



Nitrogen cycle of a typical *Suaeda salsa* marsh ecosystem in the Yellow River estuary

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Abstract

The nitrogen (N) biological cycle of the *Suaeda salsa* marsh ecosystem in the Yellow River estuary was studied during 2008 to 2009. Results showed that soil N had significant seasonal fluctuations and vertical distribution. The N/P ratio (15.73 ± 1.77) of *S. salsa* was less than 16, indicating that plant growth was limited by both N and P. The N absorption coefficient of *S. salsa* was very low (0.007), while the N utilization and cycle coefficients were high (0.824 and 0.331, respectively). The N turnover among compartments of *S. salsa* marsh showed that N uptake from aboveground parts and roots were 2.539 and 0.622 g/m², respectively. The N translocation from aboveground parts to roots and from roots to soil were 2.042 and 0.076 g/m², respectively. The N translocation from aboveground living bodies to litter was 0.497 g/m², the annual N return from litter to soil was far less than 0.368 g/m², and the net N mineralization in topsoil during the growing season was 0.033 g/m². N was an important limiting factor in *S. salsa* marsh, and the ecosystem was classified as unstable and vulnerable. *S. salsa* was seemingly well adapted to the low-nutrient status and vulnerable habitat, and the nutrient enrichment due to N import from the Yellow River estuary would be a potential threat to the *S. salsa* marsh. Excessive nutrient loading might favor invasive species and induce severe long-term degradation of the ecosystem if human intervention measures were not taken. The N quantitative relationships determined in our study might provide a scientific basis for the establishment of effective measures.

Key words: compartment model; nitrogen biological cycle; *Suaeda salsa*; Yellow River estuary

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Introduction

Nitrogen (N) is an essential nutrient affecting plant photosynthesis and primary production in terrestrial ecosystems (Mooney et al., 1987). The N biological cycle in marshes performs many important biogeochemical functions, such as N transformation and fate, N removal and storage, and nitrous oxides (N₂O) emission. The vast majority of N in marshes is in organic form, contained in vegetation, plant detritus, macrofauna, microorganisms, soil, and water (dissolved organic compounds and suspended sediments). In general, soil N mainly exists in organic and inorganic forms, although the proportion of inorganic N is very low. As inorganic N can be utilized by plants directly, the transformation rate of organic N to inorganic N significantly affects the productivity of marsh ecosystems (Mistch and Gosselin, 2000).

Many studies have been conducted on the N cycle

process in ecosystems such as paddy fields (Yoshinaga et al., 2007; Ahmad et al., 2009), freshwater marshes (Sun and Liu, 2008; van Damme et al., 2009), salt marshes (Boyer and Fong, 2005; Zhou et al., 2007), and mangrove marshes (Silva et al., 2007; Naidoo, 2009). Some studies adopted stable isotope techniques to quantify movement, transformation, and fate of N in marsh ecosystems (Fair and Heikoop, 2006; Sjøvik and Mørkved, 2008). Tidal marshes are important within coastal zones, and are sensitive to global climate change and human activities. Tidal marshes generally undertake large amounts of nitrogenous compounds from terrestrial human activities, and its N cycle is closely related to global environmental problems (Fang et al., 2002). However, information on N cycle processes in tidal marshes remains limited. In addition, current studies mostly focus on narrow processes of the N cycle, and lack systemic and synthetic study. The compartment model has been widely and successfully applied in recent research and is a common method for studying

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the element cycle of ecosystems (Reuss and Innis, 1977). 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, 2007a; Liu and Li, 2008), while information on the N cycle of tidal marshes remains scarce.

The Yellow River is 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 delta, which results in a 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 marsh, but also, to some extent, influences water and salinity status and the succession of plants. With an area of 964.8 km², tidal marsh is the main type of marsh in the Yellow River Delta and accounts for 63.06% of total area (Cui et al., 2009). *Suaeda salsa* is the most important vegetation in the tidal marsh of the Yellow River estuary. As a pioneer plant, it has strong adaptations to environmental stresses, such as high salinity, flooding, and sediment burial. However, information on elemental biogeochemical processes of the tidal marsh in the Yellow River estuary is limited and the systemic study on the N cycle of *S. salsa* marsh is still scarce.

In this article, the *S. salsa* marsh in the Yellow River estuary was selected to systemically and synthetically study the N biological cycle. The *S. salsa* marsh was divided into four N compartments, including aboveground living body, root, litter, and soil. The N dynamics and N stocks of each compartment were studied and N turnovers among compartments were determined. In addition, the N biological cycle compartment model of *S. salsa* marsh was established and the N cycle status was evaluated.

1 Study site and methods

1.1 Study site

This study was conducted during April 2008 to November 2009 at an experimental plot in the *S. salsa* marsh (37°46′38.9″N, 119°09′41.4″E) in the Yellow River estuary, located in the Nature Reserve of the Yellow River Delta (37°35′–38°12′N, 118°33′–119°20′E) in Dongying City, Shandong Province, China. The nature reserve has a typical continental monsoon climate with distinctive seasons; summer is warm and rainy while winter is cold. The annual average temperature is 12.1°C, the frost-free period is 196 days, and the effective accumulative 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 tidal soil and salt soil (Tian et al., 2005), and the main vegetation includes *Phragmites australis*, *S. salsa*, *Triarrhena sacchariflora*, *Myriophyllum spicatum*, *Tamarix chinensis*, and *Limonium sinense*. *S. salsa*, an annual C₃ plant,

is one of the most important halophytes in the Yellow River estuary and can tolerate coastal seawater salinity and salinity fluctuations resulting from water evaporation and tidal inundation (Han et al., 2005). It generally germinates in late April, blooms in July, matures in late September, and completely dies in late November (Gu, 1998). Since *S. salsa* is irregularly affected by tide, the salinity in soil is always high (sample depth: 10 cm; electrical conductivity: $(11.52 \pm 0.61) \mu\text{S}/\text{cm}$, $n = 30$), the leaves and stems of *S. salsa* are red-violet during the growth period and plant height is relatively short (Wang et al., 2006).

