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ARTICLE

Soil Greenhouse Gas Fluxes during Wetland Forest Retreat along the Lower Savannah River, Georgia (USA)

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Abstract Tidal freshwater forested wetlands (tidal swamps) are periodically affected by salinity intrusion at seaward transitions with marsh, which, along with altered hydrology, may affect the balance of gaseous carbon (C) and nitrogen (N) losses from soils. We measured greenhouse gas emissions (CO_2, CH_4, N_2O) from healthy, moderately degraded, and degraded tidal swamp soils undergoing sea-level-rise-induced retreat along the lower Savannah River, Georgia, USA. Soil CO_2 flux ranged from 90.2 to 179.1 mg CO_2 m^{-2} h^{-1} among study sites, and was the dominant greenhouse gas emitted. CO_2 flux differed among sites in some months, while CH_4 and N_2O fluxes were 0.18 mg CH_4 m^{-2} h^{-1} and 1.23 μg N_2O m^{-2} h^{-1}, respectively, with no differences among sites. Hydrology, soil temperature, and air temperature, but not salinity, controlled the annual balance of soil CO_2 emissions from tidal swamp soils. No clear drivers were found for CH_4 or N_2O emissions. On occasion, large ebbing or very low tides were even found to draw CO_2 fluxes into the soil (dark CO_2 uptake), along with CH_4 and N_2O. Overall, we hypothesized a much greater role for salinity and site condition in controlling the suite of greenhouse gases emitted from tidal swamps than we discovered, and found that CO_2 emissions—not CH_4 or N_2O–contributed most to the global warming potential from these tidal swamp soils.

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Introduction

Tidal and non-tidal forested wetlands provide for long-term storage of carbon (C) as progressive layers of organic matter are produced via root growth or laid down in the form of litter, branch, and wood necromass (Clymo et al. 1998; Donato et al. 2011). Conditions under which C and nutrients are retained, however, depend upon the biogeochemical state of soils as well as on flooding, sediment deposition, C, and nutrient gradients (Noe and Hupp 2009). Mineralization of organic C to CO_2 under both aerobic and anaerobic conditions, and to CH_4 in the absence of oxygen, depends upon local site condition and can represent a major conduit for C loss from forested wetlands (Happell and Chanton 1993). Likewise, efflux of N_2O can represent a significant pathway for nitrogen (N) loss from wetlands (Reddy and DeLaune 2008).

A number of greenhouse gas flux studies have been conducted on forested wetlands (Harriss and Sebacher 1981; Harriss et al. 1982; Wilson et al. 1989; Pulliam 1993; Miller et al. 1999; Chimner 2004; Yu et al. 2006, 2008), yet few research programs have considered freshwater forested wetlands developing under tidal conditions (tidal swamps), where CO_2, CH_4, and N_2O release from soils may fluctuate diurnally and with periodic incursion of salt water. Tidal swamp vegetation is often killed by pulses of concentrated salt water, and chronic salinization with even low salinity concentrations drives changes in forest vegetation to marsh, alters the availability of N and phosphorus in the soil, and can reduce overall net primary productivity (Pezeshki et al. 1987; Hackney et al. 2007; Krauss et al. 2009).

Studies of estuaries and freshwater wetlands revealed that CH_4 emissions were 37 times greater from freshwater marshes than salt marshes in Louisiana (DeLaune et al. 1983), and two subsequent investigations have indicated a sharp decline in marsh CH_4 flux at salinities of 13–18 ppt (Bartlett et al. 1987; Poffenbarger et al. 2011). Much less has been documented for CO_2 and N_2O versus salinity, and data from tidal swamps are not readily available. Yet, low levels of salinity pulsed to tidal freshwater marshes can promote organic C mineralization, and higher fluxes of both CO_2 and CH_4 (Weston et al. 2011). In this study, we focus on greenhouse gas fluxes (CO_2, CH_4, N_2O) from soils as tidal swamps along the lower Savannah River, Georgia, USA undergo salinity-induced retreat.

Methods

Study Sites

Study sites were located along the lower Savannah River within the Savannah National Wildlife Refuge (NWR) along the border of South Carolina and Georgia, USA (Fig. 1). Water discharge is affected by three upstream dams and river dredging in support of shipping. A one-way tidal flap gate was installed at river-km 23 in 1977, and removed in 1991 because of vegetation shifts associated with decadal-scale increases in salinity (Pearlstein et al. 1993). Tidal swamp hydrology is controlled by a 2.4-m tidal range superimposed on mean river stage which itself fluctuates between wet and dry years.

