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Sulfur biological cycle of the different *Suaeda salsa* marshes in the intertidal zone of the Yellow River estuary, China

Zhigao Sun[a,*], Xiaojie Mou[a,b], Hongli Song[a,b], Huanhuan Jiang[a,b]

[a] Key Laboratory of Coastal Zone Environmental Processes, Yantai Institute of Coastal Zone Research (YIC), Chinese Academy of Sciences (CAS); Shandong Provincial Key Laboratory of Coastal Zone Environmental Processes, YICCAS, Yantai, Shandong 264003, PR China
[b] University of Chinese Academy of Sciences, Beijing 100049, PR China

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ABSTRACT

To evaluate the sulfur (S) biological cycle status in the marshes of the intertidal zone, this study explored the S biogeochemical processes in the two *Suaeda salsa* marshes [middle *S. salsa* marsh (MSM) and low *S. salsa* marsh (LSM)] of the Yellow River estuary during April 2008 to November 2009. Results showed that soil S fluctuated seasonally and varied with depth in both MSM and LSM. The variations in S content in different parts of plant were significantly influenced by water and salinity. The *S. salsa* litter in MSM and LSM released S to the decomposition environment throughout the year. The S absorption coefficients of *S. salsa* in MSM and LSM were very low (0.0031 and 0.0004, respectively), while the S biological cycle coefficients were high (0.9014 and 0.8625, respectively). The S turnovers among compartments of MSM and LSM indicated that the uptake amounts of roots were 1.237 and 0.160 g m^{-2} yr^{-1} and the values of aboveground parts were 3.885 and 1.276 g m^{-2} yr^{-1}, the re-translocation quantities from aboveground parts to roots were 2.770 and 1.138 g m^{-2} yr^{-1}, the translocation amounts from roots to soil were 0.154 and 0.018 g m^{-2} yr^{-1}, the translocation quantities from aboveground living bodies to litter were 1.115 and 0.138 g m^{-2} yr^{-1}, and the annual return quantities from litter to soil were less than 1.096 and 0.188 g m^{-2} yr^{-1}, respectively. Although S was not a limiting nutrient in *S. salsa* marshes, its high biological cycle rate might significantly inhibit the production and emission of methane (CH_4), which had important significances to reduce CH_4 emission from the Yellow River estuary. The S quantitative relationships determined in the compartment model might provide some scientific basis for us to reveal the special inhibition mechanism in future studies.

1. Introduction

Sulfur (S) is the fourth important nutrient [after nitrogen (N), phosphorus (P) and potassium (K)], which plays an important role in many biogeochemical processes, such as participating in the composition of protein, aminophenol and chlorophyll, controlling the metabolism of carbohydrates in the photosynthesis process, and influencing the respiration and the stress-resistance of plants (Lu, 2003; Li et al., 2007a). The S cycle is one of the most complex cycles in wetland ecosystems, which is responsible for a series of important biogeochemical processes, such as carbon mineralization, water acidification and pyrite formation (Nedwell and Watson, 1995; Mandernack et al., 2000). There has been increasing interest in understanding the S cycle in wetland ecosystems because high inputs of organic matter into wetland soils, along with oxic surface and anoxic subsurface zones, potentially allow S to play a critical role in the biogeochemistry of wetlands (Giblin and Wieder, 1992).

Many studies have been conducted on the processes of the S cycle in different wetland ecosystems, such as salt marshes (Thamdrup et al., 1994; Madureira et al., 1997; Zhou et al., 2007), freshwater marshes (Spratt and Morgan, 1990; Küsel et al., 2001; Liu and Li, 2008), peatlands (Wieder and Land, 1988; Mandernack et al., 2000) and mangrove swamps (Zhang, 1996; Lallier-verges et al., 1998; Ferreira et al., 2007). Some studies adopted S isotope (^{34}S) techniques to identify the sources of organic matter (Peterson et al., 1985; Moncreiff and Sullivan, 2001) or to reconstruct the historical patterns of S cycle in wetlands (Bottrell and Coulson, 2003). Tidal marshes are very important in coastal zones, which are sensitive to global climate change and human activities. The sulfate (SO_4^{2-}) content in tidal marshes is very high, and the dynamic equilibrium of SO_4^{2-} and its reduction products constitute the special S

