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Key Points:

- Peat drainage carbon geochemistry varies in space and time and is broadly responsive to seasonal changes in Delta island hydrology
- Net lateral carbon exports can be the same order of magnitude as vertical carbon emissions from various land use types in this system
- Drainage DIC, DOC, and POC fluxes to surrounding waterways were greatest during winters of wet and dry water years

Supporting Information:

- Supporting Information S1

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Lateral Carbon Exports From Drained Peatlands: An Understudied Carbon Pathway in the Sacramento -San Joaquin Delta, California

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Abstract Degradation of peatlands via drainage is increasing globally and destabilizing peat carbon (C) stores. The effects of drainage on the timing and magnitude of lateral C losses from degraded peatlands remains understudied. We measured spatial and temporal variability in lateral C exports from three drained peat islands in the Sacramento-San Joaquin Delta in California across the 2017 and 2018 water years using measurements of dissolved inorganic C (DIC), dissolved organic C (DOC), and suspended particulate organic C (POC) concentration combined with discharge. These measurements were supplemented with stable isotope data (δ^{13}C-DIC, δ^{13}C-POC, δ^{15}N-PON, and δ^{2}H-H_2O values) to provide insight into hydrological and biogeochemical controls on lateral C exports from drained peatlands. Drainage DOC and DIC concentrations were seasonally variable with the highest values in the winter rainy season, when discharge was also elevated. Seasonal differences in the mobilization of dissolved C appeared to result from changing water sources and water table levels. Peat island drainage C contributions to surrounding waterways were also greatest during the winter. Although temporal variability in C cycling processes and trends were generally similar across islands, baseline drainage DIC, DOC, and POC concentrations were spatially variable, likely a result of sub-island-scale differences in soil organic matter content and hydrology. This spatial variability complicates system-wide assessments of C budgets. Net lateral C exports were water year dependent and comparable to previously published vertical C emission rates for this system. This work highlights the importance of including lateral C exports from drained peatlands in local and regional C budgets.

1. Introduction

Peatlands are an important land-based carbon (C) sink, storing almost one third of the world's soil C (Gorham, 1991; Jenkinson et al., 1991). Human disturbances to peatlands are increasing globally, destabilizing peat C stores and compromising their capacity to serve as C sinks (Leifeld & Menichetti, 2018; Sanderman et al., 2017). Over 10% of the planet's peatlands have been drained or mined (Joosten, 2009). Drainage of peatlands can alter prevailing biogeochemical processes, with effects on dissolved/particulate (lateral) and gaseous (vertical) C exports. Greenhouse gas (GHG) emissions have been the focus of many studies in degraded peatlands as these systems can emit large amounts of CO_2, CH_4, and N_2O to the atmosphere (Leifeld & Menichetti, 2018). Lateral C exports, as dissolved inorganic C (DIC), dissolved organic C (DOC), and suspended particulate organic carbon (POC), remain an understudied component of peatland C budgets (Worrall et al., 2005). Past work suggests that lateral C losses from peatlands and other C-rich systems can be significant components of local C budgets (Krauss et al., 2018) and not accounting for lateral C terms can lead to mischaracterizations of net C sequestration. DOC exports in some systems were reported to account for 10% of C losses (Limpens et al., 2008), and water flowing through peatlands is typically supersaturated with respect to CO_2 (Billett & Moore, 2008; Dawson et al., 2002, 2004), indicating that DIC exports may also be important. Lateral C exports can impact downstream ecosystems through the delivery of organic and inorganic C with effects on water quality, primary productivity, calcification, bacterial production, metal mobilization, and light availability (Carpenter & Pace, 1997; Schindler et al., 1997; Wetzel, 2003; Williamson et al., 1999; Wit et al., 2018). Many questions still exist regarding the nature of and controls on the magnitude of lateral C exports from peatlands, especially in altered and drained systems.

Drainage changes fundamental hydrologic properties of peatlands (e.g., water storage, recharge, and release). Water table declines induced by drainage have been documented in a number of altered peatlands in boreal and temperate climates (Deverel et al., 2007; Deverel & Rojstaczer, 1996; Holden et al., 2011; Price, 2003; Strack et al., 2008). Drainage has also been shown to shift flow pathways through peat; Holden et al. (2006) found drainage reduces overland flow and increases throughflow. These changes in peat hydrology can affect subsurface properties (e.g., macropore density, bulk density, soil water content, oxygen availability, and temperature). Water table drawdown is commonly associated with an ingress of O_2, which can shift historically anaerobic peat systems to aerobic environments (Limpens et al., 2008). These physicochemical properties control biotic and abiotic C storage and release mechanisms. For example, Chow et al. (2006) found that C mineralization rates and CO_2 production respond to changes in soil water content and temperature in peat soils.

In this study, we leverage the artificial infrastructure of drained peatlands in the Sacramento-San Joaquin Delta (the Delta) in central California, a system that provides freshwater to over 27 million people and generates 1.6 billion dollars in economic output from agriculture (DPC, 2012), to better understand variability and controls on peat drainage C geochemistry and exports. The Delta is a ~2,800 km^2 inverted river delta wherein the seaward side is constrained by the Coast Ranges, which focus flow through a narrow channel, and the landward side fans out into a complex network of distributaries. The landward portion of the Delta consists of ~57 peat islands that are drained into surrounding river channels; nearly all drainage occurs via managed outlets, allowing for relatively robust estimates of discharge. Peat oxidation from continuous drainage of Delta islands for farming over the past century has led to land subsidence of up to 15 m in some locations (Deverel & Leighton, 2010). While gaseous C exchange has been extensively studied on Delta islands (Anderson et al., 2016; Baldocchi et al., 2012; Hatala et al., 2012; Hemes et al., 2019; Knox et al., 2015; Teh et al., 2011; Windham-Myers et al., 2018), little quantitative work exists documenting the magnitude and timing of lateral C exports. A better understanding of lateral C losses from Delta islands is needed to address current knowledge gaps in local C budgets and C accounting and, more broadly, degraded peatland C balances. This is especially relevant in the Delta as stakeholders and agencies are pursuing new initiatives to reduce GHG emissions in the Delta using GHG accounting to incentivize low-emissions land use management practices. Lateral C exports from Delta islands may also create water quality issues in surrounding waterways and in water conveyed to other areas of California (Fleck et al., 2007; Fujii et al., 1998). Previous work has shown that dissolved organic matter (DOM) inputs from drained Delta islands are associated with seasonal changes in downstream river DOM quality (Kraus et al., 2008), suggesting that lateral C exports from these islands are measurable and important sources of C to Delta waters seasonally. In this study, we present hydrological and biogeochemical data from three artificially drained peat islands in the Delta over the course of two water years to (1) quantify lateral C exports from drained Delta peat islands, (2) examine the timing and magnitude of lateral C exports to better understand physical and biogeochemical controls on C geochemistry, and (3) compare lateral C fluxes to vertical C fluxes to assess the importance of this term in peat C budgets. This work will improve our conceptual understanding of similarly drained and cultivated peatlands elsewhere, which are growing in number worldwide due to human alteration.

2. Methods

2.1. Study Location

The Delta, which makes up the landward region of the San Francisco Estuary (Figure 1), has a Mediterranean climate that is generally defined by cool, wet winters and hot, dry summers. The Sacramento and San Joaquin Rivers provide the majority of freshwater inflow and allochthonous organic C to Delta waters as they drain ~40% of California's land area (Jassby & Cloern, 2000; Roy et al., 2006). Wastewater treatment plants are major anthropogenic sources of allochthonous C to the Delta as well, with the Sacramento Regional County Wastewater Treatment Plant contributing the greatest mass fluxes of DOC (~350 to 550 Mg C per month) (Sickman et al., 2007).

The central Delta is largely composed of surficial peat deposits, up to 15 m thick, and mineral soils at depth (Atwater & Belknap, 1980; Tugel, 1993). We use the terms “peat” and “peatlands” to describe soils that are high in organic C content, recognizing that though much of the central Delta has soils with >20% organic C content, some locations have values between ~5% to 20% C (Deverel et al., 2016; Drexler et al., 2009). This

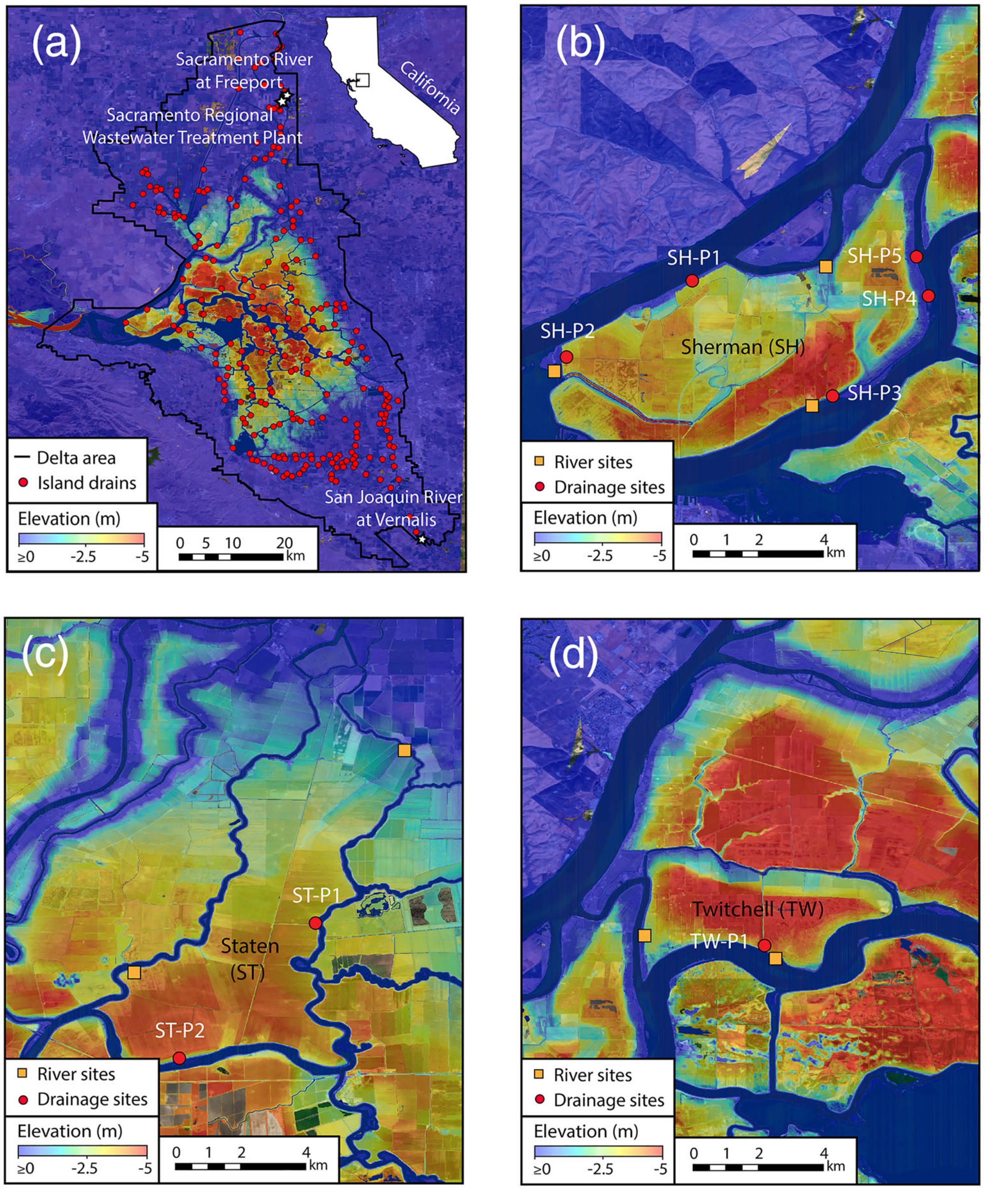

Figure 1. (a) Map of the study area, the Sacramento-San Joaquin Delta (shown as a black box on subfigure), in central California with a high-resolution (10 m/pixel) digital elevation model (DEM) showing drain locations (red circles) from a digitized version of CDWR (1995). (b–d) Overviews of islands sampled, Sherman (SH), Staten (ST), and Twitchell (TW), showing where drainage samples (red circles) and river samples (orange squares) were collected between June 2017 and September 2018. The DEM depicts land elevations between 0 and −5 m below sea level. DEM is available from Fregoso et al. (2017).