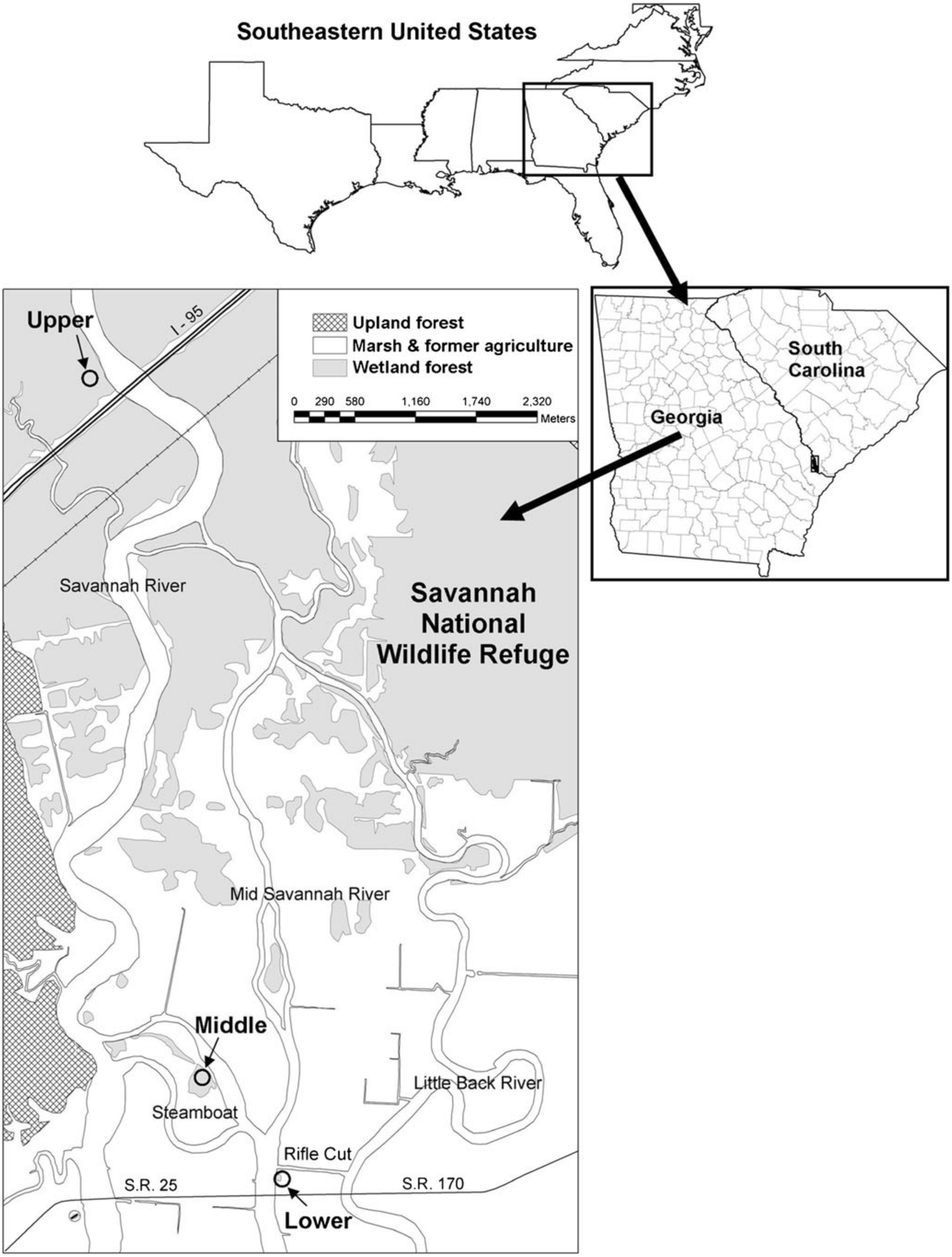
Three sites with different salinity regimes were separated by approximately 13 river km, and designated as Upper, Middle, and Lower (Fig. 1). The Upper site (river-km 39) was fresh throughout the study (salinity <0.2). The two codominant tree species were baldcypress (*Taxodium distichum*) and water tupelo (*Nyssa aquatica*), with swamp blackgum (*Nyssa biflora*), ash (*Fraxinus* spp.), red maple (*Acer rubrum*), and diamond leaf oak (*Quercus laurifolia*) in the mid-story canopy. Hazel alder (*Alnus serrulata*) was also prevalent on site as a shrub. The herbaceous (and woody vine) understory community was diverse, but mostly composed of *Polygonum hydropiperoides*, *P. arifolium*, *Thelypteris* sp., *Carex* spp., *Commelina diffusa*, *Toxicodendron radicans*, and *Iris* sp. Soils were mapped as thermic Typic Hydraquents (NRCS 2011) in a 4:2:4 ratio of Angelina, Bibb, and "other" (Chipley, Kershaw, Ocilla), described as frequently flooded with poor drainage, and characterized by a dark grey loam surface layer approximately 8 cm thick (USDA 1974). Bulk density of soils was 0.39±0.03 (SE) g cm^{-3} (Krauss et al. 2009), with an average C content of 10.1% (unpubl.).