* Corresponding author at: Key Laboratory of Coastal Zone Environmental Processes, Yantai Institute of Coastal Zone Research (YIC), Chinese Academy of Sciences (CAS); Shandong Provincial Key Laboratory of Coastal Zone Environmental Processes, YICCAS, Yantai, Shandong 264003, PR China. Tel.: +86 0535 2109121; fax: +86 0535 2109000.
E-mail address: zgsun@yic.ac.cn (Z. Sun).

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cycle system of tidal marshes (Xing et al., 2007). However, information on the processes of the S cycle in tidal marshes remains limited. In addition, current studies mostly focus on a certain process of the S cycle, while systematic and experimental studies are lacking. The compartment model has been widely and successfully applied in previous research and is a common approach to study the element cycles of ecosystems (Reuss and Innis, 1977; Wallance et al., 1978). Most compartment model studies have, however, focused on grassland ecosystems (Reuss and Innis, 1977; Li and Redmann, 1992; Li et al., 2003), forest ecosystems (Liu and Yu, 2005; Wu et al., 2006) and freshwater marsh ecosystems (Sun and Liu, 2007; Liu and Li, 2008), and information on the S cycle of tidal marshes remains scarce.

The Yellow River is well known as a sediment-laden river. Every year, approximately 1.05×10^7 tons of sediment is carried to the estuary (Cui et al., 2009) and deposited in the slow flowing landform, resulting in vast floodplain and special marsh landscape (Xu et al., 2002). Sediment deposition is an important process for the formation and development of tidal marshes in the Yellow River Delta. The deposition rate of sediment in the Yellow River not only affects the formation rate of tidal marshes, but also influences the water or salinity gradient and the succession of plants from the land to the sea. Tidal marsh is the main marsh type, with an area of 964.8 km^2, accounting for 63.06% of the total area of the Yellow River Delta (Cui et al., 2009). *Suaeda salsa*, an annual C_3 plant, is one of the most prevalent halophytes in the tidal marshes of the Yellow River estuary. As a pioneer plant, it has strong adaptations to environmental stresses, such as high salinity, flooding and sediment burial (Han et al., 2005). In the *S. salsa* distribution area, two phenotypes are generally formed in the middle marsh and low marsh, respectively, due to the differences of water and salinity status. However, information on elemental biogeochemical processes of the tidal marshes in the Yellow River estuary is limited and the systematic and comparative studies on the S cycle of the two *S. salsa* marshes are still lacking.

In this paper, the S biological cycle of the two *S. salsa* marshes in the intertidal zone of the Yellow River estuary was systemically and comparatively studied. The *S. salsa* marsh was divided into four S compartments, including aboveground living body, root, litter and soil. The objectives of this paper were (i) to examine the distribution characteristics of S in the two plant-soil systems, (ii) to determine the S turnovers among the compartments of *S. salsa* marshes, and (iii) to establish the S biological cycle compartment model of *S. salsa* marshes and evaluate the S cycle status.