1.2 Study methods

The seasonal dynamics of total nitrogen (TN), ammonium nitrogen (NH₄⁺-N), and nitrate nitrogen (NO₃⁻-N) contents in topsoil were determined at the experimental plot during 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 TN, NH₄⁺-N, and NO₃⁻-N contents in the soil profile were studied in August 2008. Three soil profiles (depth: 60 cm) were sampled at the experimental plot at 10 cm intervals, with 18 samples in total. The bulk density of each soil layer was determined simultaneously. The N stock (T_n , kg/m²) in soil was calculated by Eq. (1):

$$T_n = \sum_{i=1}^n W_i \times N_i \times h/10 \quad (1)$$

where, W_i (g/cm³) is the soil bulk density of each layer i ; N_i (%) is the N content in each layer; and h is the soil depth (10 cm).

Net N mineralization was studied by PVC tube closed-top incubation (Raison et al., 1987) at the experimental plot from April to November in 2009, with an incubation depth of 15 cm. The experiment included six incubation periods: 4.25–5.26 (I), 5.26–6.27 (II), 6.27–7.31 (III), 7.31–8.25 (IV), 8.25–9.25 (V) and 9.25–11.12 (VI). In each incubation period, ten replications were laid at the experimental plot by diagonal belt transect. Simultaneously, the soil bulk density was measured and ten soil samples were collected to determine the original values of TN, NH₄⁺-N and NO₃⁻-N contents in soil (0–15 cm). The net N mineralization rates (R_{\min} , mg N/(kg-day)) and net N mineralization amount (W , kg N/hm²) were calculated by Eqs. (2) and (3):

$$R_{\min} = (C_1 - C_0)/(T_1 - T_0) \quad (2)$$

$$W = W_v \times V \times R_{\min} \times t/1000 \quad (3)$$

where, C_0 (mg/kg), C_1 (mg/kg) are the contents of inorganic N in soil before (at the T_0 time) and after (at the T_1 time) incubation, respectively; W_v (g/cm³) is the soil bulk density; V (m³) is the soil volume per hectare (1500 m³); and t (day) is the incubation days.

Litter production, aboveground biomass, and belowground biomass were determined using quadrats (50 cm × 50 cm, five replications) at the experimental plot from May

to November 2008, with a sampling frequency of 20 days. The aboveground part of the plant was clipped near the ground, and the stem, leaf, and standing dead litter were separated immediately in the laboratory. Simultaneously, the new litter distributed in the quadrat was also collected. Roots in the quadrat were dug out (sampling depth: 30 cm) and washed carefully. All samples were weighted after being dried at 80°C for 48 hr. In the growing season, as little plant or litter could be carried away or redistributed in tidal marsh due to the irregular semidiurnal tide, the aboveground biomass and litter production were standing crops.

Litter decomposition was studied by the litterbag technique at the experimental plot from April 2008 to November 2009. The *S. salsa* litter was washed in distilled water, cut into 10 cm segments and oven-dried at 80°C for 48 hr. Each 20 cm × 20 cm litterbag was made of nylon netting (0.5 mm mesh) and filled with 15 g of litter (oven-dried weight). On April 21, 2008, the litterbags were randomly placed on the experimental plot of the *S. salsa* community. To prevent the litterbag from being carried away by the tide, one 1.6 m PPR pipe was embedded approximately 1.0 m into the sediment, and the litterbags were attached to the pipe with nylon cord. Experimental sampling was conducted nine times (with different intervals) (Table 1), and on each sampling date, three or four litterbags were retrieved from the plot. After retrieval, these litterbags were immediately taken back to the laboratory, and the plant roots, lichen, sediment, and macro-invertebrates were removed from the remaining litter. All litterbags were further cleaned in deionized water and weighted after being dried at 80°C for 48 hr.

The mass loss (R , %) and decomposition rate (k , day⁻¹) were calculated by Eqs. (4) and (5) (Olson, 1963):

$$R = ((W_t - W_0)/W_0) \times 100\% \quad (4)$$

$$W_t/W_0 = e^{-kt} \quad (5)$$

where, W_0 is the initial dry mass; W_t is the dry mass at time t ; and t (day) is decomposition time. Although much litter produced in the growing season could be easily and gradually carried away or redistributed in tidal marsh due to the tide, after the plants completely died at the end of the growing season part of litter still decomposed *in situ* in the *S. salsa* community. After one year decomposition, the annual N translocation amount from litter to soil was calculated by the change of N stock in litter.

All soil and plant samples were ground (< 0.25 mm) using a Wiely mill and analyzed for TC and TN content by an element analyzer (Elementar Vario Micro, German)

Table 1 Sampling date and decomposition time of litterbags

Sampling date (yyyy-mm-dd)	Decomposition time (day)	Sampling date (yyyy-mm-dd)	Decomposition time (day)
2008-04-21	0	2008-11-15	207
2008-07-11	80	2009-04-26	371
2008-08-09	109	2009-06-25	431
2008-09-20	151	2009-08-25	492
2008-10-20	181	2009-11-12	571

and TP content by molybdate-ascorbic acid colorimetry (digested by H₂SO₄-H₂O₂). In addition, the NH₄⁺-N and NO₃⁻-N contents in soil were determined by a sequence flow analyzer (San⁺⁺ SKALAR, the Netherlands).