Fig. 1 Location of study sites along the lower Savannah River floodplain in relation to marsh, primary river braids, and dredged access channels to marsh from an era when rice agriculture dominated land use (circa 1670–1860). The Little Back River demarcates the Georgia-South Carolina state boundary; all study sites are located in Georgia

Middle (river-km 28) and Lower (river-km 26) sites were both impacted by salinity. Monthly average porewater salinity concentrations of the Middle site ranged from 0.4 to 2.1 over a five-year period, and averaged 1.3±0.05 SE over the course of this study. This site was dominated by baldcypress, with swamp blackgum as a sparse constituent of the mid-story. The herbaceous community was composed of *Polygonum hydropiperoides*, *P. arifolium*, *Saururus cernuus*, *Pontederia cordata*, *Peltandra virginica*, *Sagittaria lancifolia*, and *Lilaeopsis chinensis*. Porewater salinity of the Lower site ranged from 1.9 to 6.8, and averaged 4.7±0.17 SE over the course of this study. Only baldcypress maintained dominant tree status on this site; however, trees were stressed and marsh was actively encroaching on the site. The herbaceous community was composed of oligohaline marsh plants: *Spartina cynosuroides*, *Zizaniopsis miliacea*, *Typha angustifolia*, *Schoenoplectus robustus, Sagittaria lancifolia*, and *Lilaeopsis chinensis*. Soils of the Middle and Lower sites were Levy series (thermic Typic Hydraquents, NRCS 2011), and described as level, very poorly drained with a very dark gray surface layer (~20 cm thick) of silty clay loam (USDA 1980). Bulk density of soils of the Middle and Lower sites was 0.24±0.01 (SE) g cm^{-3} and 0.37±0.04 (SE) g cm^{-3}, respectively (Krauss et al. 2009), with an average C content of 22.0% and 10.9% (unpubl.).

Physico-chemical and Hydrological Measurements

At all sites, hourly water levels were recorded since 2004. All sites were strongly tidal, flooded between 48 and 155 times per year, and remained flooded with surface water between 303 and 633 h per year (Fig. 2). Salinity was measured monthly from four stationary wells (inserted to 60 cm) on each site with a portable conductivity meter (YSI Model 30, Yellow Springs, Ohio, USA). Soil oxidation-reduction potential (redox) was measured at 15 cm and 30 cm depths from all sites on four separate occasions, twice during active dry periods (August 2006, August 2007) and twice during active wet periods (November 2006, March 2007). Redox procedures follow Howard and Mendelssohn (2000) in using a portable pH-mV meter, brightened platinum (Pt) electrodes, and a calomel reference probe. Electrodes were



Southeastern United States
Upper
I - 95
Upland forest
Marsh & former agriculture
Wetland forest
0 290 580 1,160 1,740 2,320
Meters
South Carolina
Georgia
Savannah River
Savannah National Wildlife Refuge
Mid Savannah River
Middle
Steamboat
Little Back River
Rifle Cut
S.R. 25
S.R. 170
Lower