region was drained beginning in the mid-1880s, and by the 1930s was transformed into a patchwork of leveed tracts of lands surrounded by fixed channels, commonly referred to as "islands." The interior elevation of Delta islands is typically below the water level of surrounding river channels, while island perimeters consist of levees elevated above adjacent river channels. To prevent island inundation and flooding, water levels on Delta islands are artificially managed by a system of ditches which route excess water for discharge at pump stations on each island. Peat island drainage waters are a combination of seepage waters, irrigation waters (water deliberately suctioned onto the island from surrounding river channels), and precipitation. The proportion of these sources varies by season, land use, and management practices.

For this study, drainage water from pump stations on three Delta islands—Sherman, Staten, and Twitchell (Figure 1)—were sampled monthly from June 2017 to September 2018 and analyzed for a suite of geochemical parameters including concentrations and stable isotope composition of dissolved and particulate C as well as ancillary water quality parameters. Sherman Island is dominated by pastureland (>55%), with cropland secondary in spatial coverage (~30%) (see Table S1 in the supporting information). Twitchell Island has a more mixed land use with several experimental wetlands (~30%), pastureland (20%), and cropland (48%). Staten Island is predominantly cropland (>95%). Crops on Staten Island include alfalfa, corn, potatoes, and wheat. In addition to the drainage waters, samples were collected from surrounding river channels at seven locations (Figure 1). A multiparameter water quality meter (YSI ProPlus) was used to measure water pH, dissolved oxygen, conductivity, and temperature at the time of sample collection. This study focuses on the peat drainage C geochemistry data and only limited river geochemistry data are presented. Additionally, we excluded geochemistry data for any drainage water sites where monthly discharge was zero (e.g., May 2018 to September 2018 at SH-P4 and all of SH-P1).

2.2. Geochemistry Sample Collection and Analysis

Drainage samples were collected monthly from water in ditches within ~2 m of pump stations, and river samples were collected from island shores (Figure 1). Water samples were collected in 1 to 4 L bottles for subsampling. Samples for DIC were immediately poured off into 125 ml borosilicate bottles with Si-free greased glass stoppers and poisoned with $HgCl_2$ to inhibit biological activity. DIC concentrations were measured using a UIC Carbon Coulometer Analyzer. DOC samples were vacuum filtered to 0.2 μm in the lab (generally within 24 hr) into 22 ml glass vials and frozen for storage until analysis (typically within a week of collection). DOC concentrations were measured as nonpurgeable organic carbon (NPOC) on a Shimadzu TOC-VCPH TOC/TN Analyzer. The NPOC method was used instead of the total organic carbon (TOC) method due to the effect of high DIC concentrations on TOC measurements in fresh waters (Findlay et al., 2010). SiO_4^{4-} concentrations were measured using a Lachat AutoAnalyzer AA3, and Cl^- concentrations were determined using a Dionex ICS-2000 ion chromatography analyzer. Absorbance of light at 254 nm was measured for all samples on a Thermo Genesys 10S UV–Visible Spectrophotometer. These values were normalized to DOC concentration to obtain mass-specific UV absorbance ($SUVA_{254}$). Errors on precision and accuracy for all of the above analyses were generally below 5%. Total suspended sediment (TSS) concentrations were determined by weight after passing known volumes of unfiltered sample water through combusted, preweighed GF/F filters (0.7 μm). Particulate organic matter (POM) concentrations were estimated from TSS concentrations. POM was assumed to comprise the majority of TSS (75%), and 50% of POM was assumed to be C by mass (Deverel & Rojstaczer, 1996) since carbonates make up $\ll$1% of Delta soils (Drexler et al., 2009). For river TSS samples, we used previously published relationships for TSS and POC for the Delta from Murrell and Hollibaugh (2000) to calculate POC concentrations. Temperature, DIC, and pH data were used to calculate pCO_2 using CO2calc (Robbins et al., 2010). Mean values, as averages of all drainage or river sites, are denoted herein as "$\overline{x}$" and typically presented with their 1-sigma standard deviation. All seasonal means and fluxes presented in this study are grouped monthly as follows: fall (September through November), winter (December through February), spring (March through May), and summer (June through August).

2.3. Stable Isotope Sample Collection and Analysis

δ^{13}C-DIC samples were collected in 20 ml glass vials with minimal headspace and poisoned with $HgCl_2$ immediately upon collection to inhibit biological activity. δ^{13}C-DIC values were determined on a ThermoQuest Finnigan Delta PlusXL at the University of Arizona Stable Isotope Facility. Analytical precision for the δ^{13}C-DIC values was 0.2‰. δ^{13}C-POC and δ^{15}N-PON samples were collected quarterly, and all samples were processed and analyzed at the USGS-Menlo Park Stable Isotope Facility using a Carlo Erba NC 1500 elemental analyzer coupled to an Isoprime mass spectrometer. POM ratios of C to N are presented herein as molar fractions as $(C/N)_m$. Analytical precision for δ^{13}C-POC and PON values was 0.3‰ and 0.4‰, respectively, and 0.1 for $(C/N)_m$ of POM. δ^2H-H_2O samples were collected monthly and run at the University of Hawaii's Biogeochemical Stable Isotope Facility on a Picarro L2130-i. Analytical precision for the δ^2H-H_2O values was 0.5‰.

2.4. Discharge Measurements, Mass Flux Estimates, and Net Flux Estimates

Discharge for each pump site, D (ac-ft), was calculated using an empirical equation based on the unit-power consumption method, which relies on electrical usage, P (kW-hr), and measured pump efficiency, U (kW-hr ac-ft^{-1}), to generate discharge estimates where $D = P/U$ (Diamond & Williamson, 1983; Ogilbee, 1966; Ogilbee & Mitten, 1979). Electrical records were obtained from the electrical utility for each drainage outlet (pump station) from October 2016 to October 2018, and each pump was assessed for pump efficiency (defined as the unit-use coefficient which is a measure of the amount of electrical energy it takes to pump a known volume of water) within 2 months of the start of the sampling period except for TW-P1, which had a recent active test in October 2016 (Table S2). Discharge estimates were cross-checked with 1.5 years of daily flow meter data (AgriFlo XCi ultrasonic sensor) available from TW-P1 on Twitchell Island. This cross-comparison indicated that the unit-power consumption method is a relatively robust approximation of discharge ($m = 0.87$, $R^2 = 0.75$) (Figure S1). Importantly, this cross comparison suggested that the unit-power consumption method consistently underestimates actual discharge. As such, our export and flux calculations herein are considered conservative estimates of actual total lateral C losses (as the sum of DIC, DOC, and POC) from drained Delta islands.

Discharge and mass flux data are presented in the context of water years (WYs). WY 2017 (1 October 2016 to 30 September 2017) was classified as above normal (referred to herein as "wet"), with cumulative annual precipitation at California Irrigation Management Information System (CIMIS) Station 242 (located on Staten Island) totaling 95.4 cm (https://cimis.water.ca.gov/). WY 2018 (1 October 2017 to 30 September 2018) was below normal (referred to herein as "dry"), with cumulative annual precipitation at CIMIS Station 242 totaling 27.9 cm.

Peat drainage DOC and DIC fluxes were calculated from monthly concentration and discharge data for each island. On islands with more than one drainage outlet (Staten and Sherman), we summed C fluxes for each outlet. POC fluxes were generated quarterly, at the same interval as POC sample collection. We report export rates as mass flux divided by area. Drainage areas for each site were subdivided based on topographical divides within islands (see Figure S2). Export rates for WY 2017 were extrapolated from WY 2018 concentration-water yield (discharge normalized to area) relationships to fill in missing concentration data for WY 2017 (Table S3). Specifically, regressions developed from WY 2018 for each station were applied to associated WY 2017 data and sites; 19 of 25 regressions were statistically significant ($p < 0.05$) (Table S3).

DOC fluxes from other regionally important allochthonous sources were calculated for comparison to peat island drainage DOC contributions to Delta waters. DOC flux from the Sacramento River at Freeport was calculated at 15 min resolution using fluorescent-dissolved organic matter (fDOM) data corrected to DOC concentrations ($R^2 = 0.63$, $n = 26$ between 19 October 2016 and 20 August 2019) and discharge data from the U.S. Geological Survey (USGS) monitoring station 11447650 (USGS, 2019). San Joaquin River at Vernalis DOC flux was calculated using the average concentration of submonthly grab samples collected by the USGS and discharge data from USGS monitoring station 11303500. Sacramento Regional Wastewater Treatment Plant (SRWTP) DOC flux was calculated using monthly DOC concentrations and discharge data downloaded via the California Integrated Water Quality System (https://www.waterboards.ca.gov/ciwqs/).

Island water budgets were developed for WY 2017 and WY 2018 to generate baseline estimates of lateral C imports to Delta islands via river inflow for use in net lateral C calculations. Annual water inflow, including both seepage through levees and water diverted onto the island for irrigation, were calculated for each island studied (ST, SH, and TW) as follows:

$$I = O + ET - P \tag{1}$$

where I is river inflow (m^3), O is island drainage outflow (m^3), ET is evapotranspiration (m^3), and P is precipitation (m^3). Water budget data are shown in Table S4. Outflow was determined by the unit-use power consumption method discussed above. P was based on measured data from Station 247 for Sherman Island, Station 242 for Staten Island, and Station 140 for Twitchell Island via CIMIS (https://cimis.water.ca.gov/). ET was calculated at a monthly scale and summed to annual by correcting monthly reference evapotranspiration rates using crop coefficients for land use cover on each island for both a wet WY

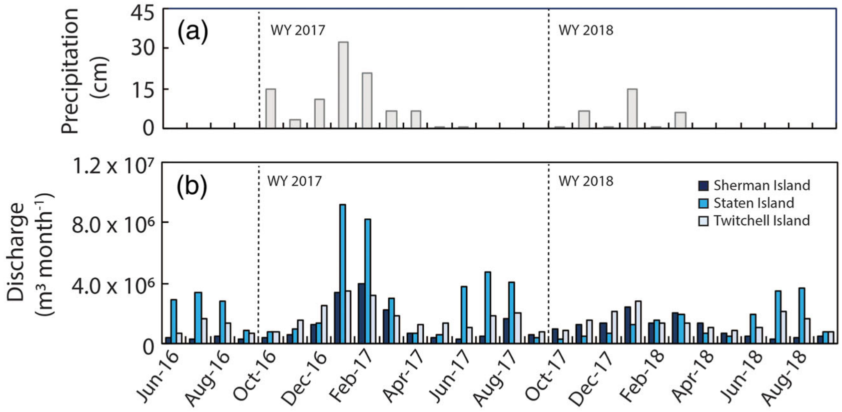

Figure 2. (a) Monthly precipitation and (b) discharge from Sherman, Staten, and Twitchell islands. Precipitation data were acquired from Station 242 via the California Irrigation Management Information System (CIMIS). Discharge data were determined using the unit-power consumption method and cross-checked with measured flow meter data (see Figure S1).

