Chin. Geogra. Sci. 2012 Vol. 22 No. 1 pp. 15–28
doi: 10.1007/s11769-012-0511-7
www.springerlink.com/content/1002-0063

Nitrogen Biological Cycle Characteristics of Seepweed (*Suaeda salsa*) Wetland in Intertidal Zone of Huanghe (Yellow) River Estuary

SUN Zhigao[1, 2], MOU Xiaojie[2, 3, 4], SUN Jingkuan[1], SONG Hongli[2, 4], YU Xiang[1], WANG Lingling[2, 4], JIANG Huanhuan[2, 4], SUN Wanlong[2, 4], SUN Wenguang[2, 4]

(*1. Shandong Key Laboratory for Eco-Environmental Science of Yellow River Delta, Coastal Wetland Ecological Research Base of Yantai Institute of Coastal Zone Research, Chinese Academy of Sciences, Binzhou 256603, China; 2. Key Laboratory of Coastal Environment Processes of Chinese Academy of Sciences, Shandong Provincial Key Laboratory of Coastal Zone Environmental Processes, Yantai Institute of Coastal Zone Research, Chinese Academy of Sciences, Yantai 264003, China; 3. Key Laboratory of Wetland Ecology and Environment, Northeast Institute of Geography and Agroecology, Chinese Academy of Sciences, Changchun 130012, China; 4. Graduate University of Chinese Academy of Sciences, Beijing 100049, China*)

Abstract: From April 2008 to November 2009, the nitrogen (N) cycle of plant-soil system in seepweed (*Suaeda salsa*) wetland in the intertidal zone of the Huanghe (Yellow) River estuary was studied. Results showed that soil N had significant seasonal fluctuations and vertical distribution, and the net N mineralization rates in topsoil were significantly different in growing season ($p < 0.01$). The N/P ratio (9.87 ± 1.23) of *S. salsa* was less than 14, indicating that plant growth was limited by N. The N accumulated in *S. salsa* litter at all times during decomposition, which was ascribed to the N immobilization by microbes from the environment. Soil organic N was the main N stock of plant-soil system, accounting for 97.35% of the total N stock. The N absorption and utilization coefficients of *S. salsa* were very low (0.0145 and 0.3844, respectively), while the N cycle coefficient was high (0.7108). The results of the N turnovers among compartments of *S. salsa* wetland showed that the N uptake amount of aboveground part and root were 7.764 g/m^{2}and 4.332 g/m^2, respectively. The N translocation amounts from aboveground part to root and from root to soil were 3.881 g/m^2 and 0.626 g/m^2, respectively. The N translocation amount from aboveground living body to litter was 3.883 g/m^2, the annual N return amount from litter to soil was more than 0.125(–) g/m^2 (minus represented immobilization), and the net N mineralization amount in topsoil (0–15 cm) in growing season was 1.190 g/m^2. The assessment of N biological cycle status of *S. salsa* wetland indicated that N was a very important limiting factor and the ecosystem was situated in unstable and vulnerable status. The *S. salsa* was seemingly well adapted to the low-nutrient status and vulnerable habitat, and the N quantitative relationships determined in the compartment model might provide scientific base for us to reveal the special adaptive strategy of *S. salsa* to the vulnerable habitat in the following studies.
Keywords: nitrogen; biological cycle; seepweed wetland; Huanghe (Yellow) River estuary

Citation: Sun Zhigao, Mou Xiaojie, Sun Jingkuan, Song Hongli, Yu Xiang, Wang Lingling, Jiang Huanhuan, Sun Wanlong, Sun Wenguang, 2012. Nitrogen biological cycle characteristics of seepweed (*Suaeda salsa*) wetland in intertidal zone of Huanghe (Yellow) River estuary. *Chinese Geographical Science*, 22(1): 15–28. doi: 10.1007/s11769-012-0511-7

1 Introduction

Material cycle and energy flow are two important fields of ecosystem research. Nitrogen (N) is one of the most essential nutrients affecting the photosynthesis and primary production of plants in terrestrial ecosystem (Mooney *et al*., 1987). The N cycle in wetland ecosystem performs many important biogeochemical functions,

Received date: 2011-05-16; accepted date: 2011-09-27
Foundation item: Under the auspices of Open Research Fund Program of Shandong Key Laboratory for Yellow River Delta Eco-Environmental Science, Binzhou, China (No. 2007KFJJ01), Knowledge Innovation Programs of Chinese Academy of Sciences (No. KZCX2-YW-223), National Natural Science Foundation of China (No. 40803023, 41171424), Key Program of Natural Science Foundation of Shandong Province (No. ZR2010DZ001)
Corresponding author: SUN Zhigao. E-mail: zgsun@yic.ac.cn

such as N transformation and fate, N removal and storage, ammonia (NH_3) volatilization and nitrous oxides (N_2O) emission. The vast majority of N in wetlands is in organic form, contained in vegetation (living plants), plant detritus, macrofauna, microorganisms, soil, and water (dissolved organic compounds and suspended sediments). The N in soil mainly exists in organic and inorganic form, but the proportion of inorganic N is very low. Since inorganic N can be utilized by plants directly, the transformation rate of organic N to inorganic N, to a great extent, affects the productivity of wetland ecosystems (Mistch and Gosselin, 2000).