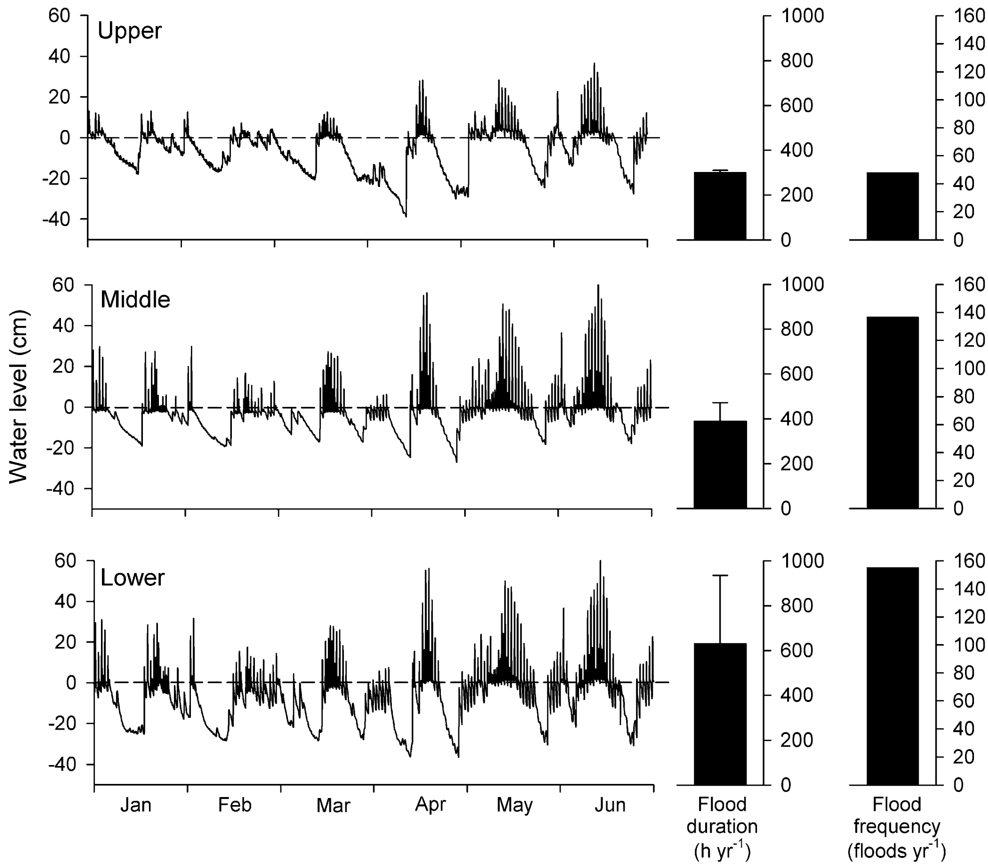


Fig. 2 Representative 6-month hydrographs, with average site-specific flood duration (± 1 SE) and flood frequency (from Krauss et al. 2009), from tidal swamps located at Savannah Upper, Middle, and Lower from late 2005 through 2007. 0 on the y-axis of the hydrographs indicates the soil surface

constructed using a 2-cm Pt tip welded to Cu wire and sealed with an epoxy for waterproofing (Faulkner et al. 1989); electrode calibration was checked against a quinhydrone solution mixed using pH 4 and pH 7 buffers. Probes were inserted into the soil and allowed to sit for a minimum of 30 min before measurements were taken.

Soil Greenhouse Gas Fluxes

We installed six, white-plastic 29.4×29.4×30.5-cm soil chambers (sampling area =864 cm^2) in undisturbed, representative areas of each site. The chambers were darkened during measurements in order to moderate temperature fluctuations during 60-min sampling periods (Yu et al. 2008). Chambers consisted of a base that was inserted to a soil depth of approximately 5 cm, and left in place for the two-year duration of study. Most areas selected for chambers were not heavily vegetated, and the few residual plants were clipped at the soil surface just after chamber installation. Very little vegetation recolonized the chambers, but new plants were also clipped prior to each round of measurement.

Chamber bases were constructed with a trough around the rim that was filled with water before sample tops were placed to restrict leakage of gases while sampling. Tops were installed just prior to sampling and removed immedi-

Table 1 Summary of means (± 1 SE) and ANOVA results for soil greenhouse gas fluxes of CO_2 (mg m^{-2} h^{-1}), CH_4 (mg m^{-2} h^{-1}), and N_2O (μg m^{-2} h^{-1}) from tidal swamps subjected to increased salinization and state change to marsh along the lower Savannah River, Georgia, USA

Site	CO_2		CH_4		N_2O	
Upper	179.1±19.2		0.126±0.038		−3.32±5.79	
Middle	162.3±19.9		0.209±0.058		−1.91±4.05	
Lower	90.2±17.6		0.191±0.061		8.91±4.77	
ANOVA [$DF_{num,den}$]	F Value	P > F	F Value	P > F	F Value	P > F
Site [2, 15]	3.20	0.0695	0.98	0.3993	1.12	0.3513
Rep(Site) (15, 328]	4.65	0.0001	3.04	0.0001	1.50	0.1039
Time [22, 328]	16.87	0.0001	4.22	0.0001	1.47	0.0823
Site×Time [44, 328]	1.78	0.0028	1.11	0.3062	1.37	0.0658

ately after. Tops added approximately 27 cm to total chamber height. Each chamber top was fitted with two brass, 0.9-cm inlets with rubber septa for gas sample extraction. Gas samples were extracted with a hypodermic needle at intervals of 0, 20, 40, and 60 min, and injected into a 5-mL vacuum-sealed vial for transport to a laboratory. Samples were analyzed for CO_2, CH_4, and N_2O with a multi-column gas chromatograph (CP-3800, Varian, Inc., Palo Alto, CA, USA), calibrated using certified standards (Scott Specialty Gases, Inc., Plumsteadville, PA, USA), at the USGS National Wetlands Research Center, Lafayette, Louisiana, USA. Flux rates were determined by the linear portion of fit saturation curves contrasting time with the concentration of gas, adjusted to sample chamber volume.

