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ORIGINAL PAPER

Export of organic matter from a coastal freshwater wetland to Lake Erie: an extension of the outwelling hypothesis

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Abstract I tested the hypothesis that seiches in large lakes play a role similar to tides in marine system by exporting detrital carbon from coastal wetlands to adjacent open waters. The study was conducted at a wetland site located along the shore of the Lake Erie. Water samples were collected at the outlet of the marsh, during inflow and outflow events, over a 19-month period. Water isotopes were also measured in the lake and in the marsh to establish the magnitude of the mixing between the two water masses. On average, the concentrations of the outflow water samples was enriched by 7.3 mg DOC l^{-1} and 3.4 mg POC l^{-1}compared to the inflow water samples, while no difference observed in inorganic carbon fluxes. Organic carbon was exported during fall, winter and early spring which coincide with period of organic matter decomposition. Such a concept of outwelling is not new for marine ecosystem, but is demonstrated in this study for the first time in a large lake setting influenced by seiche events. Ultimately to understand the role that these fluxes may play in maintaining the integrity of the wetland-lake system, it will be necessary to investigate whether the detrital material exported from coastal freshwater wetlands is incorporated into the open lake foodweb.

Keywords Carbon fluxes · Detrital · Great Lakes · Hydrology · Marsh · Seiche

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Introduction

Adjacent ecosystems are interconnected through the transfer of energy (nutrients, organic matter and species) involving both biotic and abiotic mechanisms. This notion of ‘‘coupled systems’’ has been successfully applied to evaluate the exchange of energy between riparian systems and rivers during floods, or between salt marshes and coastal waters during tides. The flood pulse concept (Junk et al. 1989) describes riparian banks as providers of organic matter to watercourses, and in some respect is an extension of the river continuum concept (Vannote et al. 1980) that emphasizes longitudinal links between upstream and downstream river segments. The outwelling concept (Odum 1968) states that tidal events export detrital material produced in salt marshes offshore. Strong evidence also indicates that the export of organic matter from upland (e.g., riparian zones and salt marshes) to aquatic systems supports secondary production (Deegan et al. 2000). Such existence of hydrological interdependence between aquatic and adjacent terrestrial ecosystems is considered to be one of the most important forcing functions driving the ecological integrity of both systems.

In salt marshes, only a small proportion of plant biomass is exported to coastal seawater as macro-detritus. Most detrital organic matter produced by halophytes is decomposed within salt marshes (Bouchard and Lefeuvre 2000; Newell and Porter 2000) and then exported to coastal waters through abiotic (Teal and Howes 2000; Childers et al. 2000) or biotic (Deegan et al. 2000) vectors. Budgets of detrital carbon between salt marshes and open waters generally favor a net export of dissolved material and import of suspended material (Nixon et al. 1980; Lefeuvre and Dame 1994; Childers et al. 2000). Several studies, however, contradicted the outwelling concept by showing import of organic matter from marine waters to salt marshes (see review by Childers et al. 2000). After more than 30 years of research, the fluxes of detrital material from salt marshes continue to be evaluated in relation to tidal range, plant communities, primary production, and microbial activity (Lefeuvre and Dame 1994; Childers et al. 2000).

Despite the fact that many coastal wetlands of large lakes are hydrologically connected to adjacent open-water through wind-driven seiches (i.e., periodic oscillations with irregular amplitudes of water level), little information regarding the fluxes of detrital carbon between these two systems is currently available. Coastal wetlands in the Laurentian Great Lakes experience seiche-driven water level oscillations with regular intrusion of lake water (Keough et al. 1999; Trebitz et al. 2002). This hydrological connection is known to regulate the dynamics and retention of nutrients within a wetland and between a wetland and the adjacent lake (Mitsch and Reeder 1992; Morrice et al. 2004). A few studies have suggested the potential for the export of organic matter from coastal wetlands to the Great Lakes during the mixing of water masses (Barth et al. 1998; Brazner et al. 2000), but, to my knowledge, no study has actually demonstrated whether such exchanges occur.