(2017) and dry WY (2018) (http://www.itrc.org/etdata/index.html). Land use cover on each island was determined using a statewide crop mapping geodatabase available online (https://data.cnra.ca.gov/dataset/statewide-crop-mapping) (see Table S1). Change in storage was assumed to be negligible on an annual scale based on previous studies that show island water tables are generally stable at this time scale (Deverel et al., 2015, 2016). Our annual *ET* and *P* estimates at the island level were also in close agreement with values estimated by the Delta Channel Depletion model (L. Liang, California Department of Water Resources, personal communication, Jul 2020). Inflow C import rates were calculated using C species concentration data for waterways surrounding each island and inflow volumes separated based on time (September to May; June to August, see Table S5) to generate more refined import rates as most inflow on Delta islands occurs in the summer when river C concentrations are lower. Net C fluxes from each island were calculated by subtracting the annualized inflow C flux (or import), which was taken as the weighted average of the previously discussed rates with respect to time, from the annualized drainage C flux (or export).

3. Results

3.1. Discharge Trends From Peat Island Drainage Outlets

Peat drainage discharge was highly variable across islands and water years, though seasonal trends were apparent. Across all three islands, discharge was generally greatest in the winter (December to February), with 49% and 32% of annual discharge occurring in winter of WY 2017 and WY 2018, respectively (Figure 2). Additional pulses of high discharge occurred in the summer on Twitchell and Staten Islands, both of which contain greater proportions of irrigated cropland relative to Sherman Island (Table S1).

Cumulative discharge from all islands was substantially higher in wet WY 2017 than in dry WY 2018. On Sherman Island, discharge decreased 17%, from 1.57×10^7 m^3 yr^{-1} to 1.31×10^7 m^3 yr^{-1}, between WY 2017 and WY 2018. On Staten Island, discharge decreased 55% from 3.75×10^7 m^3 yr^{-1} to 1.70×10^7 m^3 yr^{-1}; this decrease was mainly driven by much lower discharge (up to 87%) during winter months in WY 2018. On Twitchell Island, annual discharge decreased 19% from 2.16×10^7 m^3 yr^{-1} in WY 2017 to 1.75×10^7 m^3 yr^{-1} in WY 2018.

3.2. Peat Drainage Geochemistry

δ^2H-H_2O values as well as concentrations of Cl^- and SiO_4^{4-} were used as semiconservative tracers of water source. Peat drainage samples generally had an inverse relationship between (1) Cl^- and δ^2H-H_2O and (2) Cl^- and SiO_4^{4-} (Figure 3). The two most southern drainage sites on Sherman Island, SH-P2 and SH-P3, generally had higher Cl^- concentrations compared to all other sites (Figure 2). These sites also had higher δ^2H-H_2O values, but a wide range of SiO_4^{4-} concentrations (120 to 590 μM). The two other Sherman Island drain

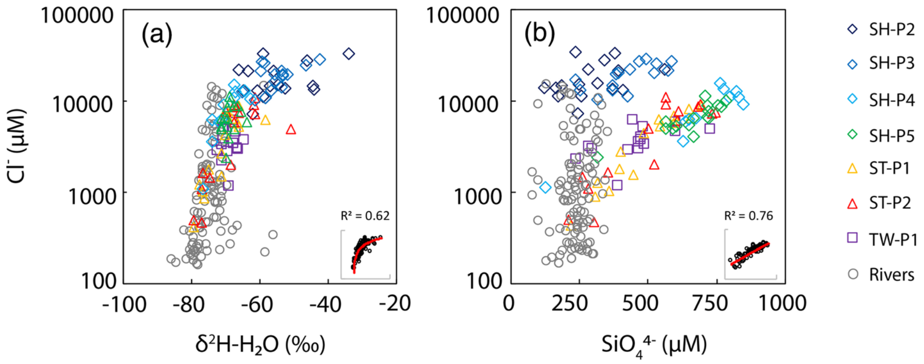

Figure 3. Peat drainage Cl^- concentration versus (a) δ^2H-H_2O values and (b) SiO_4^{4-} concentrations. Inset figures show cumulative R^2 between (a) all sites and (b) all sites except SH-P2 and SH-P3. See Figure 1 for site locations (SH: Sherman Island sites, ST: Staten Island sites; TW, Twitchell Island sites).

sites, SH-P4 and SH-P5, had slightly lower Cl^- concentrations and δ^2H-H_2O values, but higher SiO_4^{4-} values than the sites to the south.

Seasonal and annual mean DOC and DIC concentrations in peat island drainage waters were much higher than surrounding rivers and monthly DOC and DIC concentrations typically peaked in winter and early spring (Tables 1 and 2 and Figures 4a and 4b). On islands with multiple pump sites, DIC and DOC concentrations in drainage waters were highly variable between sites. On Sherman Island, mean annual DIC concentrations in drainage waters for all four sites (SH-P2, SH-P3, SH-P4, and SH-P5) ranged from 2,380 ± 690 to 5,580 ± 2,120 µM, and mean DOC concentrations ranged from 1,120 ± 410 to 3,540 ± 1,280 µM. Peat

Table 1
Water Year (WY) 2018 Mean and Standard Deviation of River and Drainage C Geochemistry and Related Parameters

Site		Rivers	SH-P2	SH-P3	SH-P4[a]	SH-P5	ST-P1	ST-P2	TW-P1
POC (µM)	mean	70	2,180	1,810	640	2,060	1,700	1,440	1,140
	stdev	65	720	440	380	660	940	860	530
DOC (µM)	mean	290	2,230	3,540	1,850	1,120	1,320	2,670	1,460
	stdev	150	880	1,280	900	410	630	1,400	600
DIC (µM)	mean	1,180	5,580	5,560	3,300	2,380	3,160	3,800	2,400
	stdev	360	2,120	1790	1,000	690	1,240	1,460	260
pCO_2 (µatm)	mean	1,270	20,480	11,280	25,800	10,830	11,940	14,150	13,500
	stdev	920	16,700	9,800	4,250	7,250	6,000	6,800	3,800
$SUVA_{254}$ (L mg C^{-1} m^{-1})	mean	2.6	4.3	4.1	4.4	4.4	3.8	4.1	4.7
	stdev	1.1	0.3	0.3	0.7	0.7	0.6	1.1	1.6
$\delta^{13}C$-DIC (‰)	mean	−8.4	−10.8	−9.0	−14.1	−10.5	−12.3	−7.3	−12.2
	stdev	1.5	1.8	2.3	0.8	2.0	1.4	3.0	1.1
POM $(C/N)_m$	mean	8.7	8.0	8.7	12.0	10.3	9.7	10.7	11.1
	stdev	0.9	1.1	2.1	0.9	2.8	1.7	1.8	1.1
$\delta^{13}C$-POC (‰)	mean	−28.3	−34.4	−33.7	−31.1	−29.7	−27.0	−28.6	−29.1
	stdev	1.3	3.0	0.9	3.2	1.5	1.0	2.1	0.6
$\delta^{15}N$-PON (‰)	mean	4.9	3.0	3.3	0.1	−0.1	3.2	2.4	1.6
	stdev	2.1	3.4	3.2	3.0	0.5	0.9	1.5	1.4
pH (NBS)	mean	7.6	7.2	7.6	6.5	7.1	7.0	7.1	6.8
	stdev	0.4	0.3	0.5	0.2	0.4	0.2	0.1	0.2
DO (mg L^{-1})	mean	9.4	7.1	7.2	1.2	6.6	3.8	2.6	2.5
	stdev	1.4	2.3	3.3	1.2	1.8	2.3	2.0	1.9
δ^2H-H_2O (‰)	mean	−73.7	−59.5	−56.5	−67.1	−68.7	−69.7	−67.3	−68.9
	stdev	4.5	4.1	4.9	3.5	1.7	5.4	7.3	1.9
SiO_4^{4-} (µM)	mean	240	310	440	790	670	510	540	500
	stdev	60	120	100	60	130	140	170	110

Note. WY 2017 data are not included so as not to bias the annual mean. For explanation of site abbreviations and locations see Figure 1.
[a] SH-P4 water year data are incomplete as data collected during net zero discharge months were not included.

Table 2
Seasonal Means of Peat Island Drainage Carbon (C) Geochemistry and Ancillary Water Quality Parameters in Drainage From Sherman Island (SH), Staten Island (ST), and Twitchell Island (TW) for Data Across Water Year (WY) 2017 and WY 2018