Samples were collected when water levels were <3 cm above the soil surface. Samples were collected 24 times from 26 October 2005 to 18 December 2007. Air temperature at chamber height and soil temperature at a 5 cm depth were recorded near each chamber during each measurement series.

Statistical Analyses

Soil redox data were analyzed with an ANOVA model using a full factorial design. Soil CO_2, CH_4, and N_2O flux data were analyzed using an ANOVA in a split-plot framework, with time as the whole-plot (repeated measures effect). Because there were 24 time points from which data were collected, but only three sites, the assumption that n+1>q (where n is sample size—in this case sites—and q is the number of repeated measures) was not met (Johnson and Wichern 1988). Therefore, we did not use a repeated measures analysis. Rather, we nested terms to account for the randomization restrictions under the split-plot framework. One sampling period (November 2005) was omitted from analysis because of extremely disparate values relative to measurements made during the other sampling periods. Regression analysis was used to test whether CO_2, CH_4, and N_2O flux data (untransformed) were related to soil temperature, air temperature, water level, or salinity. All data were subjected to a linear rank transformation prior to ANOVA in order to meet normality and homoscedastic variance standards. Data were analyzed using SAS (Version 9.1, SAS Institute, Cary, NC, USA).

Results

Soil redox potentials across all sites varied significantly between wet (38.4±12.1 SE mV) and dry (126.6±15.5 SE mV) periods ($F_{1,317}$=22.42; p<0.001). The Upper site (105.3±19.6 SE mV) had higher redox potentials than the Lower site (38.4±14.6 SE mV; $F_{2,317}$=4.88; p=0.008). The Middle site (86.5±16.3 SE mV) did not differ from the other two sites.

CO_2 dominated soil greenhouse gas fluxes relative to CH_4 and N_2O (Table 1). Averaged across all sites and sampling periods, soil CO_2 flux was 143.9 mg CO_2 m^{-2} h^{-1} (range, 6.7 to 684.5), CH_4 flux was 0.18 mg CH_4 m^{-2} h^{-1} (range, −0.17 to 1.12), and N_2O flux was 1.23 μg N_2O m^{-2} h^{-1} (range, −35.2 to 30.7) over 2 years. Time (i.e., month of sample collection) was an important factor mediating fluxes of CO_2 and CH_4 from soils (Table 1), but had no influence on N_2O flux.

Soil CO_2 fluxes were characterized by large variation among months and did not differ significantly by site on an annual basis (Table 1), despite a mean CO_2 flux rate of 90.2 mg CO_2 m^{-2} h^{-1} on the Lower site versus the Middle and Upper sites (162–179 mg CO_2 m^{-2} h^{-1}). There was a significant interaction between site and time for soil CO_2 fluxes that was not evident for other gases (Table 1), with site differences becoming significant during 2 months (Fig. 3). Specifically, CO_2 fluxes were greater from the Middle site than the Lower site in February 2006 by 335.4 mg CO_2 m^{-2} h^{-1} and greater from the Upper site than the Lower site in May 2006 by 257.1 mg CO_2 m^{-2} h^{-1}.

Soil CO_2 flux was correlated with soil temperature, which ranged from highs of 27–29°C in August to lows of 8–10°C in February. Overall, soil temperature explained 17% of the variation in soil CO_2 flux [y (mg CO_2 m^{-2} h^{-1}) =12.12 × (°C) – 90.34; r^2=0.170], while air temperature explained 12% of the variation in soil CO_2 flux [y (mg CO_2 m^{-2} h^{-1}) =11.23 × (°C) – 125.61; r^2=0.116]. Across all sites, seasonal peaks were not consistent between both years for soil CH_4 and N_2O fluxes (Fig. 3). Fluxes of CH_4 and N_2O also did not correlate with either soil or air temperature.

Among the three greenhouse gases assessed, only CO_2 emissions were related in any way to water level [y (mg CO_2 m^{-2} h^{-1}) = −4.98 × (cm) + 92.24; r^2=0.104]; soil CO_2 flux increased as tidal swamps became progressively drier. On several occasions, we registered CO_2 uptake from soils that typically occurred in the winter. When they did occur (8 of 69 times), rates of uptake were low (mean of 31.7 mg CO_2 m^{-2} h^{-1}). The incidence of CO_2 uptake by soils increased with mean tidal amplitude; 4 times at the Lower site, 3 times at the Middle site, and 1 time at the Upper site. Mean salinity levels collected within days of each sample date were not correlated with soil CO_2, CH_4, or N_2O fluxes (data not shown).