The N biological cycle characteristics of the *S. salsa* marsh ecosystem can be expressed by absorption coefficient (A), utilization coefficient (U) and cycle coefficient (C) (Eq. (6)–(8)) (Chen and Lindley, 1983):

$$A = \text{PAN}/\text{SN} \quad (6)$$

$$U = \text{PAN}/\text{PSN} \quad (7)$$

$$C = \text{PRN}/\text{PAN} \quad (8)$$

where, PAN (g/(m²·yr)) is the N absorption amount of the plant; PSN (g/m²) is the N standing crop of the plant; PRN (g/(m²·yr)) is the N return amount of the plant; and SN (g/m²) is the N stock in soil (0–60 cm).

According to the calculation method of Li and Redmann (1992), the N stocks in plant compartments (N_n , g/m²) and the N turnovers among plant compartments (F_a , g/(m²·yr)) can be calculated by Eqs. (9) and (10):

$$N_n = C_n B_n \quad (9)$$

$$F_a = C_a B_a \quad (10)$$

where, C_n (mg/kg) is the N content of compartment; B_n (g/m²) is the biomass of compartment; C_a (mg/kg) is the N content as aboveground biomass reaches maximum; and B_a (g/m²) is the maximum aboveground biomass.

Litter N stock (F_{da} , g/m²) in aboveground dead plants, the N translocation amount from aboveground part to root (F_{rt} , g/(m²·yr)), and the N uptake amount of root (F_r , g/(m²·yr)) were calculated by Eq. (11)–(13):

$$F_{da} = C_d B_a \quad (11)$$

$$F_{rt} = F_a - F_{da} \quad (12)$$

$$F_r = F_a - F_{rt} + \Delta N_u \quad (13)$$

where, C_d (mg/kg) is the N content of aboveground dead plant; B_a (g/m²) is the amount of aboveground dead plant; and ΔN_u (g/m²) is the net N increment of root in the growing season.

The N translocation amounts from litter to soil (F_s , g/(m²·yr)) and from root to soil (F_T , g/(m²·yr)) were calculated by Eq. (14)–(16):

$$F_s = F_l - F_y \quad (14)$$

$$F_T = T \times B_{\max} \times C_{\max} \quad (15)$$

$$T = P_m / B_{\max} \quad (16)$$

where, F_l (g/m²) is composed of F_{da} and F_p (g/m²), F_p is the N stock in un-decomposed litter previously accumulated *in situ*; F_y (g/m²) is the N stock in un-decomposed litter after a period of time. T (%) is the turnover rate of root; P_m (g/m²) is the deficit of maximum biomass and minimum biomass of root; B_{\max} (g/m²) is the maximum root biomass; and C_{\max} (mg/kg) is the N content as root biomass reaches maximum.

1.3 Statistical analysis

Samples were presented as means over the replications, with standard error (SE). The analysis of variance (ANOVA) tests (SPSS for windows 11.0) was employed to determine if samples differed significantly ($p < 0.05$).

2 Results and discussion

2.1 N dynamics, distribution, and stock in soil

2.1.1 Seasonal dynamics of N in topsoil

The NO_3^- -N, NH_4^+ -N, and TN contents in topsoil had significant seasonal variations (Fig. 1). From April to August, the NO_3^- -N content increased slowly, while the NH_4^+ -N content fluctuated greatly. After that, both changed consistently and reached their minimum values on 27 October (0.01 ± 0.00 and 2.87 ± 0.33 mg/kg, respectively). The maximum values of NO_3^- -N and NH_4^+ -N content were observed on 25 August (4.36 ± 0.02 mg/kg) and 12 November (9.48 ± 6.24 mg/kg), respectively. The changes of TN content and NH_4^+ -N content were opposite, with the maximum value (422.28 ± 49.07 mg/kg) on 25 April and

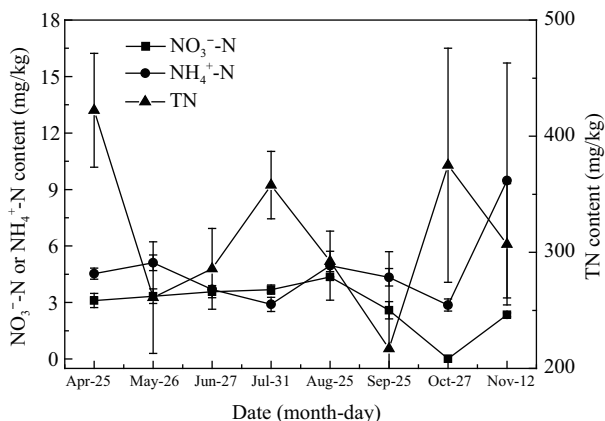


Fig. 1 Seasonal dynamics of TN (total nitrogen), NH_4^+ -N, NO_3^- -N contents in topsoil (0–15 cm) of *Suaeda salsa* marsh. Values are means (\pm SE, $n = 10$).

minimum value (216.94 ± 83.55 mg/kg) on 25 September. In general, the seasonal changes of NO_3^- -N and NH_4^+ -N content were probably related to mineralization, physical movement, plant absorption, and the ebb and flow of tides during different periods (Mou, 2010), while TN content mainly depended on the distribution of soil organic matter and the effect of tide. Estimation results showed that the N stock in topsoil (0–15 cm) during the growing season was 53.30 – 103.76 g/m², and the inorganic N and organic N were 0.71 – 2.91 and 51.60 – 101.88 g/m², respectively.

