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Factors controlling sediment and nutrient fluxes in a small microtidal salt marsh within the Venice Lagoon

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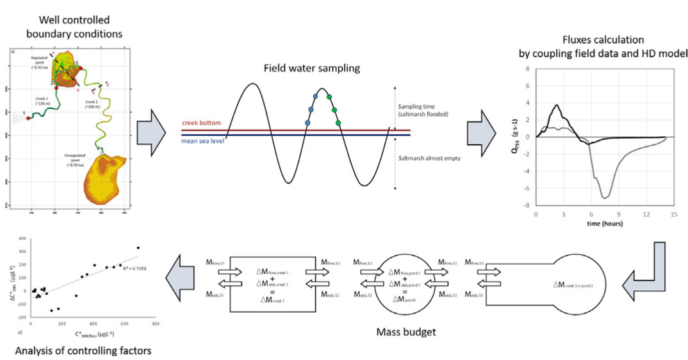
HIGHLIGHTS

- Sediment and nutrients fluxes within saltmarshes were studied.
- Fluxes were assessed by coupling field sampling and HD modeling.
- The saltmarsh resulted to act alternatively as a sink or as a source.
- Sediment and nutrient concentrations during flow phase and tidal excursion resulted the most important controlling factors.
- Vegetated intertidal area provided the major nitrogen removal function.

GRAPHICAL ABSTRACT



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ABSTRACT

Coastal salt marshes are among the Earth's most productive ecosystems and provide a number of ecosystem services. Water quality regulation by storing, transforming and releasing nutrients, organic matter and suspended sediment is recognized as one of the most important functions of salt marshes. The self-purification capacity of intertidal ecosystems contributes to mitigating nutrient inputs, acting as a buffer zone between watersheds and coastal waters, especially in relation to climate change and the increasing frequency of impulsive extreme events. Understanding sediment and nutrient fluxes and assessing the mechanisms that control them are valuable for the preservation and future restoration of salt marshes and for enhancing their effectiveness in providing water quality regulation services.

To investigate the main driving factors in microtidal environments, changes in suspended sediment and nutrient concentrations were measured during several tidal cycles in a small microtidal reconstructed salt marsh in the Venice Lagoon, which was selected as the experimental site. The tidal amplitude, nutrients and total suspended solid concentrations were measured during 6 tidal cycles between September 2011 and October 2013. The water discharge was derived by forcing the hydrodynamic MIKE-DHI numerical model with the measured tidal levels. Fluxes were assessed by coupling field data with the calculated discharges. The salt marsh filtering function was related to the inflow matter concentrations and tidal amplitude. When high suspended solid and nutrient concentrations enter the salt marsh, accumulation processes prevail on release. In contrast, in the case of low concentrations and high tidal excursion, the salt marsh functions as a nutrient and sediment source. During all campaigns, the nitrogen removal function was more effective within the intertidal vegetated areas. Sediment release was the dominant process in the outermost creek, whereas sedimentation prevailed in the inner area of the salt marsh because of the attenuation of hydrodynamic forcing during tide propagation.

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1. Introduction

Salt marshes are highly productive ecosystems and are widely distributed, globally covering 200,000–400,000 km^2 (Fagherazzi et al., 2013). These intertidal habitats provide distinctive biodiversity and other important ecosystem services, including coastal protection, carbon sequestration, fishery support, nutrient cycling and water quality regulation (Mossman et al., 2012; Temmerman et al., 2013; Costanza et al., 1997).

Understanding the role that tidal salt marshes play in nutrient and sediment dynamics is an open issue in the fields of research focused on transitional waters (i.e., estuaries, lagoons, brackish wetlands and similar). Studies regarding nutrients and organic matter tidal fluxes between salt marshes and adjacent waters receive significant attention from scientists and managers because of their influence on both water quality and availability of essential elements at the base of the food web (Piehler and Smyth, 2011). Several authors have investigated the nutrient removal function of salt marshes, concluding that salt marshes act as a sink of nutrients and organic matter (Etheridge et al., 2014; Velinsky et al., 2017; Poulin et al., 2009); it has also been emphasized that vegetated and structured habitats enhance the efficiency of denitrification processes (Piehler and Smyth, 2011).

The purification capacity of intertidal ecosystems could play an important role in the mitigation of nutrient inputs, acting as a buffer zone between watersheds and coastal waters, especially in relation to climate change and the increase in impulsive extreme events (Etheridge et al., 2014). However, other studies obtained opposite results, following the so-called "Outwelling Hypothesis" (Dame et al., 1986; Odum, 1980), postulating that salt marshes are exporters of organic matter to the coastal zone, providing food resources that support marine productivity in coastal systems (Simas and Ferreira, 2007; Whiting et al., 1985).