Discussion

Greenhouse Gas Losses from Tidal Swamps

Fluxes of C and N from CO_2, CH_4, and N_2O on our tidal swamps were within the range reported from other forested

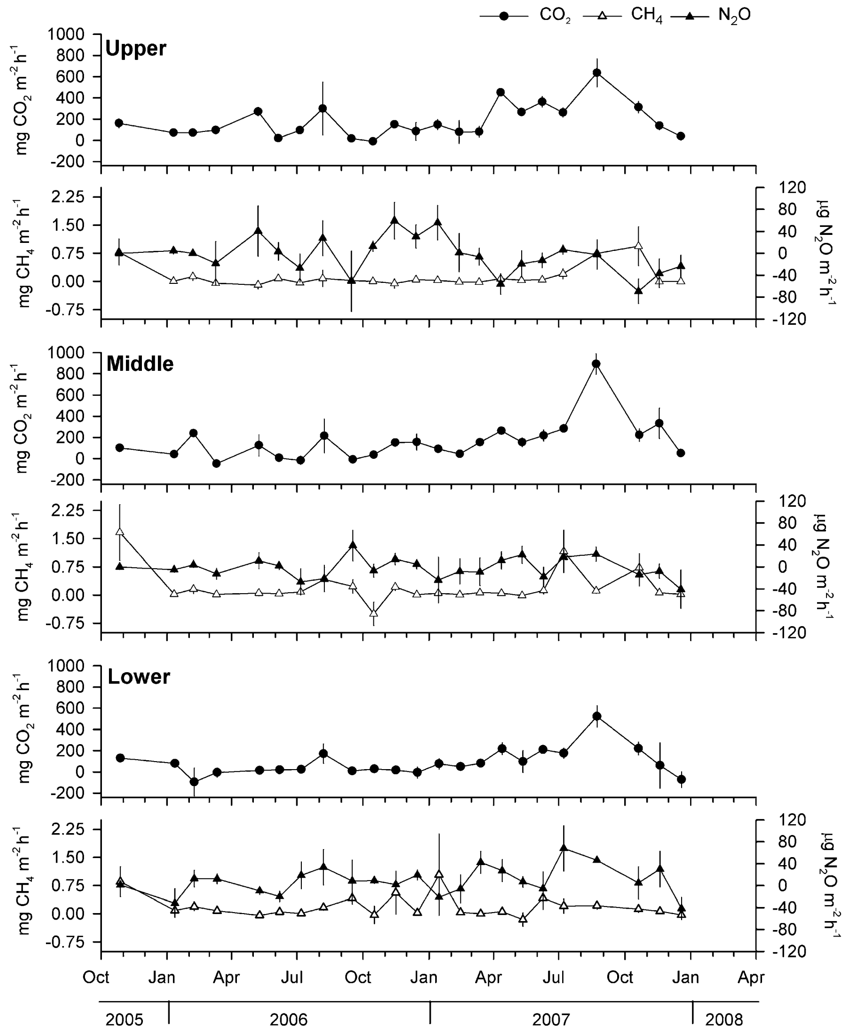


Fig. 3 Monthly soil CO_2, CH_4, and N_2O flux from tidal swamps at Savannah Upper, Middle, and Lower. Site × time interactions were significant only for CO_2 flux (Table 1)

wetlands in the eastern United States (Table 2). While our data do not demonstrate large peaks in gaseous C and N flux rates reported by other studies, variation in flux rates were still high (Fig. 3), especially for CO_2, making detection of consistent, annual differences among sites difficult.

Miller et al. (1999) found that CO_2 fluxes were highest in early spring and remained high through mid-summer, then both soil CO_2 and CH_4 fluxes decreased in late summer. Late summer corresponded to the greatest soil CO_2 fluxes in our study (Fig. 3), and was associated with soil temperature increases and peak biomass of herbaceous plants. It remains unclear what specific factors are driving CH_4 flux from Savannah River tidal swamps. Based upon regression analyses reported by Poffenbarger et al. (2011) and Bartlett et al. (1987), we would expect a salinity of 0.2 (our Upper site) versus 4.7 (our Lower site) to promote between 1.8 and 2.4 times greater CH_4 efflux from our freshwater site. However, we found no significant differences among sites, suggesting that a number of other factors differed between study sites (e.g., vegetation type, antecedent hydrology, etc.). Kelley et al. (1995) and Megonigal and Schlesinger (2002) found that as much as 52–96% of CH_4 produced in situ in tidal swamps can be oxidized and converted to CO_2 through the activities of methanotrophic bacteria. Low rates of CH_4 emissions may also help to explain why salinity did not seem to drive differences among our tidal swamp sites.