2.1.2 Vertical distribution of N in soil

The NO_3^- -N, NH_4^+ -N, and TN contents in the soil profile showed different vertical distributions (Fig. 2). The NO_3^- -N content showed no significant change with increasing soil depth, and values ranged from (0.60 ± 0.04) mg/kg to (0.87 ± 0.09) mg/kg. The NH_4^+ -N content generally decreased except for an obvious peak (4.05 ± 2.35 mg/kg) observed at 40–50 cm depth. The TN content and N stock in different soil layers changed consistently, decreasing significantly at 0–30 cm and increasing obviously at 30–50 cm. In general, the vertical changes of NO_3^- -N, NH_4^+ -N, TN content and N stock depended on the spatial heterogeneity of soil organic matter (Mou, 2010) and the effect of soil water condition change resulting from the tide. The calculation results indicated that in August 2008 the total N stock in soil (0–60 cm) was 404.14 g/m², and the inorganic N and organic N were 2.68 and 401.46 g/m², respectively.

2.1.3 Net N mineralization in topsoil

Net N mineralization rates (NNMR) in topsoil during different incubation periods were significantly different ($p < 0.01$) (Fig. 3). The NNMRs during I, II, and III incubation periods were negative (-0.137 ± 0.052 , -0.103 ± 0.017 and -0.008 ± 0.012 mg/(kg-day), respectively), while during periods IV, V and VI the values were positive (0.182 ± 0.038 , 0.050 ± 0.033 , 0.038 ± 0.005 mg/(kg-day), respectively). In general, the inorganic N produced by

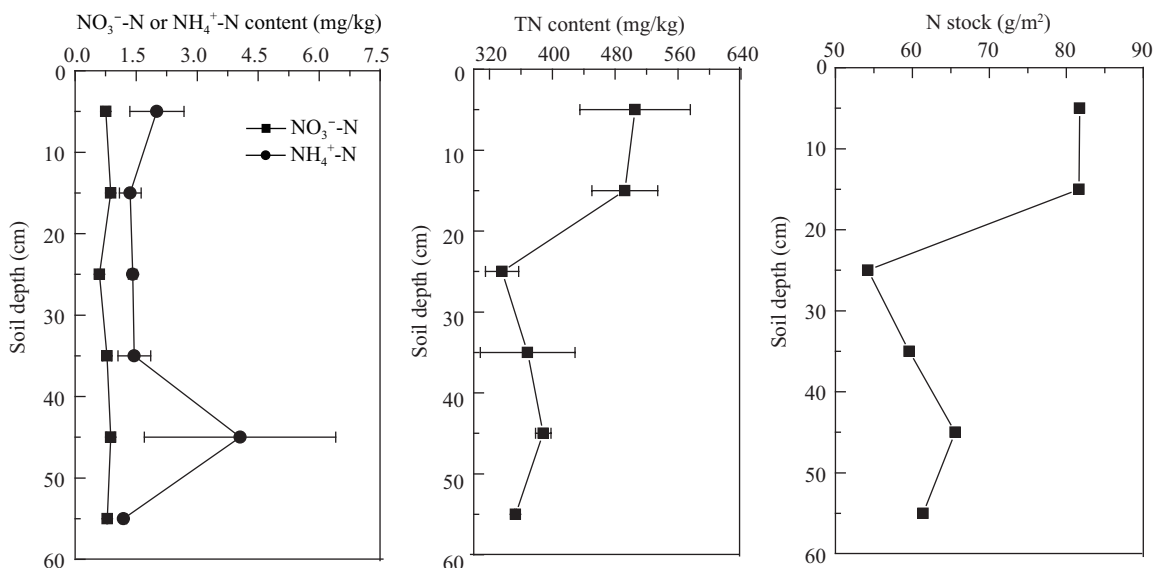


Fig. 2 Vertical distributions of TN, NH_4^+ -N, NO_3^- -N content and N stock in soil profile (0–60 cm) of *S. salsa* marsh. Values are means \pm SE ($n = 3$).

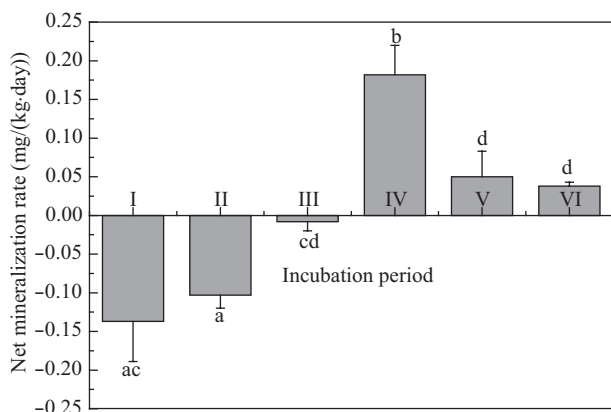


Fig. 3 Net N mineralization rates in tidal marsh soil (0–15 cm). Values are means (\pm SE, $n = 10$); bars with different letters were significantly different at the level of $p < 0.05$.

mineralization remained after immobilization by microbes and soil animals. Maximum NNMR was observed in mid-summer (August), while minimum was observed in spring, indicating that hydrothermal conditions may have significant effects on mineralization. Sierra (1997) indicated that temperature and moisture had significant interaction. In midsummer, the hydrothermal status in topsoil was optimal for survival and reproduction of microbes (Pérez et al., 1998), which generally enhanced mineralization rate. The temperature in spring was very low, however, and the high moisture in the soil caused by tide may be disadvantageous to mineralization. Poor aeration status resulting from high moisture may also enhance denitrification (Nadelhoffer and Aber, 1985), which could induce significant N loss (N_2 , N_2O) of soil. The estimation results showed that the net N mineralization amount in topsoil (0–15 cm) during the growing season was 0.033 g/m^2 .

