate significance  
 7 at the following levels:  $p < 0.001$  (\*\*\*),  $0.001 \leq p \leq 0.01$  (\*\*),  $0.01 < p \leq 0.05$  (\*).

8

Site	Variable	Treatment	Season	Treatment × Season
TS	NEP	0.04	27.74***	0.41
	ER	0.59	65.13***	0.08
	GEP	0.21	109.12***	0.88
SRS	NEP	132.44***	2.79	2.88
	ER	11.45**	0.14	3.52
	GEP	117.98***	2.91	3.82

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1 **Table 2.** Mean  $\pm$  one SE for CO<sub>2</sub> exchange rates ( $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ ) and F-values for the  
 2 variables net ecosystem production (NEP), ecosystem respiration (ER), and gross  
 3 ecosystem production (GEP). Means and F-values are reported for one-way ANOVAs  
 4 performed to compare data from Taylor Slough (TS) during the dry and wet seasons  
 5 individually with seasonally-pooled data from Shark River Slough (SRS). An asterisk  
 6 indicates that the TS data for a given variable were significantly different from data from  
 7 SRS ( $p < 0.001$ ).

8

Variable	<u>TS Dry Season</u>		<u>TS Wet Season</u>		<u>SRS</u>
	Mean $\pm$ SE	F-value	Mean $\pm$ SE	F-value	Mean $\pm$ SE
NEP	2.49 $\pm$ 0.27	1.12	0.82 $\pm$ 0.26	27.78*	2.92 $\pm$ 0.28
ER	-2.53 $\pm$ 0.19	181.14*	-0.97 $\pm$ 0.09	17.03*	-0.55 $\pm$ 0.09
GEP	5.11 $\pm$ 0.33	14.40*	1.79 $\pm$ 0.24	12.69*	3.35 $\pm$ 0.31

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1 **Table 3.** Results from multiple regression analyses in which full models for NEP and GEP  
 2 included the predictor variables water depth relative to the soil surface, air temperature  
 3 ( $T_{\text{air}}$ ), vapor pressure deficit (D), and photosynthetically active radiation (PAR). The PAR  
 4 term was excluded from the full ER models. Missing values indicate that a given predictor  
 5 variable was not included in the final model. An asterisk next to a predictor variable's  
 6 coefficient indicates significance at  $p < 0.10$ .

7

	<u>Taylor Slough (TS)</u>			<u>Shark River Slough (SRS)</u>		
	NEP	ER	GEP	NEP	ER	GEP
Intercept	5.68	-0.17	4.83	2.55	1.13	0.29
Water depth	--	1.30	-2.13*	--	--	--
$T_{\text{air}}$	-0.37*	--	-0.27	0.12	-0.10*	0.12*
D	3.56*	-0.81*	3.31	--	0.80*	--
PAR	--	NA	--	-0.002	NA	--
F-statistic	3.29	11.63	9.03	2.42	7.56	5.57
Tolerance	0.63	0.32	0.27	0.59	0.32	0.59
$R^2_{\text{adj}}$	0.26	0.62	0.65	0.24	0.59	0.34
p-value	0.0761	0.0002	0.0034	0.1594	0.0178	0.0460
AIC	8.13	-9.76	8.04	-0.24	-19.54	1.57

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1 **Figure Legends**

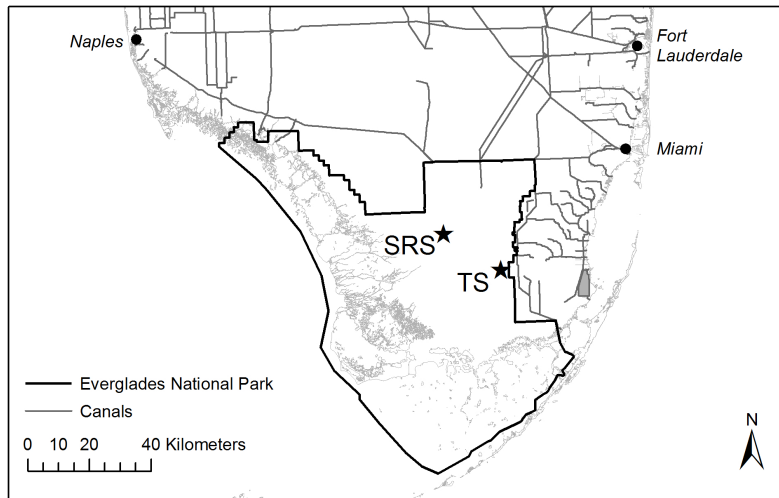
2 **Figure 1.** Map showing the location of the study sites Taylor Slough (TS) and Shark River  
3 Slough (SRS) within Everglades National Park.