Site	Season	POC (μM)	DOC (μM)	DIC (μM)	pCO_2 (μatm)	$SUVA_{254}$ (L mg C^{-1} m^{-1})	$\delta^{13}C$-DIC (‰)	POM $(C/N)_m$	$\delta^{13}C$-POC (‰)	$\delta^{15}N$-PON (‰)	pH (NBS)	DO (mg L^{-1})	δ^2H-H_2O (‰)	SiO_4^{4-} (μM)
SH-P2	Fall	2,030	1,690	4,340	8,920	4.4	−9.0	8.5	−34.5	2.8	7.41	7.2	−55.1	240
	Winter	1,710	2,860	6,340	19,590	4.2	−10.8	n.a.	−38.0	2.3	7.10	7.8	−62.4	380
	Spring	3,250	2,650	7,360	37,900	4.3	−12.1	n.a.	−30.7	−0.3	6.93	7.4	−60.3	340
	Summer	1,760	2,150	5,160	13,380	3.9	−9.8	7.7	−33.6	5.5	7.36	6.7	−49.0	260
SH-P3	Fall	3,080	4,890	6,470	7,120	4.0	−6.0	7.7	−34.2	3.8	7.68	10.2	−48.9	480
	Winter	1,670	4,130	6,810	21,300	4.0	−10.1	9.9	−34.0	1.6	7.08	5.4	−57.4	490
	Spring	2,450	3,480	5,940	15,640	4.0	−11.4	11.1	−32.7	0.3	7.25	3.8	−58.7	430
	Summer	1,580	2,750	3,580	1,470	4.2	−7.3	8.6	−31.7	7.7	8.20	9.0	−56.8	340
SH-P4	Fall	530	1,240	2,530	29,800	3.9	−14.1	13.8	−29.4	−0.5	6.35	0.7	−70.8	860
	Winter	380	1,410	2,970	24,500	4.2	−14.0	11.3	−33.4	−2.0	6.46	2.0	−68.4	810
	Spring	910	3,040	4,460	24,890	4.9	−13.9	12.6	−28.8	2.2	6.79	0.3	−63.5	820
	Summer	1,380	940	2,160	21,800	4.0	−11.5	12.2	−31.0	−0.6	6.58	1.2	−74.1	750
SH-P5	Fall	1,690	1,140	2,420	15,010	4.1	−11.7	8.7	−31.6	−0.1	6.77	4.1	−70.3	710
	Winter	1,600	1,300	2,920	14,530	4.5	−10.9	12.0	−28.2	−0.1	6.87	7.4	−68.5	730
	Spring	3,040	1,120	2,400	9,870	4.1	−11.1	13.4	−28.9	−0.2	7.11	7.1	−67.2	600
	Summer	1,200	1,020	1,820	7,600	4.5	−8.8	7.7	−31.1	2.6	7.19	6.2	−68.3	620
ST-P1	Fall	1,810	1,920	3,050	13,800	3.7	−12.5	9.7	−28.9	2.9	6.97	1.8	−68.5	520
	Winter	940	1,630	4,180	17,330	4.3	−11.5	10.0	n.a.	2.9	6.93	3.4	−65.5	620
	Spring	1,530	1,090	3,470	10,090	3.5	−13.2	11.1	−27.3	2.0	7.12	5.0	−68.9	560
	Summer	1,280	600	1,540	5,240	3.7	−11.9	7.3	−27.8	4.1	7.15	4.6	−76.9	320
ST-P2	Fall	2,540	3,980	4,350	18,290	3.5	−7.4	8.4	−32.5	4.5	7.01	2.9	−65.9	600
	Winter	1,270	3,680	4,690	15,760	3.5	−5.0	11.3	n.a.	1.0	7.06	1.4	−61.5	600
	Spring	2,700	2,550	4,590	14,390	3.7	−6.0	13.0	−27.2	1.5	7.15	2.7	−64.2	680
	Summer	840	690	1,460	5,430	5.0	−9.4	9.1	−27.6	4.4	7.09	5.2	−76.7	280
TW-P1	Fall	1,150	1,270	2,240	14,970	3.2	−11.5	11.4	−28.9	1.3	6.73	1.9	−71.4	500
	Winter	830	1,790	2,440	14,170	5.2	−12.1	10.1	−29.7	2.6	6.73	3.3	−69.3	550
	Spring	550	1,670	2,530	13,890	4.8	−12.5	12.6	−28.3	0.5	6.82	2.1	−67.3	560
	Summer	1,130	1,370	2,320	12,790	5.1	−11.9	10.5	−28.5	2.3	6.91	1.4	−67.6	360

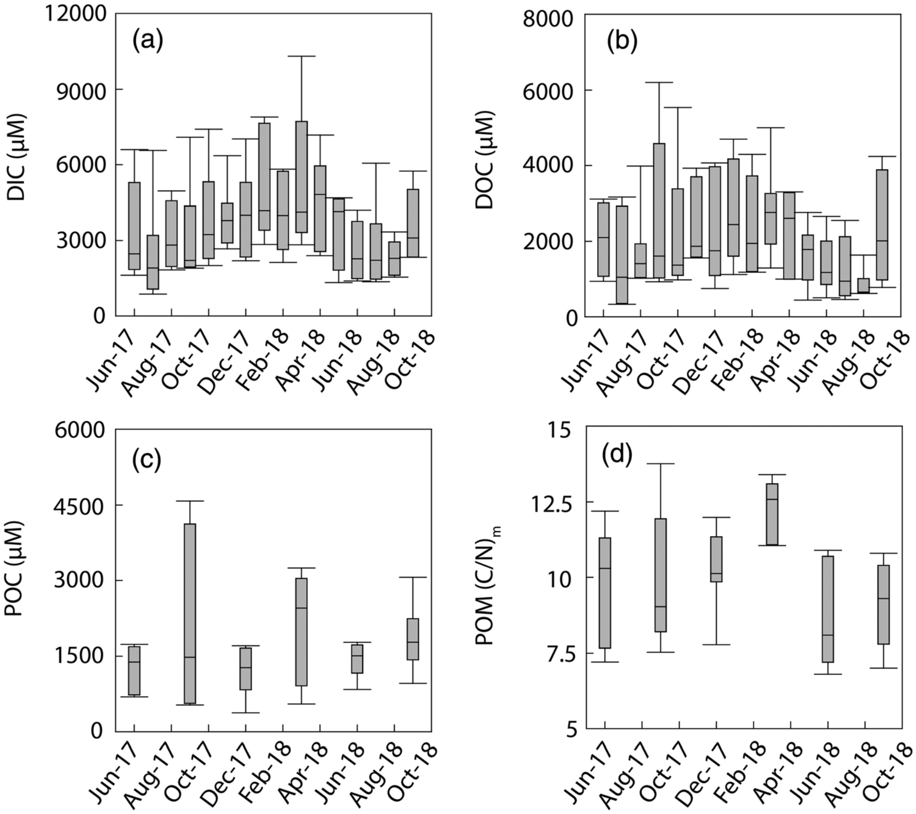

Figure 4. Box plot time series for (a) monthly DIC concentrations, (b) monthly DOC concentrations, (c) quarterly POC concentrations, and (d) quarterly POM $(C/N)_m$ in peat island drainage waters from all active drainage pump sites sampled across WY 2017 and WY 2018. Boxes represent the bounds of the middle quartiles, and lines represent median values. Whiskers show the bounds of the outer quartiles (5th and 95th) of the data.

drainage on Staten Island (ST-P1 and ST-P2) had mean DIC and DOC concentrations of 3,160 ± 1,230 to 3,800 ± 1,460 μM and 1,320 ± 630 to 2,670 ± 1,400 μM, respectively. Mean DIC and DOC concentrations in drainage from TW-P1 on Twitchell Island were less variable at 1,460 ± 600 μM and 2,400 ± 260 μM, respectively. Mean peat island drainage water POC concentrations across all sites ranged from 640 ± 380 to 2,180 ± 720 μM, with no clear spatial or temporal trends (Table 1 and Figure 4c). $(C/N)_m$ ratios of drainage POM were seasonally variable and generally fluctuated between 7.3 to 10.5 ($\bar{x} = 9.0 \pm 1.8$) in the summer and 9.9 to 13.4 ($\bar{x} = 11.5 \pm 1.2$) in the winter/spring (Table 2 and Figure 4d). Nearly all drainage sites were supersaturated with CO_2 each month, and the highest pCO_2 values occurred in winter and spring (Table 2). Multiple sites on Sherman Island had pCO_2 values over 20,000 μatm.

Peat drainage $SUVA_{254}$ values ranged between 3.8 to 4.7 L mg C^{-1} m^{-1}, with no notable patterns by site or date (Table 1). δ^{13}C-DIC values were highly variable both spatially and temporally (Figure 5a and Tables 1 and 2). Similar to variability in dissolved C concentrations, significant differences in δ^{13}C-DIC values were recorded even for samples collected on the same island; for example, mean δ^{13}C-DIC values for ST-P1 and ST-P2 were −7.3 ± 3.0 and −12.3 ± 1.4, respectively. δ^{13}C-POC and δ^{15}N-PON values generally changed seasonally as well, alternating between (1) lower δ^{13}C-POC values and higher δ^{15}N-PON values in the summer and (2) higher δ^{13}C-POC values and variable, but low δ^{15}N-PON values in the winter and spring (Figures 5b, 5c, and S3).

3.3. Lateral C Exports From Drained Peatlands

Mean annual DOC and DIC exports for each drainage site in WY 2018 ranged between 4.3 and 19.8 g C m^{-2} yr^{-1} and 6.9 to 30.7 g C m^{-2} yr^{-1}, respectively (Figure 6, Table 3). Mean annual POC exports ranged from 2.1 to 18.3 g C m^{-2} yr^{-1}. DIC and DOC exports positively correlated with water yield at all sites,

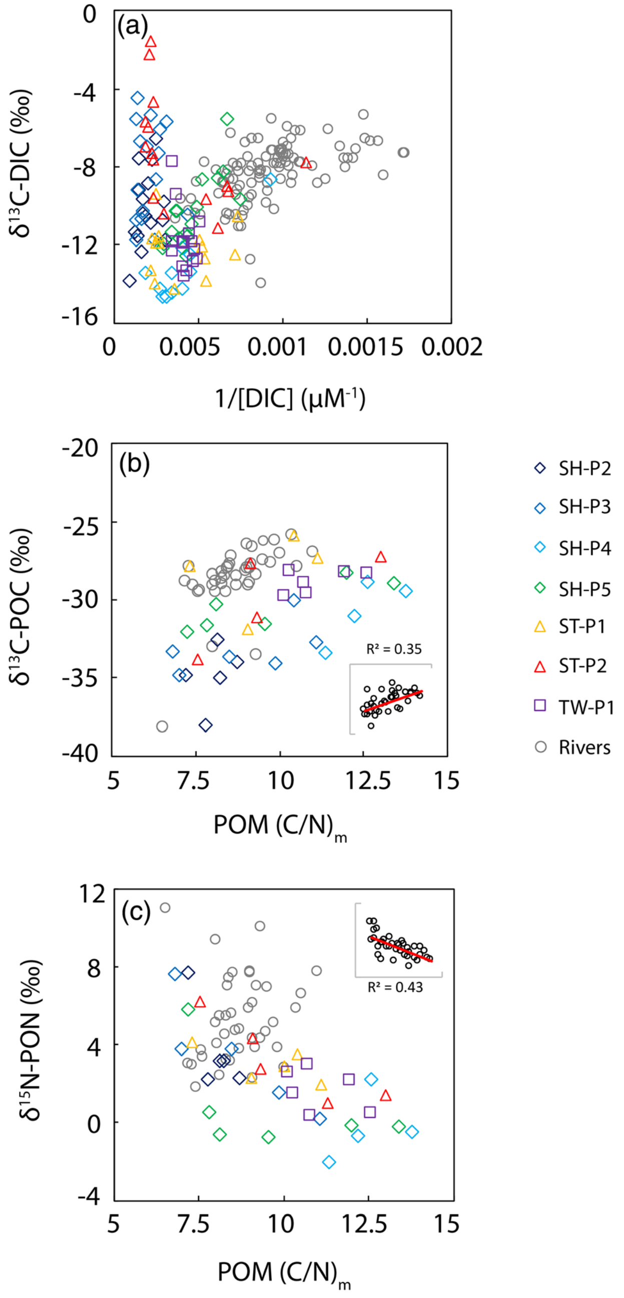

Figure 5. (a) Monthly δ^{13}C-DIC values (‰) versus 1/[DIC]. (b) Quarterly δ^{13}C-POC values versus POM $(C/N)_m$. (c) Quarterly δ^{15}N-PON values versus POM $(C/N)_m$. Inset figures in (b) and (c) show cumulative trends between all drainage sites and associated R^2 values. Sites shown include river water (gray circles), Sherman Island drainage sites (diamonds), Staten Island sites (triangles), and Twitchell Island drainage sites (squares). See Figure 1 for site locations (SH: Sherman Island sites, ST: Staten Island sites; TW, Twitchell Island sites).

though islands with substantial cropland (e.g., Staten Island) showed two distinct relationships between water yield and C exports that separated out based on season (Figures 6a–6f). POC exports also correlated linearly with water yield, but regression strength was generally lower than those for DIC and DOC trends as sample numbers were limited due to quarterly collection frequency (Figures 6g–6i and Table S3). For 2017, because not all months were sampled, we used the 2018 relationship between water yield and C export to fill in missing C concentration data where discharge data were available (Oct 2016 to May 2017) (Table 3). Extrapolated lateral C export rates for WY 2017 were 1.5 to 2.8 times greater than WY 2018. Mean annual DIC, DOC, and POC exports for WY 2017 ranged from 15.5 to 48.3 g C m^{-2} yr^{-1}, 8.8 to 30.6 g C m^{-2} yr^{-1}, and 3.9 to 19.6 g C m^{-2} yr^{-1}, respectively. Inflow C import rates were similar in magnitude across water years (Table 3). Total inflow C import rates ranged between 4.0 to 23.7 g C m^{-2} yr^{-1} for WY 2017 and 5.8 to 21.8 g C m^{-2} yr^{-1} for WY 2018. Net lateral C exports, after accounting for inflow C, ranged between 49.8 to 76.3 g C m^{-2} yr^{-1} for WY 2017 and 23.4 to 40.3 g C m^{-2} yr^{-1} for WY 2018.