We did observe lower CO_2 fluxes at the Lower site relative to the Middle and/or Upper sites in two months that may be explained by higher water levels and low redox at the Lower site. Aerobic soil respiration is reduced as soil pore space is filled with water, and the water also acts as a barrier for diffusion of CO_2 to the atmosphere. CH_4 flux can be impeded in this fashion as well (Miller et al. 1999). Soil CH_4 production generally increases as water tables flood above ground, and soil CO_2 production generally decreases under these conditions (Moore and Knowles 1989). CO_2:CH_4 flux ratios relative to water level in our study generally

Table 2 Published rates of soil CO_2–C, CH_4–C, and N_2O–N effluxes from a range of forested wetland locations in the eastern United States

Location	mg CO_2–C m^{-2} day^{-1}	mg CH_4–C m^{-2} day^{-1}	mg N_2O–N m^{-2} day^{-1}	Reference
Savannah River, Georgia[a]				
Upper	925 to 1,422	0.90 to 3.62	−0.22 to 0.12	This study
Middle	805 to 1,321	1.69 to 5.83	−0.15 to 0.09	This study
Lower	363 to 818	1.26 to 5.60	−0.01 to 0.28	This study
Barataria Basin, Louisiana				
Warm season	392 to 3,303	−0.41 to 583	0.92 to 33.9	Yu et al. 2008
Cool season	286 to 1,565	0.20 to 273	−0.76 to 1.07	Yu et al. 2008
Red Maple/Hemlock Swamp, New York	−444 to 1,657	0 to 1,561 (approx.)	n/a	Miller et al. 1999
Ogeechee River, Georgia	1,750 to 3,000	−14 to 256	n/a	Pulliam 1993
Pocosin and Nyssa swamp, North Carolina	1,021 to 5,827	n/a	n/a	Bridgham 1991
Four Holes Swamp, South Carolina	n/a	3 to 16	n/a	Harriss and Sebacher 1981
Creeping Swamp, North Carolina	n/a	0 to 240	n/a	Mulholland 1981
Great Dismal Swamp, Virginia	n/a	−4 to 15	n/a	Harriss et al. 1982
Newport News, Virginia	n/a	0 to 752	n/a	Wilson et al. 1989
Corkscrew Swamp, Florida	n/a	−2 to 205	n/a	Harriss et al. 1988
Corkscrew Swamp, Florida	n/a	6 to 1,998	n/a	Harriss and Sebacher 1981
Freshwater Swamp, Louisiana	n/a	86 to 420	n/a	Alford et al. 1997
White Oak River Estuary, North Carolina	n/a	−2 to 79	n/a	Kelley et al. 1995

[a] Data were converted to daily elemental fluxes of C and N from the greenhouse gases CO_2, CH_4, and N_2O. Ranges represent a 95% confidence limit for the hourly means reported in Table 1

agree with this finding except that we recorded many CH_4 flux readings of ~0 mg CH_4 m^{-2} h^{-1} when water levels were between 0 and 20 cm below ground. As water tables decreased to a depth of 40 cm beneath the peat surface in laboratory simulations, CO_2 flux increased by 4.3 times while CH_4 emissions were reduced by 5 times (Moore and Dalva 1993). Along the White Oak River, North Carolina, USA, CH_4 flux peaked at around 80 mg CH_4 m^{-2} day^{-1} just as incoming tidal water levels reached the soil surface, and decreased considerably as soil surface water depths increased to 20 cm (to ~45 mg CH_4 m^{-2} day^{-1}: Kelley et al. 1995). However, as tidal water levels dropped and returned to the soil surface with ebb, soil CH_4 flux exceeded pre-flood levels (~97 mg CH_4 m^{-2} day^{-1}) reflecting a release of CH_4 produced under anaerobic conditions.

CO_2 made up the majority of the CO_2/CH_4 balance of ecosystem-level greenhouse gas flux from a tidal freshwater marsh (Neubauer et al. 2000); and it accounted for an even greater proportion of the balance from soils in our study. Hydroperiods were likely not long enough to promote strong and consistent methanogenesis on our tidal swamp sites, which are positioned in the upper intertidal zone.

Table 3 Annual soil CO_2, CH_4, and N_2O (mean±SD) fluxes, along with GWP estimates, for 2006 and 2007 as extrapolated from static flux chambers placed over tidal swamp soils along the lower Savannah River, Georgia, USA

	Annual flux			GWP[a]		
Site	CO_2 (g m^{-2})	CH_4 (g m^{-2})	N_2O (mg m^{-2})	(CO_2eq)	CH_4 (CO_2–eq)	N_2O (CO_2–eq)
Upper	1691.2±54.2	1.10±0.42	−36.1±34.1	1691.2	27.5	−10.8
Middle	1543.8±10.3	1.32±0.16	−15.2±51.3	1543.8	33.0	−4.5
Lower	844.2±178.6	1.36±0.50	84.6±40.0	844.2	34.0	25.2

[a] Calculations of global warming potentials (GWP) were based on mass conversions reported in Forster et al. (2007) over a 100-year time horizon; conversions were 1, 25, and 298 for CO_2, CH_4, and N_2O, respectively, and are calculated here on a cumulative annual basis (g CO_2–eq m^{-2} $year^{-1}$)

Also, our assessments excluded flux of CH_4 through the vegetation (Garnet et al. 2005).