4 **Figure 2.** Micrometeorological data from the short-hydroperiod Taylor Slough (TS) and  
5 long-hydroperiod Shark River Slough (SRS) sites. Shown are water level data relative to  
6 the soil surface with site specific wet seasons indicated by horizontal bars (A), air  
7 temperature ( $T_{\text{air}}$ , °C, B), vapor pressure deficit (D, kPa, B), and daytime maximum  
8 photosynthetically active radiation ( $\text{PAR}_{\text{max}}$ ,  $\text{mol m}^{-2} \text{s}^{-1}$ , D). All data are presented as 7-day  
9 running means so that seasonal patterns rather than day-to-day variation can be readily  
10 observed. Note that micrometeorological measurements did not begin until early July 2008  
11 at SRS.

12 **Figure 3.** Means  $\pm$  one SE for  $\text{CO}_2$  exchange rates ( $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ ) measured at the short-  
13 hydroperiod Taylor Slough (TS) site. Shown are values for net ecosystem production (NEP,  
14 A), ecosystem respiration (ER, B), and gross ecosystem production (GEP, C) for both  
15 control and periphyton removal treatments. Dry and wet seasons are indicated by white  
16 and grey shading, respectively.

17 **Figure 4.** Means  $\pm$  one SE for  $\text{CO}_2$  exchange rates ( $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ ) measured at the long-  
18 hydroperiod Shark River Slough (SRS) site. Shown are values for net ecosystem production  
19 (NEP, A), ecosystem respiration (ER, B), and gross ecosystem production (GEP, C) for both  
20 control and macrophyte removal treatments. Dry and wet seasons are indicated by white  
21 and grey shading, respectively.