4. Discussion

4.1. Hydrological and Biogeochemical Controls on Peat Drainage C Geochemistry

The spatial and temporal trends in drainage water particulate and dissolved C concentrations and associated stable isotope values show that the biogeochemical controls on peat C geochemistry are complex. Previous work in peatlands has documented the dominant effect of hydrology on subsurface biogeochemistry, and many studies exist showing the key hydrologic role that water table elevation plays in peat C storage and release (Aguilar & Thibodeaux, 2005; Chow et al., 2006; Limpens et al., 2008). While not measured directly in this study, work by Deverel et al. (2007) showed that Delta island water tables rise and fall seasonally. These seasonal trends in water table elevation and their connection to C biogeochemistry are corroborated by several years of historical data from Delta islands, available from Deverel et al. (2015) and online through the California Integrated Water Quality System (https://www.waterboards.ca.gov/ciwqs/), which show similar winter peaks and summer lows in not only water table elevation but also peat drainage DOC concentrations (Figures 7a and 7b). In fact, peat drainage DOC concentrations were strongly positively correlated to normalized changes in groundwater levels (Figure 7c). Past work by Chow et al. (2006) showed that these increases in DOC concentrations during water table rises or "rewetting periods" arise from changes in biogeochemistry, and this wet-dry cycling is often described as the "tea bag effect" (Thibodeaux & Aguilar, 2005). The rewetting phase induces DOC concentration increases through (1) abiotic generation of a "quick-release" DOC fraction from simple hydrolysis, and (2) biotic generation of a slow-release fraction from ongoing microbial C cycling (Aguilar & Thibodeaux, 2005).

This "tea bag effect" also likely impacts related C parameters measured in this study, such as DIC and pCO_2, due to the close connection between higher rates of organic matter decomposition and CO_2 production. Other geochemical variables, such as pH and dissolved oxygen content, are also linked to C cycling

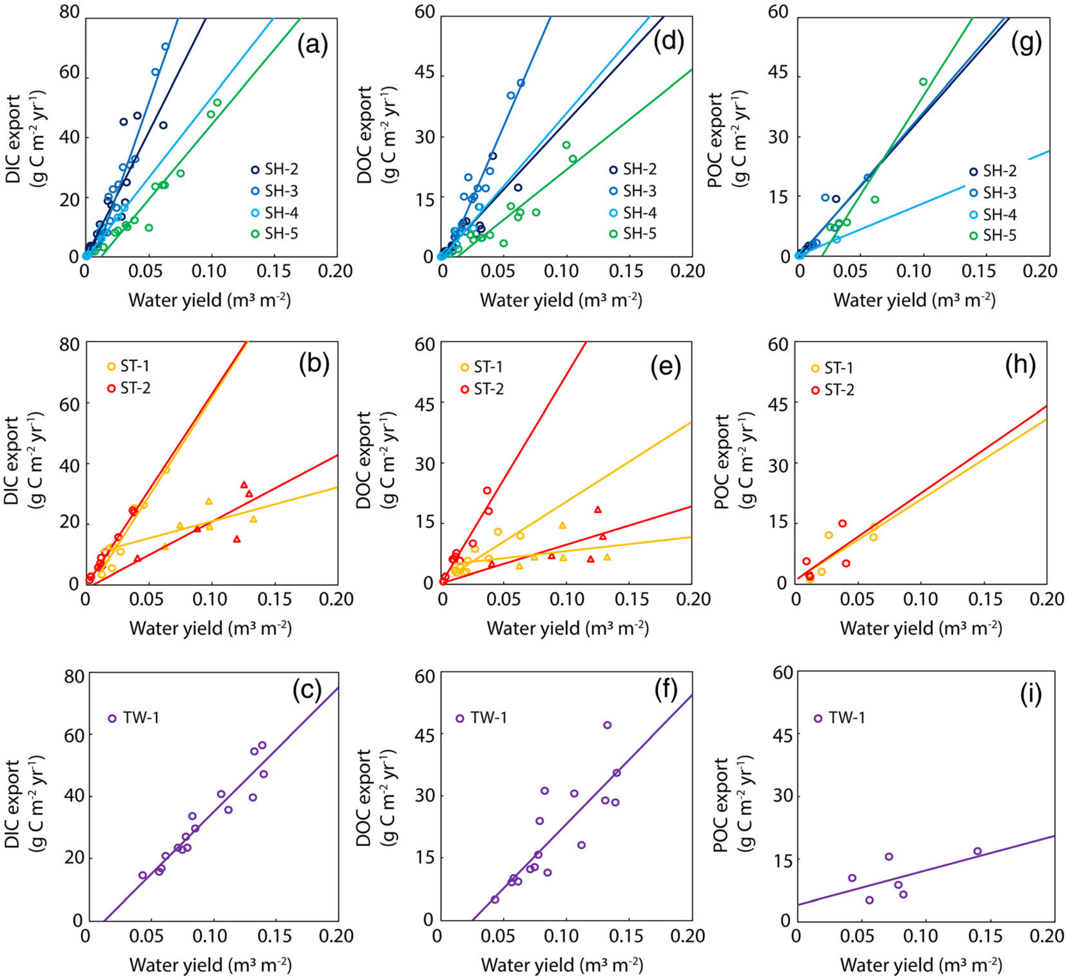

Figure 6. Peat island drainage DIC, DOC, and POC annual exports versus water yield for (a, d, g) Sherman Island (SH), (b, e, h) Staten Island (ST), and (c, f, i) Twitchell Island (TW). Summer month (June, July, and August) DIC and DOC exports on Staten Island are shown as triangles, whereas summer month POC exports on Staten Island (ST) were not seasonally separated due to sample number limitations. Regression equations, sample numbers, and R^2 values are presented in Table S3 in the supporting information.

processes and can induce shifts in carbonate chemistry and oxygen availability. High pCO_2 values in peat drainage, an indication of heterotrophic utilization of organic matter, were generally associated with (1) low pH and dissolved oxygen content, (2) high DOC, DIC, and SiO_4^{4-} concentrations, and (3) low δ^{13}C-DIC values (Figure 8). These trends indicate differences in biogeochemical process and water source that are best explained by changes in groundwater elevation.

In the wet winter typical of Mediterranean climates, water tables rise and saturate the upper section of soils on Delta islands, which are rich in organic matter replenished during and after the summer growing season (Figure 9a). Discharge of this shallow groundwater to drainage ditches constitutes a seasonal source of C with distinct geochemical characteristics (Deverel et al., 2007). Respired soil CO_2 from upper soil layers dissolves in the water, which is subsequently transported to drainage ditches through hydraulic gradients induced by pumping. High pCO_2 values in this water were associated with high SiO_4^{4-} concentrations, which is consistent with increased groundwater contributions (Uhlenbrook et al., 2000). The high pCO_2 drainage waters in the winter were also generally associated with (1) low dissolved oxygen concentrations, which indicates oxygen utilization for aerobic respiration (without sufficient replenishment from photosynthetic production of O_2), (2) low pH from increases in dissolved CO_2 from respiration, and (3) low δ^{13}C-DIC values, which represent seasonally increased contributions of DIC from mineralization of soil organic matter

Table 3
Comparison of Annual Water Year (WY) 2017 and WY 2018 Carbon (C) Exports From Drainage Sites and C Imports From Rivers

	WY 2017 (g C m^{-2} yr^{-1})				WY 2018 (g C m^{-2} yr^{-1})			
Site	DIC	DOC	POC	Total	DIC	DOC	POC	Total
Exports								
Export SH-P2	21.8	8.8	8.9	39.5	17.3	7.0	6.7	31.0
Export SH-P3	48.3	30.5	16.7	95.6	25.6	16.0	8.2	49.8
Export SH-P4	15.5	10.2	3.9	29.6	6.9	4.3	2.1	13.3
Export SH-P5	n.a.	n.a.	n.a.	n.a.	20.2	9.6	18.3	48.1
Export ST-P1	45.3	15.5	19.6	80.4	16.3	6.3	10.1	32.7
Export ST-P2	34.9	26.5	16.8	78.2	13.1	8.6	5.9	27.6
Export TW-P1	44.6	30.6	14.2	89.4	30.7	19.8	12.3	62.8
Imports								
Import-SH	6.5	1.4	0.6	8.6	9.5	2.1	0.8	12.4
Import-ST	3.1	0.8	0.1	4.0	4.4	1.3	0.1	5.8
Import-TW	18.7	4.4	0.6	23.7	17.1	4.0	0.6	21.8

Note. WY 2017 estimates for SH-P5 are not included as this site was missing discharge data for WY 2017. Exports for SH-P4 when discharge was zero were not included in its water year mean (May through September of 2018). WY 2017 inflow C imports are based on concentration data from WY 2018.

in the winter. While high pCO$_2$ values in peat drainage were associated with low δ^{13}C-DIC values at most of our sampling sites, ST-P2 showed increases in δ^{13}C-DIC values with elevated pCO$_2$ under low oxygen conditions (Figure 8c, S4). This site drains seasonally flooded agricultural fields that are CH$_4$ emission hotspots (Pellerin et al., 2013). The winter enrichment in δ^{13}C-DIC values at ST-P2 is likely a consequence of acetoclastic methanogenesis, a biogeochemical process that occurs under anaerobic conditions and produces DIC enriched in ^{13}C (Campeau et al., 2017). Carbonate mineral dissolution could also potentially increase DIC concentrations and δ^{13}C-DIC values, but sediment cores from Delta islands indicate carbonates comprise $\ll$1% of sediment (Drexler et al., 2009), making this mechanism unlikely. Drainage POM in the winter/spring was generally dominated by soil organic matter, as indicated by higher (C/N)$_m$ ratios of the POM (9.9 to 13.4, $\bar{x} = 11.5 \pm 1.2$), elevated δ^{13}C-POC values that best reflect degradation of terrestrial POM sources, and variable, but low δ^{15}N-PON values that support N sources originating from recycling of soil N (Figure S3) (Kendall et al., 2001).