N_2O fluxes were very low to neutral from our tidal swamps, perhaps also because of relatively short hydroperiods (Ensign et al. 2008), or due to sampling at low tide. We documented net rates of N_2O–N flux generally lower than published studies (Table 2). Additional study is required to develop stronger links, but what N_2O efflux was recorded was detected predominantly at the highest salinity Lower site (Table 1). Greater N_2O emissions may reflect a byproduct of nitrification of NH_4 released during mineralization of N (Freeman et al. 1997); increased N mineralization at slightly higher salinities has been found experimentally (Weston et al. 2006).

Greenhouse Gas Uptake from Tidal Swamp Soils

On some sampling dates, we measured CO_2 uptake by soils (Fig. 3). While soil uptake of CH_4 and N_2O can occur simply through concentration gradients between the atmosphere and soil (Yu et al. 2006), such descriptions are not common for CO_2. However, Miller et al. (1999) measured CO_2 uptake (up to 67.8 mg CO_2 m^{-2} h^{-1}) from a New York, USA floodplain swamp and Lovelock (2008) discovered uptake of up to 39.6 mg CO_2 m^{-2} h^{-1} from a dwarf, tidal mangrove forest in Australia. While uncertain of an exact cause, biological uptake of CO_2 may be continuing for some time in the darkness of the chamber (e.g., by algae) (C.E. Lovelock, pers. comm), pressure gradients developing as tides continue to drop or remain low may mask normal concentration gradients, or CO_2 may be absorbed directly by soil water through pH gradients (or some other mechanism). These results create a new challenge for modeling soil greenhouse gas fluxes from tidal sites, and may be especially acute given that we do not really know why the CO_2 fluxes are sometimes directed into the soil.

Annual Greenhouse Gas Emissions and Radiative Forcing

Greenhouse gas fluxes from wetlands are reported in different ways, including molecular (as in Table 1), elemental (as in Table 2), and as greenhouse gas equivalents that highlight the differential global warming potential (GWP) for CH_4 and N_2O relative to CO_2 (Montzka et al. 2011). We can estimate annual contributions of greenhouse gas emissions from tidal swamps to the atmosphere by summing emissions reported in Fig. 3 by hour and month for both study years. Among sites, CO_2 flux ranged from 844 to 1,691 g m^{-2} $year^{-1}$, CH_4 flux ranged from 1.1 to 1.4 g m^{-2} $year^{-1}$, and N_2O flux ranged from −36.1 to 84.6 mg m^{-2} $year^{-1}$ (Table 3). CO_2 flux was responsible for 99.0, 98.2, and 93.4% of the GWP among the suite of greenhouse gases measured from the Upper, Middle, and Lower sites, respectively. CO_2 contributed to 90.0–94.7% of GWP (warm season) for drier freshwater forested wetland sites in Louisiana (ridge, transition: Yu et al. 2008), but CH_4 (at 47.7%) was much more important than CO_2 (at 4.4%) to GWP from a permanently flooded site in the same study. CH_4 made up 2.3% of greenhouse gas emissions from our tidal swamps from a GWP perspective (Table 3), with no clear influence of site. In contrast, GWP from CH_4 emissions in tidal marshes was enhanced by nearly 3.6 times in tidal oligohaline marshes (salinity of 0.5–5.0) relative to tidal freshwater marshes (salinity <0.5); however, the significance of that result was driven by a single site (Poffenbarger et al. 2011).

Conclusions

As tidal swamps along the lower Savannah River undergo retreat, we found a modest influence of this transition on soil greenhouse gas emissions. Salinity, which ranged from 0.2 to 4.7, was not a significant driver of soil greenhouse gas emissions from these sites. Soil temperature, air temperature, and water level—in that order—had the greatest influence on soil CO_2 emissions, but none of those factors influenced soil CH_4 or N_2O emissions. Future studies should not only focus on identifying the specific drivers of greenhouse gas emissions from tidal swamps (especially CH_4 and N_2O), but also identify the spatial variability among those drivers for specific tidal swamp sites. Future work should also focus on discerning how the balance of CO_2, CH_4, and N_2O shifts along additional oligohaline salinity gradients in tidal swamps versus marsh.

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