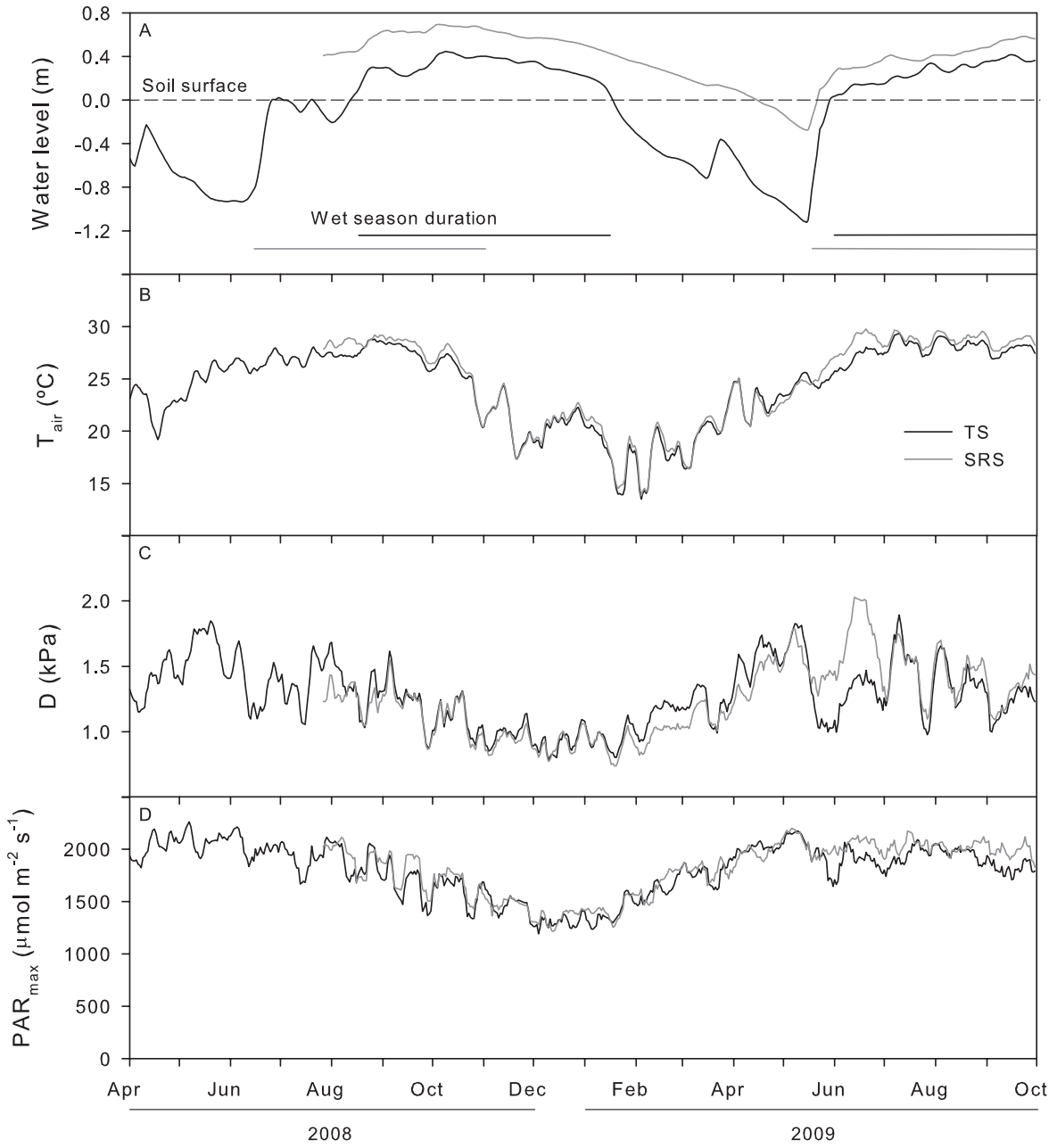
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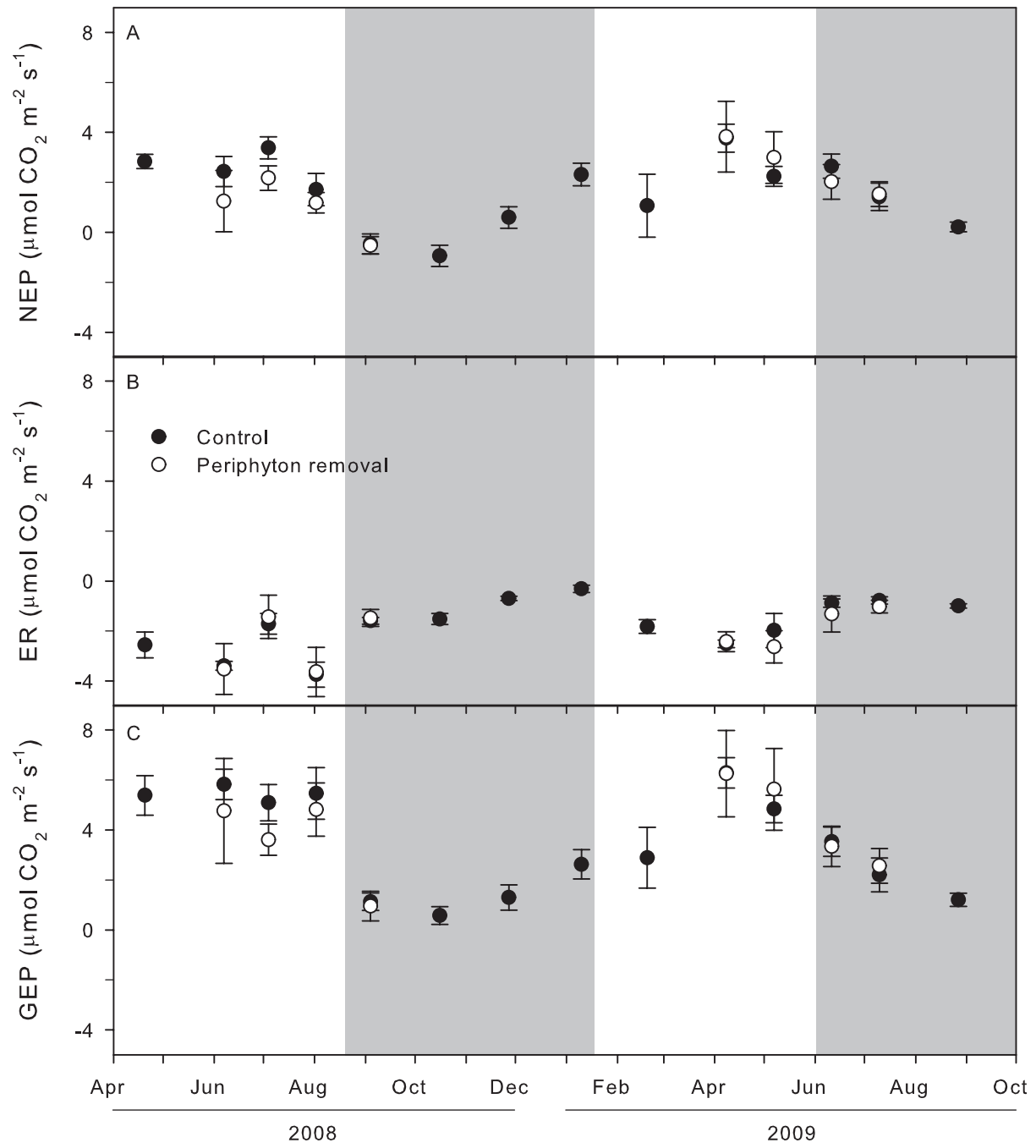
Fig. 1