During the summer, groundwater levels on Delta islands decrease due to diminished surface recharge (Figure 9b). Summer also marks the start of the growing season, and islands with crops maintain water tables below the rooting zone via managed pumping. These water table declines, whether they result from natural weather patterns or crop management, allow for seasonal windows of peat oxygenation during times when soil temperatures are also elevated. Peat aeration increases aerobic C respiration in the unsaturated zone. Previous work on vertical C fluxes on Delta islands generally showed increases in the magnitude of CO$_2$ fixed and produced by ecosystem photosynthesis and respiration during this time frame (see Hemes et al., 2019). At the same time as these increases in C emission and fixation, two seasonal differences in island hydrology drive changes in peat drainage C concentrations and isotopic composition in the summer: (1) Drainage receives less groundwater and the groundwater that does drain is from deeper soil layers, which contribute less DOC (as C found at depth on Delta islands is generally more humified, under reducing conditions, and not replenished as frequently as surface soils; Deverel et al., 2007), and (2) drainage receives more surface water runoff in the form of excess irrigation water diverted from surrounding channels, which dilutes groundwater C inputs and shifts peat drainage C composition toward river C geochemistry (Tables 1 and 2). Soils at depth on Delta islands generally have lower organic matter content (Drexler et al., 2009), and past work by Deverel et al. (2007) showed that deep groundwater on Delta islands has low DOC concentrations (~1,570 μM) relative to shallow groundwater (~6,870 μM), though the exact magnitude of each likely varies island-to-island from differences in soil organic matter content and C cycling. Deverel et al. (2007) also found seasonal differences in SUVA$_{254}$ values in peat drainage. In this study, drainage SUVA$_{254}$ values were generally consistent across sites and through time, suggesting that drainage DOC remained compositionally similar year-round. This consistency in SUVA$_{254}$ values, indicating the DOC pool was predominantly composed of aromatic, high molecular weight compounds (Hansen et al., 2018), is possible since groundwater sources (shallow or deep) maintain DOC concentrations that are generally an order of magnitude greater than surrounding river DOC concentrations. As a result, groundwater DOC contributions dominate the DOC pool regardless of the season, and irrigation runoff contributions to drainage mainly act to dilute deep groundwater DOC inputs in the summer. This could account for the observed overall reductions in drainage DOC concentrations in peat drainage during the summer, while allowing drainage DOC to remain compositionally similar year-round.

These lower peat drainage DOC concentrations translate to lower DIC concentrations and pCO$_2$ values during the summer as organic matter availability for mineralization (and thus, CO$_2$ production) in the saturated zone is diminished relative to shallow winter C pools (Table 2). Summer enrichment of δ^{13}C-DIC values under oxic conditions also suggest increases in photosynthesis by algae and/or aquatic vegetation growing within the ditches; photosynthesis preferentially uses DIC containing ^{12}C which leaves remaining DIC

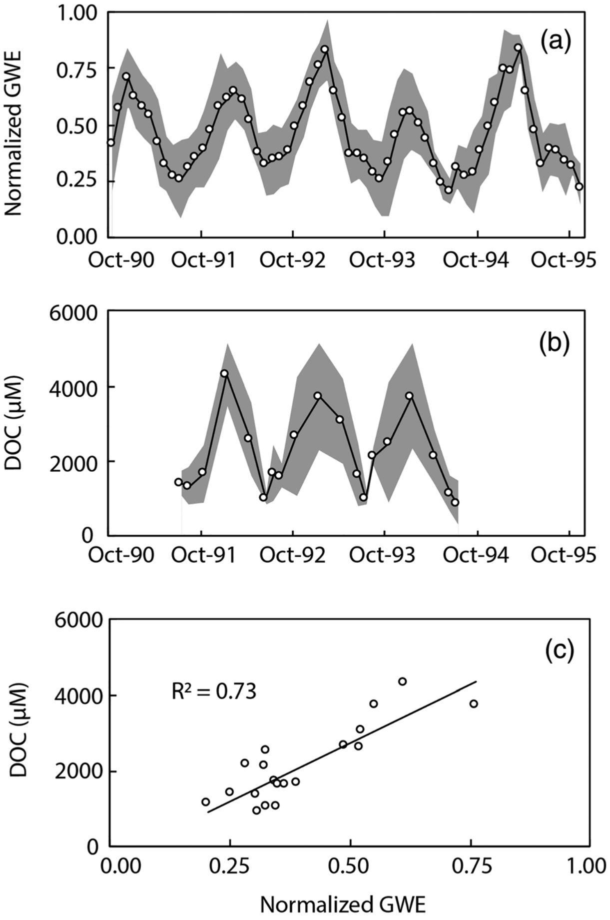

Figure 7. (a) Historical time series mean normalized groundwater elevation (GWE) from seven Delta islands (Bouldin, Empire, Mandeville, Palm, Staten, Twitchell, and Webb), (b) historical time series DOC concentrations from seven drainage outlets in the Delta (Bacon, Bouldin, Holland, Mandeville, Palm, Staten, and Webb), and (c) drainage DOC concentrations versus mean normalized GWE. Gray areas show the standard deviation around the mean of each sample date. Groundwater elevation data are from Deverel et al. (2015) and were aggregated first using a three-point moving average and then min-max normalized individually for each site. Peat drainage DOC concentration data are available online from the California Integrated Water Quality System (https://www.waterboards.ca.gov/ciwqs/).

enriched in ^{13}C. Summer algal production is further evidenced by the generally low $(C/N)_m$ ratios of POM (7.3 to 10.5, $\bar{x} = 9.0 \pm 1.8$), low δ^{13}C-POC values, and high δ^{15}N-PON values observed in peat island drainage during this timeframe (Kendall et al., 2001) (Figure S3). These blooms would help explain several other summer trends in peat island drainage geochemistry. Specifically, photosynthetic CO_2 fixation should decrease pCO_2 values and increase pH and dissolved oxygen concentrations, similar to trends observed for most drainage sites in the summer (Figure 8). Unsurprisingly, the algal POM signal was strongest in summer and fall, when physical conditions (e.g., increased sunlight availability and lower rates of discharge which increase residence time) can best support photosynthetic activity.

The suite of geochemical tracers we analyzed provide new information on the dominant sources of, and processes affecting, peat island drainage C delivered to Delta waters and the quality of organic matter delivered to the greater Delta ecosystem from peat drainage. In the summer, drainage POM is likely more bioavailable (N-rich), while indicators of DOC quality (e.g., $SUVA_{254}$) suggest DOC remains compositionally similar year-round. δ^{13}C-DIC values revealed that DIC is mostly affected by photosynthesis and respiration of C, though methanogenesis was evident in some locations. While these general seasonal trends in C biogeochemistry (evidenced by C concentrations and stable isotope composition) were discernable, peat drainage C concentrations and stable isotope compositions show significant spatial variability when observed at higher temporal resolution. Moreover, some sites were inconsistent with overall seasonal trends (e.g., SH-P2 and SH-P3), and this variability suggests that controls on metabolic processes affecting C biogeochemistry are probably spatially heterogeneous at the sub-island level.

4.2. Transport-Driven Lateral C Losses From Drained Peatlands

In line with Gibson et al. (2009), who found that DOC exports in northern boreal peatlands are transport driven, a majority of peat drainage DIC, DOC, and POC exports in the Delta were strongly positively correlated to water yield (discharge normalized by catchment area). This suggests that seasonal changes in water yield are a common major driver of C flux in both drained boreal and temperate peatlands. Interestingly, islands with substantial cropland cover, like Staten Island, showed two distinct trends in export-yield relationships, which likely arose from the seasonality in the hydrological regime on Delta islands, as discussed previously: (1) summer when precipitation is negligible and surface irrigation increases, and (2) winter when inflow is high (from increased levee seepage and rainfall contributions) and subsurface flow dominates. DOC and DIC exports on Staten Island, when divided based on these two seasons which represent distinct hydrological regimes, correlated well with water yield (Figure 6). The winter hydrologic regime is ubiquitous across all Delta islands as increased discharge is a regional response to higher water tables from increases in river water levels and direct precipitation in the winter rainy season. Exports during this period are driven by (1) high rates of pumping to remove excess water from the islands, and (2) elevated dissolved C concentrations as water interacts with rewetted soils via subsurface flow pathways. In the summer, irrigation-driven discharge is a localized response to dominant land use and crop type, which varies between and across islands. Dissolved C concentrations during this time are lower, and exports are less consequential to overall island C budgets. These export trends highlight the importance of discharge in C loss, and future efforts aimed at minimizing winter discharge could help curb lateral C losses from Delta islands (Deverel et al., 2017). Reductions in winter discharge may

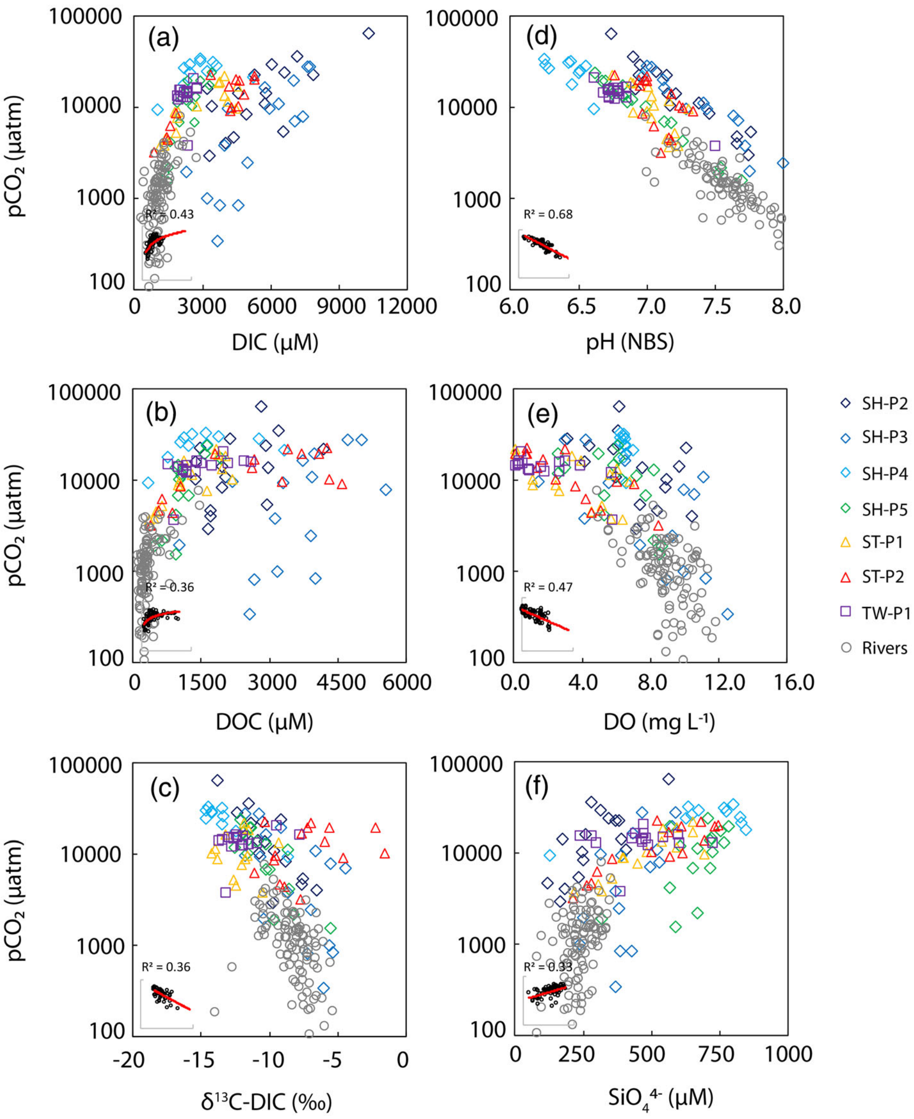

Figure 8. Peat island drainage and river pCO_2 values versus (a) DIC concentrations, (b) DOC concentrations, (c) δ^{13}C-DIC values, (d) pH, (e) DO, and (f) SiO_4^{4-}. Inset figures show cumulative R^2 between all drainage sites except SH-P2 and SH-P3 for all figures, while (c) also excludes ST-P2.

also affect gaseous CO_2 and CH_4 emissions, and the potential tradeoff in lowering lateral C fluxes at the expense of increased GHG emissions needs to be carefully considered in future work.