The objective of the study was to assess whether a coastal wetland located on the shore of Lake Erie (USA) contributes detrital carbon to the lake. Using oxygen and hydrogen isotopic composition (δ^{18}O and δD) of water, the study first identified whether water masses from Lake Erie and from the marsh were mixing, and to what extent this mixing occurred. Then, this work quantified whether the water leaving the marsh to the lake during seiche events was enriched in dissolved and particulate carbon compared to the water entering the marsh from the lake.

Materials and methods

Site description

This study was conducted at Metzger Marsh, a 300-ha wetland located along the southern shore of western Lake Erie (41°37′ N, 83°14′ W; Ohio, USA). Originally protected from the lake by a barrier beach and connected to Lake Erie by a single outlet, the wetland was opened to the lake in 1973 when the beach was decimated by a severe storm. To restore the site, an artificial dike was built in 1998 with the objective of mimicking the protective function of a barrier beach (Kowalski and Wilcox 1999). The dike includes a 10 m wide outlet that allows exchange with the lake (Fig. 1). The location and design (i.e., width) of the outlet was chosen to mimic the natural outlet (Kowalski and Wilcox 1999; Wilcox and Whillans 1999). At the site, seiche amplitude averages 0.2-m over a period of 10- to 14-h which is fairly typically of seiche events in Lake Erie (Bedford 1992; Hamblin 1987). The seiche-induced flow is permanent at the outlet of the marsh, with the exception of a 15–30 min slack period every 5- to 7-h. Seiches with amplitudes reaching 1.5 m and periodicity of 18–24-h can also occur. Storm events also alter the amplitude and periodicity of the seiche. Tributary inflows to the marsh have been cut off but dikes.

Stable isotopes analysis

Water stable isotopes (δ^{18}O and δD) have been used successfully as tracers to identify flow paths in diverse hydrological conditions (e.g., Huddart et al. 1999). In this study, stable isotopes were

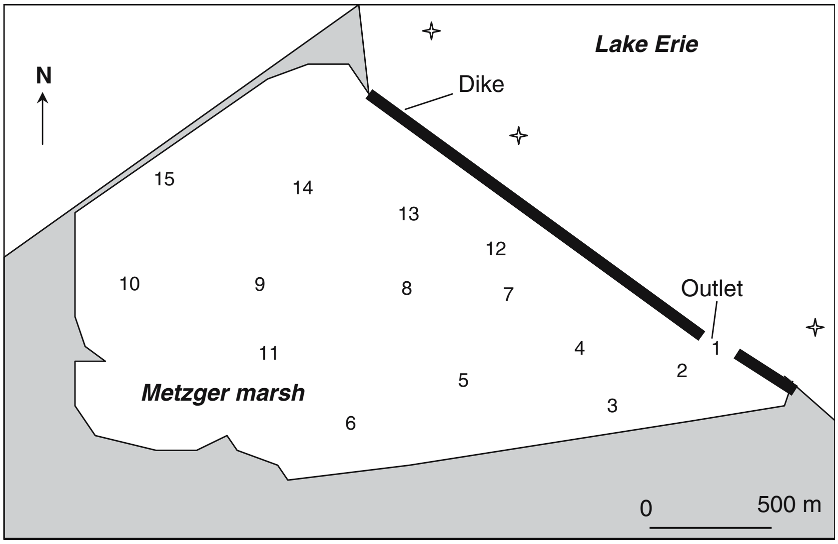


Fig. 1 Schematic map of the studied site (Metzger Marsh, Ottawa National Wildlife Refuge, northeast Ohio, USA) with location of the wetland (numbered from 1 to 15) and Lake Erie (indicated with ✧) sampling stations. A detailed description of the site is found in Kowalski and Wilcox (1999)

used to assess the extent of the mixing between the lake and wetland water masses. Water samples were collected at 18 stations located throughout the wetland and in the lake (Fig. 1) and analyzed for stable oxygen ($^{18}O/^{16}O$) and hydrogen ($^{2}H/^{1}H$) isotopic signatures. In the wetland, 15 stations were located along transects positioned between the outlet and the back of the wetland. Three stations in the lake were located along the dike. Sampling was conducted on October 5, 2001, April 18, 2002, and August 4, 2002. All water samples were collected at a depth of approximately 0.2 m in clean 500-ml nitrile bottles. Water samples were analyzed using a gas source mass-spectrometer. Oxygen- and hydrogen-isotope ratios are reported in the standard delta (δ) notation in parts per thousands relative to Vienna standard mean ocean water (VSMOW).