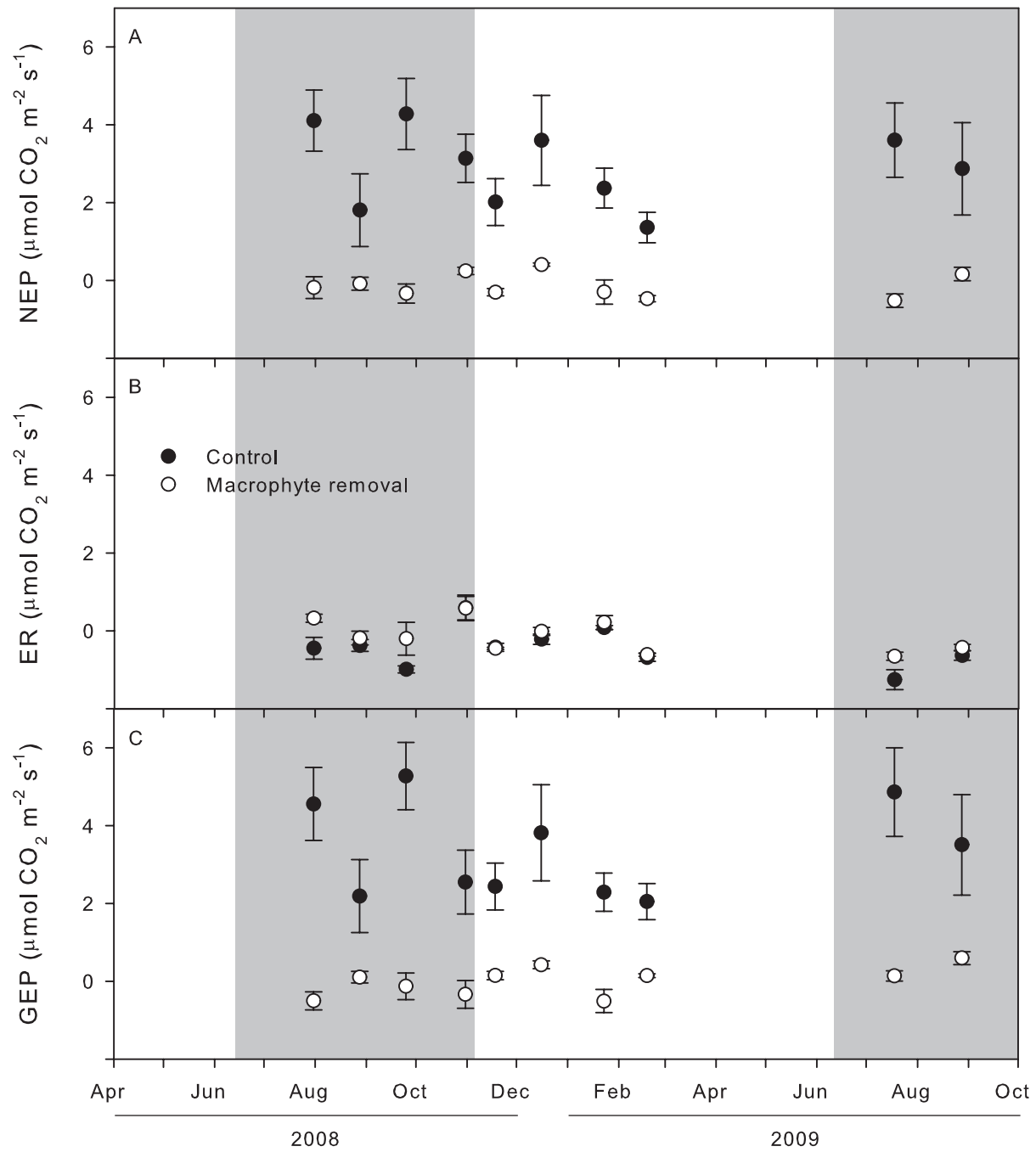
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Fig. 2



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Fig. 3



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