2.2 Nitrogen dynamics, stocks and turnovers in plant

2.2.1 Dynamics of biomass and N content in plant

The aboveground biomass and belowground biomass of *S. salsa* showed significant seasonal changes (Fig. 4a). Both increased with the improvement of hydrothermal condition from 17 May, and reached maximum values on 31 August (253.28 ± 26.93 and $23.11 \pm 1.23 \text{ g/m}^2$, respectively). After that, both decreased gradually with the coming of autumn and minimum values (136.45 ± 13.53 and $13.39 \pm 1.37 \text{ g/m}^2$, respectively) were observed on 15 November. The seasonal changes in stem and leaf biomass were similar to aboveground biomass, and maximum values (111.37 ± 11.27 and $141.91 \pm 17.43 \text{ g/m}^2$, respectively) were also observed on 31 August. The TN contents in roots and stems of *S. salsa* generally decreased during the growing season (Fig. 4b), and reached minimum values (3646.55 ± 153.28 and $5758.49 \pm 169.47 \text{ mg/kg}$, respectively) on 15 November. The TN content in leaves decreased gradually before 20 September and increased rapidly from 20 September to 15 November. The decrease before 20 September was mainly related to the dilution effect caused by the increase in biomass, while the increase in TN content was related to N transfer from root or stem to leaf and seed during seed growth in

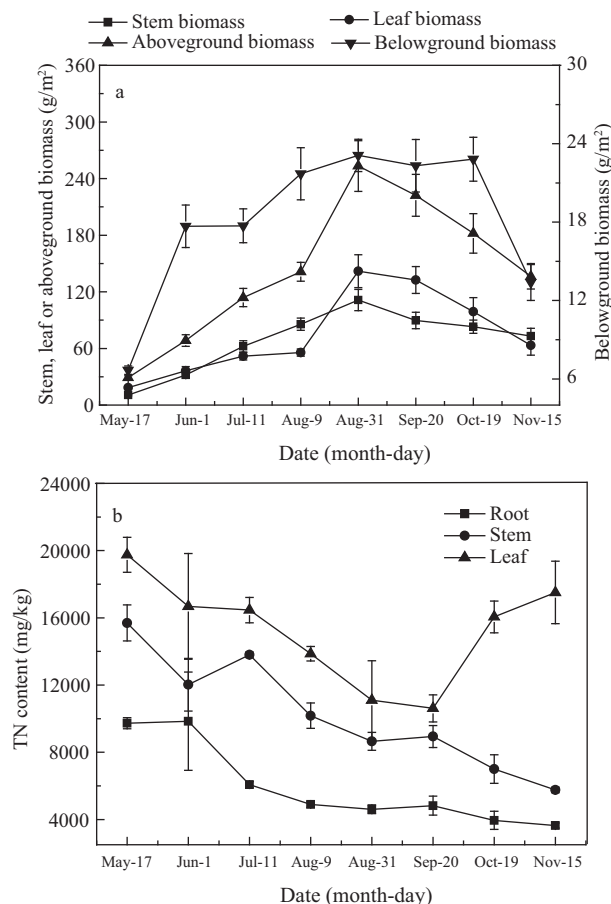


Fig. 4 Seasonal dynamics of biomass (a) and TN content (b) in different parts of *S. salsa*. Values are means (\pm SE, $n = 5$ for biomass, $n = 3$ for TN content).

autumn. Comparatively, the TN contents in leaves were much higher than those of roots and stems, indicating that leaves were the main N accumulation organ. Tessier and Raynal (2003) indicated that the N/P ratio was an effective indicator to estimate nutrient limitation and N saturation. Koerselman and Meuleman (1996) found that marsh plant growth was limited by N if the N/P ratio was less than 14; if the N/P ratio was between 14 and 16, growth was limited by both N and P; if the N/P ratio was more than 16, growth was limited by P. This relationship helps explain nutrient limitation of *S. salsa*. Our results showed that the N/P ratios of *S. salsa* in late spring were less than 16 (Table 2), indicating that plant growth was limited by both N and P. In summer, N/P ratios were more than 16, indicating that plant growth was limited by P. From late summer to early winter, the N/P ratios were all less than 14, indicating that the growth of *S. salsa* was limited by N. The annual average value of N/P ratio (15.73 ± 1.77) was less than 16 (Table 2), indicating that *S. salsa*, as a whole, were limited by both N and P. Moreover, the N/P ratios in different parts changed significantly during the growing season, which mainly depended on the nutrient absorption status of the plant and the nutrient supply status of soil in different periods. Calculation results showed that the N stock in roots, stems, and leaves of *S. salsa* were 0.049 – 0.174 , 0.166 – 0.964 and 0.365 – 1.589 g/m^2 , respectively. The N uptake amounts of aboveground parts and roots were 2.539

Table 2 Dynamics of N/P ratios in different parts of *Suaeda salsa*

Item	N/P ratio								Mean value ± SE
	May-17	Jun-1	Jul-11	Aug-9	Aug-31	Sep-20	Oct-19	Nov-15	
Root	10.58	15.57	26.50	15.99	12.27	12.89	9.87	21.35	15.63 ± 2.02
Stem	13.05	12.94	23.05	18.67	13.71	14.15	12.96	16.93	15.68 ± 1.29
Leaf	18.36	15.24	32.59	20.82	14.21	10.87	11.15	11.93	16.90 ± 2.56
Plant	15.31	14.56	26.50	19.30	13.89	11.72	11.39	13.17	15.73 ± 1.77

and 0.622 g/m², respectively. The N translocation amounts from aboveground part to root and from root to soil were 2.042 and 0.076 g/m², respectively.

2.2.2 Dynamics of litter production and N content in litter

Litter production and TN content in litter showed different changes (Fig. 5). Litter production was low at the initial stage (0.19 ± 0.02 g/m²), after which values increased and reached maximum value (46.25 ± 5.52 g/m²) on 15 November. The *S. salsa* in the tidal marsh produced significant amounts of litter at the end of the growing season, and the low litter production determined in this study was related to the low litter standing crop due to the strong scouring action of the tide. The TN content in litter was high at the initial stage (19750.31 ± 1040.61 mg/kg). After that, the TN contents decreased to a minimum during July to October. Calculation results showed that N stock in litter was 0.004–0.497 g/m², and the N translocation amount from aboveground living body to litter was 0.497 g/m².