Water sampling at the outlet

A sampling protocol was designed to determine whether the water leaving the wetland (i.e., outflow) was enriched in carbon compared to the water entering from the lake (i.e., inflow). Water samples were collected at the outlet at regular intervals (i.e., 3–4 times a month during seiche events) between April 2001 and December 2002. At each seiche event, a minimum of 5 samples was taken during inflow and outflow, respectively, providing a minimum of ten samples total per event. Samples were taken at 50–60 min intervals, with no samples taken during slack. Sampling was done manually from April to September 2001 using a 500-ml water bottle at a depth of approximately 0.2 m. After October 2001, sampling was done with an auto-sampler to ensure the collection of a representative water sample from the entire water column. The auto-sampler collected 500-ml water samples via a tube perforated every 10 cm and extending from the surface of the water column to the bottom.

Water samples were brought back to the lab for analysis. Half of each sample was filtered through a pre-cleaned 0.45-μm pore-size glass filter to separate the dissolved and particulate fractions. Samples were analyzed for dissolved organic and inorganic carbon (DOC), particulate organic carbon (POC), and inorganic carbon (IC) with a Rosemount Dohrman DC-190 Total Organic Carbon Analyzer.

Statistical analysis

Differences in inflow and outflow concentrations in the various forms of carbon were compared by using a repeated measure analysis of variance (SAS Institute Inc. 2000), evaluating the effects of flow direction and month of sampling. Significance was evaluated at the 0.05 level, and Tukey tests were used for comparison of means.

Results

The water samples taken in Lake Erie had relatively constant isotopic composition ($\delta^{18}O_{av}$=–7.03‰, s.d. = 0.45; δD_{av}=–55.95‰, s.d. = 2.23; n = 9), independently of the station location and month of sampling (Fig. 2). In the marsh, the isotopic composition of water samples was more variable, with the isotopic values distributed along a local evaporation line (Fig. 2). The local evaporation line represents the change in the isotopic composition of the water molecules as a result of evaporation (i.e., water samples that have evaporated will be enriched in $\delta^{18}O$ and δD; Craig 1961). The stations located the furthest away from the outlet in the dike (Stations 10 and 15; Fig. 1) had the lowest δ values throughout the study ($\delta^{18}O_{av}$=–1.13‰, s.d. = 0.35; δD_{av}=–21.33‰, s.d. = 2.65; n = 6; Fig. 2). Stations located at proximity to the outlet (Stations 1, 2, 3, 4, 5, 7 and 12; Fig. 1) had isotopic compositions ($\delta^{18}O_{av}$=–6.95‰, s.d. = 1.41; δD_{av}=–54.55‰, s.d. = 1.95; n = 21) close to those of the water from Lake Erie (Fig. 2). Finally, the water collected at intermediate distance from the outlet in the dike (Stations 6, 8, 9, 11, 13, 14; Fig. 1) had isotopic values widely distributed ($\delta^{18}O_{av}$=–5.14‰, s.d. = 1.19; δD_{av}=–43.00‰, s.d. = 7.82; n = 18; Fig. 2).