2. Materials and methods

2.1. Study site

This study was conducted from April 2008 to November 2009 at two experimental plots (each 400 m × 400 m) in the *S. salsa* distribution area [middle *S. salsa* marsh (MSM) and low *S. salsa* marsh (LSM)] in the intertidal zone of the Yellow River estuary, located in the Nature Reserve of Yellow River Delta (37°35′N–38°12′N, 118°33′E–119°20′E) in Dongying City, Shandong Province, China. The nature reserve is of typical continental monsoon climate with distinctive seasons, and the average temperature in spring, summer, autumn and winter are 10.7 °C, 27.3 °C, 13.1 °C and −5.2 °C, respectively. The annual average temperature is 12.1 °C, the frost-free period is 196 d and the effective accumulated temperature is about 4300 °C. Annual evaporation is 1962 mm and annual precipitation is 551.6 mm, with about 70% of precipitation occurring between June and August. The soils in the study area are dominated by intrazonal tide soil and salt soil (Tian et al., 2005), and the main vegetations include *Phragmites australis*, *S. salsa*, *Triarrhena sacchariflora*, *Myriophyllum spicatum* and *Tamarix chinensis*.

S. salsa generally germinates in late April, blooms in July, matures in late September and completely dies in late November (Gu, 1998). The tide in the intertidal zone of the Yellow River estuary is irregular semidiurnal tide and the mean tidal range is 0.73–1.77 m (Li et al., 1991). The *S. salsa* in the low marsh generally distributed in the range 0.5–2 km (Li et al., 1991), at a very low elevation of −1.0 to 0.9 m (Song et al., 2010). Thus, the *S. salsa* in LSM is frequently and greatly inundated by the tide, which caused the moisture and salinity of topsoil is high (Table 1). Also, the *S. salsa* in LSM is very short (average height during growth peak, 33.64 ± 7.96 cm) and its leaf and stem are red-violet during the growth season. Comparatively, the *S. salsa* in the middle marsh generally distributed in the range 1–4 km (Li et al., 1991), at a higher elevation of 1.0–2.5 m (Song et al., 2010). Thus, the *S. salsa* is infrequently and irregularly flooded by the tide, which caused the moisture and salinity of topsoil is low (Table 1). Differently, the *S. salsa* in MSM is tall (average height during growth peak, 52.51 ± 9.91 cm) and its leaf and stem are green. The comparison of physical and chemical properties of topsoil (0–20 cm) in MSM and LSM are shown in Table 1.

2.2. Study methods

2.2.1. Collection of soil samples

Since the substantial root of *S. salsa* was most in upper 15 cm and most of the S transfers between soil and plant occurred in the upper zone (Mou, 2010), the seasonal dynamics of total sulfur (TS) content in topsoil (0–15 cm) was studied at the two experimental plots from April to November in 2009. Ten soil samples were collected per month at a sampling depth of 0–15 cm and soil bulk densities were determined at the same time. The vertical distributions of TS content in the soil profile were studied in August 2008. Three soil profiles (depth: 60 cm) were sampled at each experimental plot at 10 cm interval, with 18 samples in total. The bulk density of each soil layer was determined simultaneously. The S stock (T_n, kg m^{-2}) in soil was calculated by Eq. (1):

$$T_n = \sum_{i=1}^{n} W_i \times S_i \times \frac{h}{10} \tag{1}$$

where W_i (g cm^{-3}) is the soil bulk density of the *i* layer, S_i (%) is the TS content in the *i* layer and *h* is soil depth (10 cm).

2.2.2. Determination of litter and biomass

Litter production, aboveground biomass (AGB) and belowground biomass (BGB) were determined using a quadrat method (50 cm × 50 cm, five replications) at the two experimental plots from May to November in 2008, with a sampling frequency of 20 d. On the sampling dates, the aboveground part of plant was clipped near the ground, and the stem, leaf and standing dead litter were separated immediately in the laboratory. The new litter distributed in the quadrat was also collected. Roots in the quadrat were dug out and washed carefully. All samples were weighed after being dried at 80 °C for 48 h. In the growing season, since little parts of the plant or the litter could be carried away or redistributed in tidal marshes during the ebb and flow, the AGB and litter production were standing crops.

2.2.3. Determination of litter decomposition rates

Litter decomposition was studied with a litterbag technique at the two experimental plots from April 2008 to November 2009. In order to weaken the fragmentation impact of snowfalls and strong winds in winter, the standing litter (collected on April 5, 2008)