2.2.3 Dynamics of litter decomposition and N content in litter

The mass loss of *S. salsa* litter generally increased during decomposition, and the local decrease was related to the determinate error (Fig. 6). The mass lost rapidly from April to November 2008 (0–207 days), accounting for 75.81% of the total loss in the experiment, mainly depended on the moderate hydrothermal condition during the growing season. From November 2008 to April 2009 (207–371 days), the mass was lost slowly due to the low temperature, and mass loss only increased 1.92%. After April 2009 (371 days), mass loss rapidly increased again, mass loss reached 77.00% ± 1.88% after 571 days. The TN contents in *S. salsa* litter increased rapidly

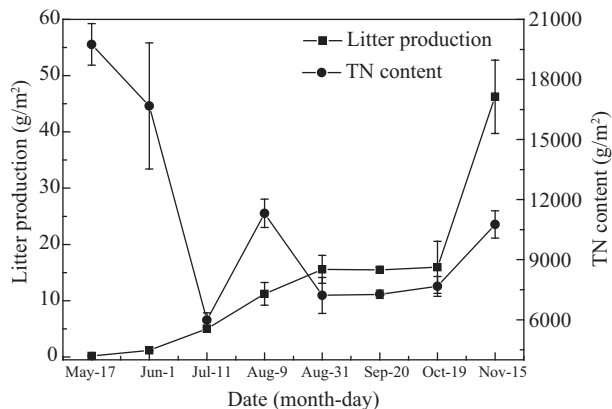


Fig. 5 Seasonal dynamics of litter production and TN content in litter. Values are means (± SE, n = 5 for litter production, n = 3 for TN content).

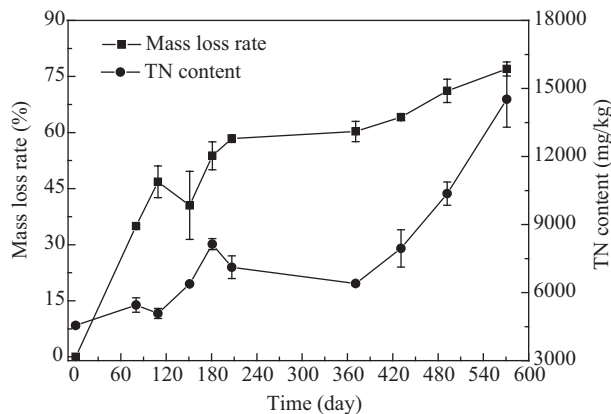


Fig. 6 Dynamics of mass loss and TN content during litter decomposition. Values are means (± SE, n = 3)

from 0 to 181 days, and then decreased gradually until 371 days. After that, the TN contents rapidly increased again, and reached maximum on day 571 (Fig. 6). The changes of C/N ratios in litter were opposite those of TN content (Table 3). They also showed significant negative correlation ($r = -0.919, p < 0.01, n = 10$), indicating that C/N ratios might have significant influence on the N dynamics of *S. salsa* litter during decomposition. This result was similar to conclusions of Köchy and Wilson (1997). The TN contents in litter during decomposition were 111.59%–319.13% of the initial value, indicating that N might accumulate in the litter at all times. The increase of N in *S. salsa* litter might relate to N immobilization by microbes from N sources (such as tidewater and topsoil) in a decomposition environment. Similar results were also reported by Gessner (2000) who found that the increase of TN content in *P. australis* litter was mainly related to external biological immobilization from lake water. Our calculation results showed that the decomposition rate of *S. salsa* litter was 1.1880/yr, indicating that the litter in the *S. salsa* community decomposed completely within one year, and the N standing crop of litter approximated 0. The annual N return amount from litter to soil was 0.368 g/m², which indicated that the litter released N to the decomposition environment. As quite a few *S. salsa* litters

Table 3 Dynamics of C/N ratio in litter during decomposition

Decomposition time (day)	C/N ratio (mean ± SE, n = 3)	Decomposition time (day)	C/N ratio (mean ± SE, n = 3)
0	82.08 ± 3.58	207	57.20 ± 4.01
80	75.20 ± 2.64	371	64.62 ± 0.26
109	81.19 ± 2.83	431	53.56 ± 6.33
151	58.03 ± 0.86	492	39.25 ± 0.37
181	47.58 ± 1.27	571	30.98 ± 2.92

were removed by the tide and the N released from litter to soil was also affected by the tide, the actual N return amount was far less than 0.368 g/m². The N return amount in the tidal marsh showed that the *S. salsa* marsh might be lacking in N, indicating N might be an important limiting nutrient. This result was consistent with the conclusion mentioned in Section 2.2.1.

2.3 Nitrogen allocation and cycle in marsh ecosystem

2.3.1 Nitrogen allocation in marsh ecosystem

Studying N allocation in the *S. salsa* marsh ecosystem showed that aboveground living bodies were the main N stock of the plant subsystem with a value of 1.666 g/m², accounting for 80.18% of the total N stock of plant subsystem (Table 4). In the plant-soil system, N stock of the plant subsystems was very low, accounting for only 0.51% of the total N stock. Soil organic N was the main N stock of the plant-soil system, accounting for 98.83%. In contrast, soil inorganic N accounted for only 0.66%, indicating that available N in *S. salsa* marsh soil was very low. The high proportion of organic N indicated that it was the circulation hinge in the N cycle process, which could prevent N from being lost easily. On the other hand, low available N stock indicated that the supply of effective N was limited.