Water sampling at the outlet of Metzger marsh was conducted regularly from April 2001 until December 2002, with the exception of January 2002 and October 2002 when ice and other difficulties did not allow for adequate sampling. Over the sampling period, the mean DOC and POC concentrations were higher in the water leaving the marsh to the lake (n = 114; 30.4 mg l^{-1} ± s.d. 6.1; 6.1 mg l^{-1} ± s.d. 4.2, respectively) than in the water entering the marsh from the lake (n = 117; 23.1 mg l^{-1} ± s.d. 4.9; 2.7 mg l^{-1} ± s.d. 1.4, respectively) (Figs. 3, 4). On average, the fluxes of DOC in and out the marsh were four times greater than the fluxes of POC. The difference between inflow and outflow concentrations was the most pronounced for POC ($F_{1,229}$=35.3, P = 0.002), than for DOC ($F_{1,\ 301}$=24.5, P = 0.018). Out of the 19 months sampled, the differences between inflow and outflow concentrations in DOC and POC were significant for 10 and 9 months, respectively

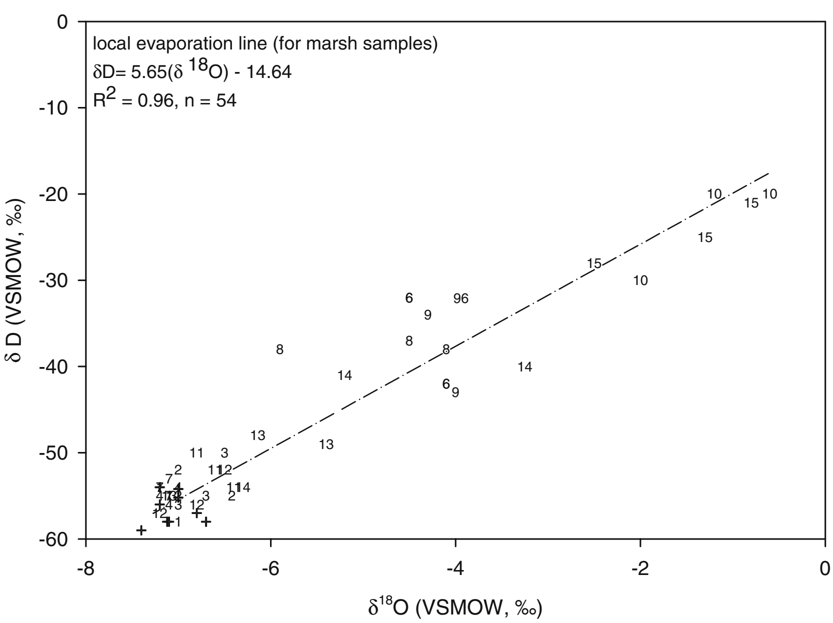


Fig. 2 Hydrogen- and oxygen-isotope compositions of water samples collected throughout the wetland and in Lake Erie. Lake Erie samples are denoted by cross sign (+). Samples from the wetland are denoted by their individual number. Stations 10 and 15 were located at the back of the wetland. Stations 6, 9 and 14 were located at intermediate distance between the back of the wetland and the lake. All other stations were located at closer proximity from the outlet in the dike. Some of the wetland stations (particularly Stations 1, 2, 4, 5, 7, 13) had isotopic composition similar to the Lake water, making their individual number difficult to distinguish on the figure

Fig. 3 Concentrations of DOC during inflow (grey bars) and outflow (black bars). A star above the bars indicates significance difference between inflow and outflow concentrations for a particular month