Quantification of sediment fluxes in coastal tidal marshes is a widespread theme throughout the literature, mainly related to examination of deposition-erosion rates and morphological evolution (Ganju et al., 2005). Sediment transport within salt marsh systems is driven by tidal and storm forcing, external sediment input, internal sediment redistribution and trapping of sediment by marsh vegetation (Rosencranz et al., 2016). The import-export of suspended sediment plays an important role in the formation and maintenance of tidal salt marshes (Rosencranz et al., 2016; Ganju et al., 2005; Reed et al., 1999; Fagherazzi et al., 2013). Sediment deposition, along with accumulation of autochthonous organic material, contributes to the vertical accretion, increasing the resilience of salt marshes to sea level rises (Reed, 1989; Morris et al., 2002; Mudd et al., 2009). Thus, healthy salt marshes are net sediment sinks (Fagherazzi et al., 2013). Conversely, if the sediment release rate is greater than the deposition rate, the salt marsh will enter into an erosive state, which can be potentially irreversible even in the absence of sea level rises (Mariotti and Fagherazzi, 2013).

Due to the value of these ecosystems, many regulatory agencies seek to protect existing tidal marshes and restore lost ones (Ganju et al., 2005, 2017). In his policy paper, originally produced in response to a request from the Scientific and Technical Review Panel of the Ramsar Convention on Wetlands, Erwin (2009) remarked that policymakers should promote wetland restoration as part of their climate change adaptation and mitigation strategies.

Understanding the factors controlling sediment and nutrient fluxes within salt marshes is an essential goal to make effective decisions about salt marsh management and restoration (Reed et al., 1999; Erwin, 2009). Assessments of sediment dynamics within salt marshes, even on short (i.e., tidal) time scales, might be useful for long-term resource management, especially in relation to sea level rises. Moreover, understanding nutrient dynamics would support the design of restoration projects aimed at enhancing the provision of targeted ecosystem services.

Most studies regarding nutrient and sediment fluxes between salt marshes and adjacent waters have been performed in ocean estuarine ecosystems, whereas only limited information about microtidal Mediterranean lagoons is available in the literature. The purpose of this paper is to contribute to understanding the dynamics in Mediterranean microtidal lagoons.

A small reconstructed salt marsh was selected as the study site to investigate the factors controlling sediment and nutrient fluxes. The site has well-controlled boundary conditions that are ensured by the elevation of creek and pond edges, which also prevent lateral water flow during high tide.

2. Material and methods

2.1. Study site

The study site is located in Italy, in the southern part of the Venice Lagoon, close to the city of Chioggia (Fig. 1a). It is part of an artificially constructed salt marsh made in 1992 by *Magistrato alle Acque di Venezia* (Venice Water Authority). A system of creeks and ponds was dredged 4 years after the salt marsh construction with a renaturalization purpose (Fig. 1b). The dredged material was placed along the edges of creeks and ponds, which resulted in them being completely embanked (Fig. 1c). The banks are topped only by exceptionally high tides, a few times per year. Consequently, the flow and ebb tides enter the system only from the mouth of creek 1, and lateral fluxes are prevented during tidal propagation through the salt marsh. The present study focuses on the resulting hydraulic system, which includes two ponds and two creeks connected with the adjacent tidal flat by a single channel mouth (Fig. 1d).

Within the first vegetated pond, during low tide, the tidal flow remains channeled, whereas during higher tide levels, the water floods the intertidal vegetated platform (Fig. 1c). Because of the bottom elevation, only the first pond is vegetated (*Salicornia*, *Puccinellia* and *Sarcocornia* spp.). The second pond, in the terminal part of the system (Fig. 1d), is often covered by a thin layer of water due to tidal time delay and amplitude attenuation.

Given its structural features, this system is an excellent experimental site, with easily controllable and measurable boundary conditions.

Previous studies have addressed changes in the morphological features of this site through remote sensing, field surveys and mathematical modeling (D'Alpaos et al., 2007; Guarnieri et al., 2009).

2.2. Sampling design

Water sampling was performed during six semidiurnal tidal cycles from September 2011 to October 2013 in different seasons (I: 28/09/2011; II: 09/03/2012; III: 26/06/2012; IV: 08/05/2013; V: 23/07/2013; VI: 17/10/2013). Organic matter, dissolved organic carbon (DOC), particulate organic carbon (POC), nutrient concentrations (ammonia NH_4^+, nitrate NO_3^-, nitrite NO_2^-, and orthophosphate PO_4^-) and total suspended solids (TSS) were measured during the flow and ebb tide. For each tidal phase, samples were collected following a water-level-based approach, sampling at intervals of approximately 0.15 m of water depth variation. Therefore, the sampling frequency ranged from 30′ to 90′, depending on the tidal gradient. During each campaign, the first sample was taken when water began to flow into the salt marsh and at all stations, the water depth was at least 10 cm, being the minimum level needed for collecting samples by bottle. Similarly, the final sample was collected during the ebb phase before the water depth decreased below 10 cm. Usually, at the end of the ebb phase, the salt marsh was almost completely empty.

These four stations were selected as representative of fluxes between the salt marsh and adjacent waters and the dynamics within the intertidal system. In particular, at Station 1, located at the mouth of the first creek, changes in water quality are expected to be a result