4.3. Importance of Lateral C Exports in C Budgets of the Delta

Previous work on lateral C exports in the Delta has been limited in scope; no estimates consider DIC exports, and no studies have comprehensively evaluated all lateral C constituents at regular time intervals with complete discharge data. We found that peat island drainage lateral C exports were similar in magnitude to previously published vertical C fluxes for various land use types in the Delta and often greater than past estimates of C losses via DOC export in drainage waters (Table 4). Previously unconsidered DIC exports comprised almost 50% of C lost laterally. After accounting for river C imports (0.01 to 0.06 g C m^{-2} day^{-1}), the three studied Delta islands were sources of lateral C to the Delta environment, with net contributions from WY 2017 (0.14 to 0.21 g C m^{-2} day^{-1}, 980 to 2,820 Mg C yr^{-1}) greater than WY 2018 (0.06 to 0.11 g C m^{-2} day^{-1}, 590 to 1,030 Mg C yr^{-1}) (Table 4). Actual net C lateral export rates may be even higher than those calculated herein as DOC concentrations are based on NPOC fractions, and outflow volumes

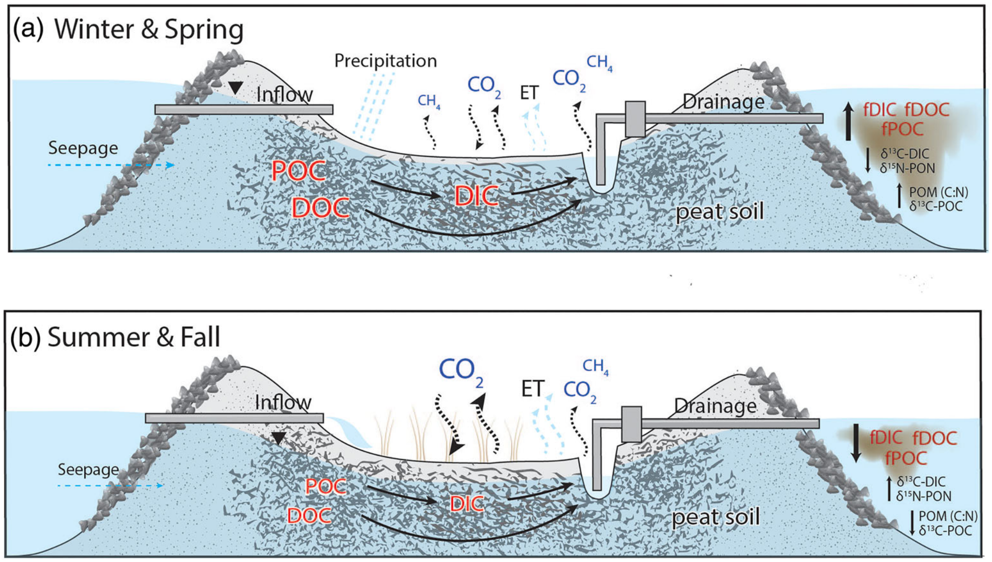

Figure 9. Generalization of seasonal changes in hydrology and C geochemistry on Delta islands in (a) winter/spring and (b) summer/fall; fPOC, fDOC, and fDIC denote flux of POC, DOC, and DIC, respectively. Figure modified from Ingebritsen et al. (2000) and not to scale.

used to generate export estimates may only represent ~87% of actual discharge (Figure S1). Net lateral C export rates for WY 2017 were comparable in magnitude to current estimates of net per area gaseous C emissions from a range of land use types (see Table 4). C inflow from rivers and outflow from Delta islands differs in terms of both concentration and speciation. Inflow C speciation was predominantly comprised of DIC (~75%), while DIC comprised only 40 to 50% of drainage C speciation. The stable isotope data presented earlier in this study also showed that dissolved and particulate organic C pools in drainage are often sourced from terrestrial organic matter, which suggests that inflow C is cycled and processed on island. Interplay between lateral and vertical C cycling complicates assessments that consider gaseous and dissolved/particulate C pathways separately, and these assessments would benefit from more refined budgeting of C imports. This study's lateral C export estimates also do not account for the fate of C in drainage waters, which could result in direct increases in CO_2 emissions via evasion (as drainage waters are super-saturated with respect to CO_2) and longer-term increases in CO_2 emissions from C cycling of drainage-sourced organics in Delta waterways. Müller et al. (2015) found that CO_2 outgassing from water can account for over 30% of C lost laterally in a peat-draining river, and future work in the Delta should explicitly account for near-term and long-term C emissions from drainage waters.

We also found that lateral C exports were spatially and temporally variable due to differences in dissolved C concentrations and water budget terms (both water inflow and discharge). Studies on gaseous C have found similar spatial variability. Even across uniform land use sites in the Delta, CH_4 flux and C fixation rates can vary substantially (Anderson et al., 2016; Hemes et al., 2018). Variability in both hydrology and soil organic matter content between sites may account for the spatial discrepancies observed in this study and previous studies on gaseous C fluxes in the Delta. Soil organic matter content varies considerably both within islands and across the entire legal Delta boundary, from ~5% to 52% (Deverel et al., 2016; Drexler et al., 2009), and we found that soil organic matter content at our study sites on Sherman Island could explain 93% the observed variability in total dissolved C concentrations for each drainage catchment (Figure S5). Similarly, water table levels can vary at the sub-island scale from differences in water management and land use. Past work by Aguilar and Thibodeaux (2005) and this study show that water table levels can drive seasonal trends in C geochemistry in the Delta's drained peatlands. These spatial differences in aqueous and gaseous C dynamics can easily be missed when sampling is sporadic or not spatially rigorous in biogeochemically complex systems, like the Delta. This study's results raise new and important questions about the uniformity of not only vertical but also lateral C exchange rates across and within Delta islands as well as across differing water years.

Table 4

Comparison of lateral (aqueous) carbon (C) export rates to published vertical (gaseous) C export rates for the Delta

Site description	Island	Study area details	Phase	Date	Export[a] (g C m^{-2} day^{-1})	Study
Lateral fluxes						
Export						
Cumulative drainage	Sherman	Weighted average of exports from all outlets on each island; wet water year	Aqueous[b]	Oct 2016 to Sep 2017	0.16	This study
Cumulative drainage	Staten		Aqueous[b]	Oct 2016 to Sep 2017	0.22	This study
Cumulative drainage	Twitchell		Aqueous[b]	Oct 2016 to Sep 2017	0.25	This study
Cumulative drainage	Sherman	Weighted average of exports from all outlets on each island; dry water year	Aqueous[b]	Oct 2017 to Sep 2018	0.10	This study
Cumulative drainage	Staten		Aqueous[b]	Oct 2017 to Sep 2018	0.08	This study
Cumulative drainage	Twitchell		Aqueous[b]	Oct 2017 to Sep 2018	0.17	This study
Drainage ditch	Jersey	Single ditch	Aqueous (DOC)	May to Jul 1990	0.30	Deverel and Rojstaczer (1996)
Drainage ditch	Orwood		Aqueous (DOC)	May 1990 to May 1991	0.02	Deverel and Rojstaczer (1996)
Drainage ditch	Sherman		Aqueous (DOC)	May 1990 to Nov 1990	0.002	Deverel and Rojstaczer (1996)
Cumulative drainage	Twitchell	Multi-year average including approximated loads	Aqueous (DOC)	Aug 2000 to Aug 2003	0.45	Deverel et al. (2007)
Managed wetlands		Average of three managed flow-through wetland cells	Aqueous (DOC)	Jul 2012 to Oct 2013	0.14	Bachand et al. (2019)
Import						
Inflow waters	Sherman	Inflow volume estimated via water budget with mean river geochemistry; wet water year	Aqueous[b]	Oct 2016 to Sep 2017	−0.02	This study
Inflow waters	Staten		Aqueous[b]	Oct 2016 to Sep 2017	−0.01	This study
Inflow waters	Twitchell		Aqueous[b]	Oct 2016 to Sep 2017	−0.06	This study
Inflow waters	Sherman	Inflow volume estimated via water budget with mean river geochemistry; dry water year	Aqueous[b]	Oct 2017 to Sep 2018	−0.03	This study
Inflow waters	Staten		Aqueous[b]	Oct 2017 to Sep 2018	−0.02	This study
Inflow waters	Twitchell		Aqueous[b]	Oct 2017 to Sep 2018	−0.06	This study
Vertical fluxes						
Grazed land	Sherman	Pastureland, disconnected from main island	Gaseous, NEE	Apr 2009 to Apr 2010	0.82	Hatala et al. (2012)
Grazed land	Sherman		Gaseous, NEE	Apr 2010 to Apr 2011	0.48	Hatala et al. (2012)
Rice paddy	Twitchell	Central part of island	Gaseous, NEE	Apr 2009 to Apr 2010	−0.23	Hatala et al. (2012)
Rice paddy	Twitchell		Gaseous, NEE	Apr 2010 to Apr 2011	−0.78	Hatala et al. (2012)
Managed wetland	Twitchell	Central part of island, impounded wetland	Gaseous, NEE	Apr 2002 to Apr 2003	−2.20	Anderson et al. (2016)
Managed wetland	Twitchell		Gaseous, NEE	Apr 2010 to Apr 2011	−0.06	Anderson et al. (2016)
Grazed land	Sherman	Footprint includes drainage ditches	Gaseous, NEE	Mar 2012 to Mar 2013	0.93	Knox et al. (2015)
Farmland (corn)	Twitchell		Gaseous, NEE	May 2012 to May 2013	0.76	Knox et al. (2015)
Farmland (rice)	Twitchell		Gaseous, NEE	Mar 2012 to Mar 2013	−0.14	Knox et al. (2015)
Managed wetland	Sherman	Young, partially disconnected from main island	Gaseous, NEE	Mar 2012 to Mar 2013	−1.01	Knox et al. (2015)
Managed wetland	Twitchell	Old, central part of island	Gaseous, NEE	Aug 2012 to Aug 2013	−1.09	Knox et al. (2015)
Farmland (corn)	Twitchell		Gaseous, NECB	May 2012 to May 2013	1.60	Hemes et al. (2019)
Farmland (corn)	Bouldin		Gaseous, NECB	Apr 2017 to Apr 2018	4.22	Hemes et al. (2019)
Farmland (rice)	Twitchell		Gaseous, NECB	2010 to 2016	0.99	Hemes et al. (2019)
Grazed land	Sherman		Gaseous, NECB	2010 to 2014	0.86	Hemes et al. (2019)
Farmland (alfalfa)	Twitchell		Gaseous, NECB	2014 to 2017	1.28	Hemes et al. (2019)
Farmland (alfalfa)	Bouldin		Gaseous, NECB	2017	0.55	Hemes et al. (2019)
Restored wetland	n.a.	Integrated flux	Gaseous, NECB	n.a.	−0.65	Hemes et al. (2019)

Note. NEE and NECB represent net ecosystem exchange and net ecosystem carbon balance (e.g., NEE + CH_4), respectively. Cumulative drainage exports from this study are taken as area-weighted averages based on catchments associated with each site (Figure S2). WY 2018 export rates for SH-P5 were used in the weighted average for Sherman Island during WY 2017, as SH-P5 was missing discharge data for that year. C imported via inflow water for WY 2017 was generated using river geochemistry data from WY 2018.