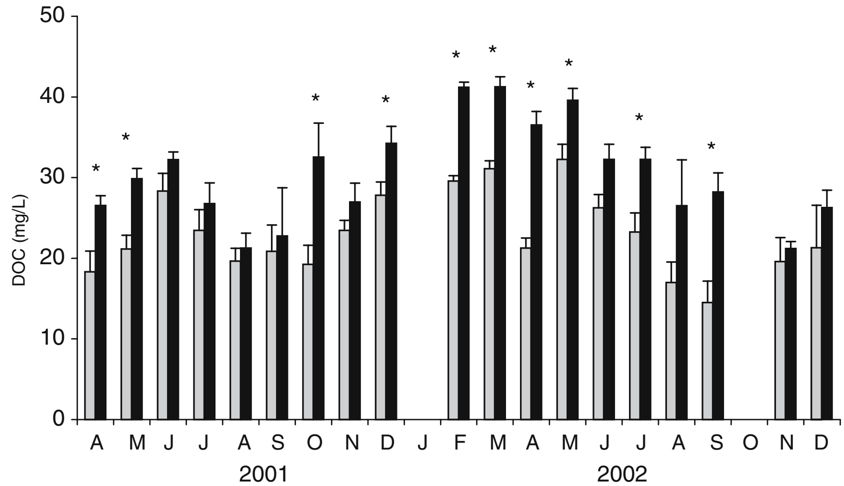


Fig. 4 Concentrations of POC during inflow (grey bars) and outflow (black bars). A star above the bars indicates significance difference between inflow and outflow concentrations for a particular month

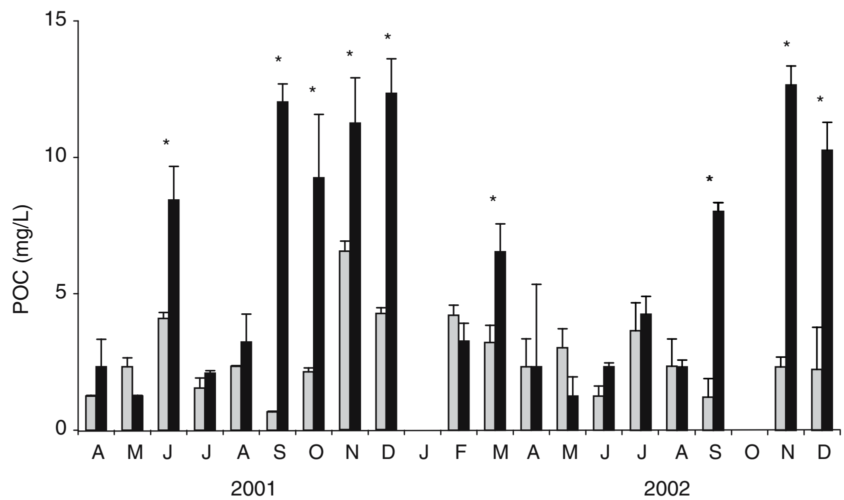
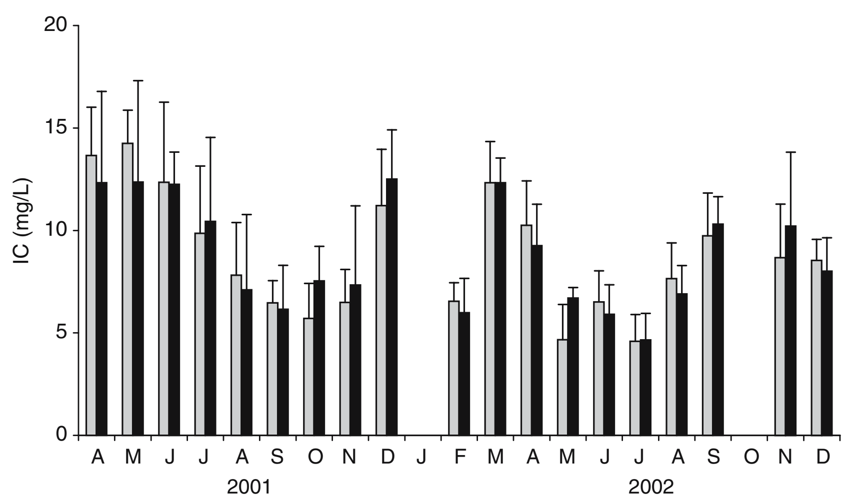


Fig. 5 Concentrations of IC during inflow (grey bars) and outflow (black bars)



(Figs. 3, 4). In contrast, mean IC concentrations were similar during inflow (n = 117; 8.8 mg l^{-1} ±2.9) and outflow (n = 114; 8.8 mg l^{-1}±2.6) ($F_{1,229}$=0.65, P = 0.659) (Fig. 5).