Presently, many studies on the N cycle process in wetland ecosystems have been conducted, and these researches were related to paddy fields (Ahmad *et al*., 2009; Yang S S *et al*., 2009), freshwater marshes (Zhang *et al*., 2007; van Damme *et al*., 2009), salt marshes (Eriksson *et al*., 2003; Boyer and Fong, 2005), and mangrove marshes (Trott *et al*., 2004; Naidoo, 2009). Some researchers adopted stable isotope technique to quantify the movement, transformation and fate of N in wetland ecosystems (Rückauf *et al*., 2004; Fair and Heikoop, 2006). Tidal wetlands are very important in coastal zone, which are sensitive to the global climate change and human activities. Tidal wetland generally undertakes large amounts of nitrogenous compounds from terrestrial human activities, and its N cycle is closely related to a series of global environmental problems. However, the information on the N cycle processes in tidal wetlands remains limited. In addition, current studies are mostly focused on a certain process of N cycle, but systemic and synthetic studies are lacking. The compartment model has been widely and successfully applied in previous researches and is a common method for studying the elements cycle of ecosystems. At present, most studies on compartment model paid attention to grassland ecosystem (Reuss and Innis, 1977; Li and Redmann, 1992; Li *et al*., 2003), forest ecosystem (Liu and Yu, 2005; Wu *et al*., 2006) and freshwater marsh ecosystem (Sun and Liu, 2007a; Liu and Li, 2008), however, little research has been devoted to the N cycle of tidal wetland ecosystems.

The Huanghe (Yellow) River is well known as a sediment-laden river. Every year, approximately 1.05×10^7 t of sediment is carried to the estuary (Cui *et al*., 2009) and deposited in the delta where the flow rate slows down, resulting in vast area of floodplain and special wetland landscape (Xu *et al*., 2002). Sediment deposition is an important process for the formation and development of tidal wetland in the Huanghe River delta. The deposition rate of sediment in the Huanghe River not only affects the formation rate of tidal wetland, but also, to some extent, influences water or salinity status and the succession of plants. Tidal marsh is the main wetland type, with an area of 964.8 km^2, accounting for 63.06% of total area of the Huanghe River delta (Cui *et al*., 2009). Seepweed (*Suaeda salsa*) is the most important plant in the tidal wetland of the Huanghe River estuary. As a pioneer plant in tidal wetland, it has strong adaptation to environmental stresses, such as high salinity, flooding and sediment burial. Presently, few studies have been done on the elemental biogeochemical processes of tidal wetland in the Huanghe River estuary and the N cycle of plant-soil system in *S. salsa* wetland.

In this paper, the N biological cycle of *S. salsa* wetland in intertidal zone of the Huanghe River estuary was studied based on the investigation in the field and the experiments in the laboratory. The plant-soil system of *S. salsa* wetland was divided into four N compartments, including aboveground living body, root, litter and soil. The purposes of this paper were: 1) to determine the distribution characteristics of N in the plant-soil system; 2) to study the N turnovers among the compartments of *S. salsa* wetland; and 3) to establish the N biological cycle compartment model of *S. salsa* wetland and assess its N cycle status. The results were beneficial to understand the ecological process and mechanism of *S. salsa* wetland.

2 Materials and Methods

2.1 Study area

This study was conducted from April 2008 to November 2009 at an experimental plot in *S. salsa* wetland (37°45′57″N, 119°09′41″E) in the intertidal zone of the Huanghe River estuary, located in the Nature Reserve of Huanghe River Delta (37°35′–38°12′N, 118°33′–119°20′E) in Dongying City, Shandong Province, China with typical continental monsoon climate. The average annual temperature is 12.1℃, the frost-free period is 196 days, and the effective accumulative temperature is about 4300℃. The annual evaporation is 1962 mm, the annual precipitation is 551.6 mm, of which 70% occur 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 plants include *Phragmites aus-*

tralis, *S. salsa*, *Triarrhena sacchariflora*, *Myriophyllum spicatum*, *Tamarix chinensis* and *Limoninum sinense*. *S. salsa*, an annual C_3 plant, is one of the most important halophytes in the Huanghe River estuary, which 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).