2.3.2 Nitrogen cycle characteristics of marsh ecosystem

Nitrogen biological cycle characteristics of the marsh showed that N absorption, utilization, and cycle coefficients of *S. salsa* were 0.007, 0.824 and 0.331, respectively. Compared with *Calamagrostis angustifolia*, *Carex lasiocarpa*, and *P. australis*, the N absorption coefficient of *S. salsa* was significantly low, while utilization and cycle coefficients were much higher (Table 5). This indicated that the N absorbed by *S. salsa* was much lower compared to the N stock in soil, and the lower N could be utilized sufficiently by the plant. In addition, the high cycle coefficient indicated that the N in *S. salsa* marsh had strong mobility and high cycle rate. As water and salinity are typical environmental factors in the Yellow River estuary, the N absorption and utilization capacity of *S. salsa* may

be significantly affected by the intense inundation and high salinity conditions. In general, water condition has a significant effect on N absorption and utilization status of plants (Wang et al., 2004), and high water conditions inhibit N absorption and utilization through diluting N (Luxmoore and Millington, 1971) and affecting the physical movement of inorganic N in marsh soil. As inorganic N is mainly derived from mineralization and nitrification, the N absorption and utilization status of plants depends on N transformation in soil. Li and Huang (2008) indicated that high salinity inhibited N transformation in soil, and N mineralization and nitrification potential generally decreased with increasing salinity. In addition, high salinity also directly affects N absorption and utilization of plants. Mashhday et al. (1982) indicated that salinity significantly affected N absorption of wheat and triticale, and N utilization efficiency decreased gradually with increasing salinity. However, our study drew a different conclusion. The *S. salsa* had low N absorption capacity and high utilization capacity in the high water and salinity conditions. The high N utilization capacity of *S. salsa* was probably related to the strong physiological adaptations to environmental stresses such as high salinity, flooding, and sediment burial. Ruan et al. (2008) found that although chlorophyll *a* and *b* content in *S. salsa* leaves grown in the tidal marsh were significantly lower than those grown under low salinity stress, betacyanin content was much higher. The *S. salsa* grown in high salinity stress likely adapted to integrative stresses by changing pigment accumulation and characteristics of photosynthesis. As analyzed previously, N was very limited in the tidal marsh and the high N utilization capacity of *S. salsa* might also be related to its self-regulation mechanism to the acquired resource. Davis (1991) found that the responses of different marsh plants (*Cladium jamaicense* and *Typha domingensis*) to nutrients varied significantly. *C. jamaicense* required lower nutrient and could adapt low-nutrient environments, while *T. domingensi* required more nutrients and could better adapt to a high-nutrient environments. Thus, we concluded that *S. salsa* might exhibit a special adaptive strategy against low-nutrient status in the tidal marsh.

Table 4 Nitrogen allocation among compartments of *S. salsa* marsh ecosystem

Item	Root ^a	Aboveground living body ^a		Litter ^a	Plant Subsystem ^a	Soil (0–60 cm) ^b		Plant-soil system
		Stem	Leaf			Organic N	Inorganic N	
N stock (g/m ²)	0.101 ± 0.013	0.631 ± 0.101	1.035 ± 0.162	0.312 ± 0.056	2.078 ± 0.325	401.46	2.68	406.22
Percentage (%)	4.86 ^c	30.37 ^c	49.81 ^c	15.01 ^c	0.51 ^d	98.83 ^d	0.66 ^d	100.00 ^d

^a Values are means ± SE (*n* = 8); ^b values are determined in August 2008; ^c percentage of plant subsystem; ^d percentage of plant-soil system.

Table 5 Comparison of the absorption, utilization and cycle coefficients of different marsh ecosystems

Site	Vegetation		Absorption coefficient	Utilization coefficient	Cycle coefficient	References
Sanjiang Plain	<i>Calamagrostis angustifolia</i>	A ^a	0.017	0.634	0.317	Sun et al., 2009
		B ^b	0.015	0.548	0.200	
	<i>Carex lasiocarpa</i>		0.415	0.926	0.115	He and Zhao, 2001
Xianghai	Erbaifangzi		0.018	0.402	0.084	Bai et al., 2010
	Fulaowenpao		0.017	0.373	0.121	
Yellow River estuary	<i>Suaeda salsa</i>		0.0065	0.8243	0.3308	This study

^a Typical meadow *C. angustifolia*; ^b marsh meadow *C. angustifolia*.

2.3.3 Establishment of N cycle model and evaluation of N cycle status

Based on the above-mentioned studies, the compartment model on the allocation and circulation of N in the *S. salsa* marsh ecosystem in the Yellow River estuary was established, and the quantitative relationships among compartments were determined (Fig. 7). According to the compartment model, we concluded that the N in *S. salsa* marsh was an important limiting factor, and the ecosystem was unstable and vulnerable. The *S. salsa* might exhibit a special adaptive strategy against low-nutrient status and vulnerable habitat in the tidal marsh. There were several probable reasons.

Firstly, the *S. salsa* marsh was an open ecosystem frequently affected by the tide. The N stock in topsoil during the growing season was 53.30–103.76 g/m², much lower than that of freshwater marsh, grassland, and forest soils (Table 6), indicating that N supply capacity of topsoil

was very low. Net mineralization N in topsoil during the growing season was also very low compared to freshwater marsh, grassland, and forest soils (Table 6), and the lower available N could be easily removed during the ebb and flow of tide. The high salinity in *S. salsa* marsh may inhibit N transformation in soil, which also reflected that the supply of available N in soil was limited. In addition, poor aeration resulting from high moisture may have enhanced denitrification and induced significant N loss (N₂, N₂O) of soil.