Seasonal variation in carbon concentration was evident throughout the study. DOC concentrations were lowest during the period from April to September, and then increased during late fall, winter and early spring months (Fig. 3). DOC was exported to the lake mainly during late fall, winter and early spring months. POC concentrations followed a similar pattern, with an increase in the fall and winter, particularly in the outflow samples (Fig. 4). During late fall and winter, POC concentrations in the water leaving the wetlands reached levels of 8.2–15.2 mg l^{-1}, which was sometimes 10 times greater than the concentrations measured in the inflow samples. Seasonal fluctuation in inorganic carbon was not as predictable from year to year. IC concentrations tended to be higher during early spring and winter months (Fig. 5).

Discussion

The outwelling hypothesis illustrates that salt marshes produce more organic matter than can be utilized within the system, and that this excess material is exported to coastal waters (Teal 1962; Odum 1968). The present study provides evidence that exchange of detrital matter also occurs between a freshwater coastal wetland and Lake Erie, with a positive mean export of DOC and POC to the lake, particularly during periods of organic matter decomposition in the marsh.

Because freshwater coastal wetlands do not dry out when water retreats during seiches, the exchange of water masses is difficult to quantify (Trebitz et al. 2002). In Metzger Marsh, the areas away from the outlet had water with heavier isotopic signatures, indicating that they were affected by evaporative loss and were poorly replenished by lake water. The isotopic similarity between Lake Erie and marsh water samples nearest to the outlet suggested that a third of the marsh was regularly influenced by lake water. This front section of the marsh is the ‘‘active marsh’’ producing organic matter that has the potential to fuel the lake by providing a source of energy. Lake intrusion is attenuated in wetlands with small outlets while the size of the outlet is often correlated with tributary flow (Trebitz et al. 2002).

While this study has demonstrated that carbon is exported from a Great Lakes' coastal wetland, scaling the carbon fluxes to a larger scale (e.g., all Lake Erie wetlands) is an ambitious task. Over the 19-months of this study, the DOC concentration of the Lake Erie water column entering the marsh averaged 23.1 mg C l^{-1}, while enriched DOC waters leaving the marsh had a mean concentration of 30.4 mg C l^{-1}. Assuming that the volume of water entering the marsh is equivalent to the volume of water leaving the marsh (which is a reasonable assumption considering the absence of a tributary), these fluxes translate into a net positive export of 7.3 mg C l^{-1} of DOC. Considering the size of the outlet at Metzger Marsh (i.e., 10 m wide, ~2 m deep), the average discharge measured at the site (i.e., 1.03 m s^{-1}; unpublished data), Metzger Marsh is delivering roughly 4,700 T of DOC to Lake Erie annually. With similar assumptions applied, an estimated 2,200 T of POC is flushed from the wetland to the lake every year. Clearly these scaling calculations are rough assumptions, and providing accurate carbon budgets for Metzger marsh will require coupling carbon fluxes to precise hydrological budgets. The additional scaling to the whole Lake Erie or the Great Lakes is even more challenging. Even in salt marsh ecosystems that have been studied for over thirty years, fluxes of carbon are still difficult to predict (e.g., Nixon 1980; Childers et al. 2000). Tidal range, geomorphological setting, and salt marshes maturity are among some of the key factors explaining the variability in the magnitude and direction of carbon and nutrients fluxes (Childers et al. 2000). Coastal wetlands around the Great Lakes also differ widely in geomorphology, structure, orientation to the lake, and vegetation (Herdendorf 1987; Trebitz et al. 2002). These factors and others could significantly influence the magnitude of water fluxes and other associated material. Therefore, the concept of outwelling needs to be considered as an hypothesis to be tested in other coastal wetlands on Lake Erie, the Great Lakes, and other large lakes.

While the interaction between salt marshes and marine coastal areas is portrayed as an essential component of coastal system sustainability (Weinstein and Kreeger 2000), I am suggesting that such interactions may also apply to freshwater coastal wetlands. Ultimately to support this conclusion, it would be necessary to investigate whether the detrital material exported from coastal freshwater wetlands is indeed incorporated into the open lake foodweb.

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