[a] Positive values indicate export from the system, either to receiving waters (lateral/aqueous) or to the atmosphere (vertical/gaseous). [b] Aqueous includes DIC, DOC, and POC unless noted otherwise.

Table 5
Total Delta-Wide Peat Island Drainage Annual and Seasonal Carbon (C) Fluxes for Water Year (WY) 2017 and WY 2018

	DIC (Mg C day^{-1})	DOC (Mg C day^{-1})	POC (Mg C day^{-1})
WY 2017	67	38	31
Summer	29	14	26
Fall	27	18	14
Winter	161	86	60
Spring	54	33	26
WY 2018	64	32	31
Summer	30	12	26
Fall	46	30	25
Winter	108	56	38
Spring	72	32	34

4.4. Temporal Variability in Peat Drainage C Loads Delivered to the Delta Ecosystem

To examine variability in the magnitude and timing of dissolved and particulate C fluxes from peat drainage, we calculated DIC, DOC, and POC fluxes for each island using the established C export relationships with water yield for the period for which discharge information is available but no geochemistry data exists (June 2016 to May 2017). While the timing of annual discharge peaks remained relatively consistent across water years, the magnitude of dissolved and particulate C fluxes changed substantially. Large differences between wet WY 2017 (95.4 cm) and dry WY 2018 (27.9 cm) precipitation had a measurable effect on the volume of water discharged from each island annually and, subsequently, the magnitude of peat drainage C inputs to surrounding Delta waters (Figure S6). In general, C fluxes from peat drainage to Delta channels were greatest in the winter of both water years, and cumulative C fluxes (the sum of DOC, DIC, and POC) from each island were 1.7 to 5.4 times larger in winters of wet years (220 to 600 Mg C month^{-1}) than winters in dry years (110 to 220 Mg C month^{-1}). Islands where summer irrigation takes place also showed secondary summer peaks in C fluxes (Figure S6).

To get an estimate of the overall C contribution to Delta waterways from all of the Delta's island drains, monthly DIC, DOC, and POC fluxes were upscaled to obtain Delta-wide C fluxes using previous discharge estimates (5.32×10^8 m^3 yr^{-1}) for peat island drainage for the entirety of the Delta from Templin and Cherry (1997) and C concentration data from this study. This allows for (1) a broader understanding of the overall magnitude of the total peat drainage C flux to Delta waters, and (2) comparison to other recognized significant contributors of DOC to the Delta (as POC and DIC concentration data for other sources is limited in this system). We scaled annual peat drainage discharge to monthly resolution using flow percentiles calculated from this study; flow percentiles were generated separately for islands dominated by pastureland (Sherman Island, SH) versus cropland (Staten Island, ST), and fluxes shown herein are the weighted mean of these values based on dominant land use in the Delta (with 82.4% cropland and 17.6% pastureland, idle, or grassland) (Figure S7). Additionally, annual differences in upscaled C fluxes presented below are driven exclusively by changes in concentration, rather than discharge, as existing estimates for Delta-wide drainage are only available for a single year as discussed previously. These C flux estimates suggested drainage from subsided peat islands contributed 67 and 64 Mg C day^{-1} of DIC to surrounding waterways in WY 2017 and WY 2018, respectively (Table 5). Mean annual POC contributions from peat drainage were 31 Mg C day^{-1} for both water years. On a seasonal basis, WY 2017 and WY 2018 total Delta peat drainage DOC estimates ranged between 12 and 86 Mg C day^{-1}, which is similar in magnitude to seasonal estimates (21 to 64 Mg C day^{-1}) from Jassby and Cloern (2000) (Table 5). Mean annual DOC contributions during WY 2017 and WY 2018 ranged between 32 to 38 Mg C day^{-1} and were also similar to recent estimates of 37 Mg C day^{-1} (Roy et al., 2006). These water year comparisons of C mass flux show how drainage C exports can change seasonally (and likely annually) in a region with increasing hydroclimatic variability (Swain et al., 2018) and suggest that more extensive monitoring of interannual variability in lateral C fluxes is needed to better assess the contribution of this flux to the whole Delta C pool, especially since this study was limited to a single historic Delta-wide drainage discharge estimate for two dynamic water years.

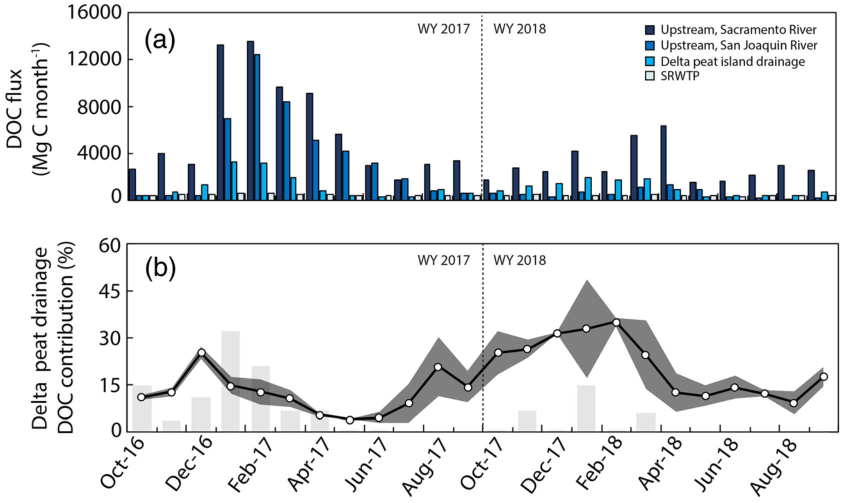

Figure 10. (a) Monthly estimates of DOC flux for the Sacramento River at Freeport (black), San Joaquin River at Vernalis (dark gray), total Delta peat island drainage (light gray), and Sacramento Regional Wastewater Treatment Plant, SRWTP (white). (b) Delta peat drainage DOC contributions as a percentage of total DOC flux from the sources considered in (a), with monthly precipitation (cm) totals shown by the transparent gray bars. The shaded region around the monthly peat drainage DOC flux estimates shows the standard deviation of the drainage DOC flux generated for cropland (ST) and pastureland-dominated systems (SH).

Relative to other regional contributors of DOC, including the San Joaquin River, Sacramento River, and SRWTP, data from this study suggests peat drainage accounted for ~13% to 25% and ~31% to 35% of DOC contributions to Delta waters during the winter months of wet WY 2017 and dry WY 2018, respectively (Figure 10). DOC contributions from drained peat islands were sustained over the course of several months in the winter of WY 2018, while drainage DOC inputs in WY 2017 quickly subsided as other inputs dominated local C mass fluxes (Figure 10a). More broadly, mean peat island drainage seasonal DOC contributions to Delta waters accounted for 11%, 13%, 18%, and 7%, and 12%, 23%, 33%, and 16% of total Delta DOC inputs during summer, fall, winter, and spring of WY 2017 and 2018, respectively. This mass flux comparison suggests that DOC inputs from drained peat islands in the Delta comprise a greater fraction of the total DOC flux during dry water years (especially during fall and winter months), even though wet water years see greater mass fluxes of DOC from peat island drainage. Our work as well as that reported by Kraus et al. (2008) shows that, on average, ~1/4 of DOC in Delta waters in the winter may be attributable to peat drainage. The delivery of DOC (and POC) from peat drainage to surrounding waterways has consequences for in-Delta water quality and water exported to other areas of California (Fleck et al., 2007); for example, high DOC concentrations in water exports to other regions can lead to the formation of harmful disinfection by-products upon chlorination (Bachand et al., 2019; Fleck et al., 2007; Hansen et al., 2018). Taken together, these results suggest that (1) peat drainage DOC inputs can, during some seasons, outpace other contributors of DOC in this system, (2) the fractional contribution of peat drainage DOC can change substantially across distinct water year types, and (3) drainage C inputs are consequential for downstream water quality.

5. Conclusions

This study is the first to measure DIC, DOC, and POC exports from multiple drained peat islands in the Sacramento-San Joaquin Delta in central California. Alongside measurements of particulate and dissolved C concentration and discharge, we used stable isotope data to better understand biogeochemical controls on drainage C geochemistry. We found that biogeochemical and hydrological controls on drainage C concentrations and stable isotope composition were complex, varying in both space and time. Seasonal changes in water table elevation shifted dominant water sources contributing to drainage. Groundwater contributions to peat drainage increased in the winter and spring, when C concentrations and discharge were high. In the summer, peat drainage C concentrations were lower (though still higher than surrounding rivers) due to reductions in shallow groundwater contributions and increases in surface water inputs as irrigation runoff. Seasonal shifts in water sources affected biogeochemical processing of C. C stable isotope values and concentrations were primarily influenced by C mineralization in the winter and autotrophic production in the ditches in the summer. While C cycling processes were generally similar across drainage sites, baseline particulate and dissolved C concentrations were site specific, likely due to differences in soil organic matter content and prevailing hydrology. This spatial and temporal variability highlights that the Delta's peat islands are not static and homogenous systems; each function as separate catchments with similar biogeochemical processes but distinct propensities to cycle C. Spatial heterogeneity in C concentrations and stable isotope composition was substantial even across individual islands, and this internal variability in C concentration, speciation, and stable isotope values is likely to also affect gaseous fluxes. Previous work on GHG emissions from many of the same islands also show substantial variability in CO_2 and CH_4 flux across uniform land use types, and more work is needed to better understand higher-order spatial controls on both lateral and gaseous C dynamics in drained peatlands.

This work more generally highlights and supports previous studies showing the importance of accounting for DIC, DOC, and POC exports in C budgets of drained boreal and temperate peatlands. The magnitude of C exported from peat drainage to Delta channels varied based on water year (WY), with wet WY 2017 (0.14 to 0.21 g C m^{-2} day^{-1}) exporting more net C than dry WY 2018 (0.06 to 0.11 g C m^{-2} day^{-1}). Peat island drainage C fluxes were also able to account for close to 1/5 and 1/3 of DOC fluxes to Delta waters during winter of wet WY 2017 and dry WY 2018, respectively. New studies that integrate measurements of both lateral and vertical C exports will improve on our understanding of C dynamics in drained peatlands, allow for more accurate C and GHG accounting, and can be used to better understand temporal controls as they relate to the increasing hydroclimatic variability projected for California and beyond.

Data Availability Statement

Data are available through HydroShare via the Consortium of Universities for the Advancement of Hydrologic Science, Inc. (CUAHSI) (http://www.hydroshare.org/resource/c9a7e238c1484b439dba619aa3169bed).

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