Secondly, litter decomposition was generally regarded as an effective path for nutrient return. The *S. salsa* litter released N to the decomposition environment in one year, with an annual N return amount of 0.368 g/m². As *S. salsa* litter was gradually removed by the tide and N release from litter to soil was also affected by the tide, the actual N return amount was far less than 0.368 g/m². In addition, because the decomposition rate of *S. salsa* litter

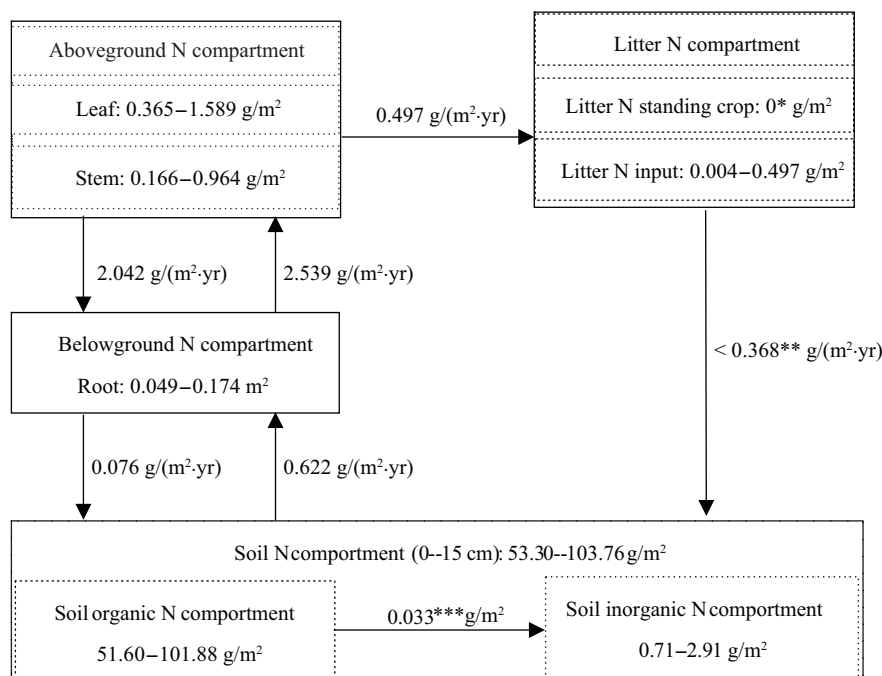


Fig. 7 Nitrogen cycle compartment model of the *S. salsa* marsh ecosystem. Numerals in panes were the N stocks of compartments; numerals above arrowhead were the N turnovers among compartments. * Approximate the value as mentioned previously; ** far less than the value; *** net mineralization N in growing season.

Table 6 Comparison of nitrogen stock and net mineralization nitrogen of marsh, grassland and forest ecosystems

Type	Site	Vegetations	Methods	Depth	N stock (g/m ²)	Net mineralization N(g/(m ² ·yr))	Reference
Marsh ecosystem	Sanjiang Plain	<i>Calamagrostis</i> A ^a	PVC tube	0–15 cm	422.69	1.941	Sun et al., 2007b
	Yellow River estuary	<i>angustifolia</i> B ^b <i>Suaeda salsa</i>	closed-top incubation	0–15 cm	383.78 53.30–103.76	0.551 0.033 ^c	This study
Grassland ecosystem	Songnen Plain	<i>Leymus chinensis</i>		0–10 cm	– ^d	3.11	Li et al., 2003
Forest ecosystem	Dongling Mountain	<i>Pinus tabulaeformis</i> <i>P. tabulaeformis</i> / <i>Quercus wutaishanica</i>		0–15 cm	327.59 261.10	2.27 5.55	Su et al., 2001
	Wisconsin, USA	<i>Pinus resinosa</i>	Buried-bags	0–20 cm	–	5.1	Gower and Son, 1992
	Connecticut, USA	<i>Pinus strobus</i>	Resin cores	0–15 cm	–	8.4	Brinkley and Valentine, 1991

^a Typical meadow *C. angustifolia*; ^b marsh meadow *C. angustifolia*; ^c net mineralization N in growing season (from April to November); ^d: no data.

was very high (1.1880/yr) and the litter in the *S. salsa* community decomposed completely within one year, the actual N return amount, as affected frequently by the tide, was significantly low.

Thirdly, the N absorption capacity of *S. salsa* was low and intense inundation or high salinity conditions may inhibit capacity, indicating that *S. salsa* was limited by N. This result was consistent with the conclusion drawn by the study of N/P ratios in *S. salsa*.

Fourthly, based on the above-mentioned analysis, available N was very limited in *S. salsa* marsh and the ecosystem. In addition, the N in the *S. salsa* marsh had a high N cycle rate and strong mobility, indicating that the lack in N may be severe. Mistch and Gosselin (2000) indicated that N is often the most limiting nutrient in marshes, and the N cycle status not only affects the structure and function of a marsh, but also, to some extent, influences stabilization and health of an ecosystem. Taken in this sense, the current *S. salsa* marsh was unstable and vulnerable. Although the *S. salsa* N absorption coefficient was low, the utilization coefficient was high, reflecting that *S. salsa* may optimize the acquired nutrient and exhibit a special adaptive strategy against low-nutrient status. Presently, N importation from the Yellow River estuary is increasing due to frequent human activities. Loading of excessive N to the estuary ecosystem may cause changes in ecological function, and often has undesirable environmental and economic consequences (Sun and Liu, 2008). As *S. salsa* is probably well adapted to the low-nutrient environment, nutrient enrichment may be a potential threat to the *S. salsa* marsh. Excessive nutrient loading from the Yellow River estuary might favor invasive species, such as *P. australis*, *T. sacchariflora* and *T. chinensis*, and induce severe long-term degradation of the ecosystem if human intervention measures (e.g., prohibit N import) are not taken.

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