2.2 Methodology

2.2.1 Collection of soil sample

The seasonal dynamics of total nitrogen (TN), ammonium nitrogen (NH_4^+-N) and nitrate nitrogen (NO_3^--N) contents in the topsoil at the experimental plot from April to November in 2009 was studied. Ten soil samples were collected per month at a sampling depth of 0–15 cm, and soil bulk density was determined at the same time. The vertical distribution of TN, NH_4^+-N, and NO_3^--N contents in the soil profile was investigated in August 2008. Three soil profiles (with the depth of 60 cm) were sampled at the experimental plot at 10 cm interval, with 18 samples in total. The bulk density of each soil layer was determined simultaneously. The N stock (T_n, kg/m^2) in soil was calculated by Equation (1) (Sun *et al*., 2009):

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

where W_i is the soil bulk density of the ith layer (g/cm^3); N_i is the N content in the ith layer (%); and h is soil depth.

2.2.2 Determination of soil mineralization rate

Net N mineralization was studied by PVC tube closed-top incubation method (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, that is, April 25–May 26 (I), May 26–June 27 (II), June 27–July 31 (III), July 31–August 25 (IV), August 25–September 25 (V) and September 25–November 12 (VI). In each incubation period, ten replications were laid at the experimental plot by diagonal belt transect method. Simultaneously, the soil bulk density was measured and ten soil samples were collected to determine the original contents of TN, NH_4^+-N and NO_3^--N in soil (0–15 cm). The net N mineralization rate (R_{min}, mgN/(kg·d)) and net N mineralization amount (W, kgN/ha) were calculated by equations (2) and (3) (Su *et al*., 2001):

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

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

where C_0, C_1 are the contents of inorganic N in soil before (at the T_0 time) and after incubation (at the T_1 time) (mg/kg), respectively; W_i is the soil bulk density of the ith layer (g/cm^3); V is soil volume per hectare (1500 m^3); and t is incubation days (d).

2.2.3 Determination of litter and biomass

Litter production, aboveground biomass and belowground biomass were determined by using quadrat method (50 cm × 50 cm, five replications) at the experimental plot from May to November in 2008, and the sampling frequency was about 20 days. On the sampling date, the aboveground part of plant was clipped near the ground, and the stem, leaf and standing dead litter were separated immediately in the laboratory. At the same time, 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 weighed after being dried at 80℃ for 48 hours. In growing season, as little part of plant or litter could be carried away or redistributed in tidal wetland due to the irregular semidiurnal tide, the aboveground biomass and litter production were standing crops.

2.2.4 Determination of litter decomposition rate

Litter decomposition was studied 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℃ for 48 hours. Each 20 cm × 20 cm litterbag was made of nylon netting (0.5 mm mesh) and filled with 15 g litter (oven-dried weight). On April 21, 2008, the litterbags were randomly placed on the experimental plot of *S. salsa* community. In order to prevent the litterbag from being carried away by the tide, one 1.6 m PPR (pentatricopeptide repeats) pipe was embedded approximately 1.0 m into the sediment, and the litterbags were attached to the pipe with nylon cord. The experiment included nine sampling times (with different intervals), and on each sampling date, three or four litter bags 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 gently in deionized water, and weighed after being dried at 80℃ for 48 hours. The litter standing crop (X_{st}), mass

loss (R) and decomposition rate (K) were calculated by equations (4)–(6) (Olson, 1963; Liu *et al*., 2000):

$$X_{st} = x / (1 - \beta) \quad (4)$$

$$R = [(W_t - W_0) / W_0] \times 100\% \quad (5)$$

$$K = -\frac{1}{t}\ln\left(\frac{W_t}{W_0}\right) \quad (6)$$

where β is the residual rate of litter (%); x is the annual average production of litter; W_0 is the initial dry mass; W_t is the dry mass at time t; and t is decomposition time (d).

The calculation of X_{st} is based on the following presumptions: 1) Ecosystem is very stable, and decomposition is the only means of litter loss; 2) litter standing crop changes dynamically and the value is the net sum of accumulation and decomposition amounts; 3) although the litter decomposition rate has significant seasonal change, the annual decomposition rate is generally steady. Taken in this sense, the annual decomposition rate is regarded as a constant (α), and the residual rate (β) is calculated by $1-\alpha$. However, *S. salsa* wetland is an open ecosystem, although quite a few litters produced in growing season can be gradually carried away or redistributed in tidal wetland due to the tide, part of them can still accumulate or decompose *in situ* in *S. salsa* community. In this study, the litter standing crop calculated by Equation (4) was a theoretical maximum value, and it was higher than the actual one since many litters were carried away by the tide. In addition, because the definite litter amount carried away by the tide was not quantified, the N standing crop estimated by litter standing crop and average N content was also a theoretical maximum value, and the '<<' was used to indicate that the actual value was far less than the theoretical one. After one year decomposition, the annual N translocation amount from litter to soil was calculated by the change of N stock in litter.

2.2.5 Measurement of soil and plant samples

All soil or plant samples were ground (< 0.25 mm) by using a Wiely mill and analyzed for TC, TN content by element analyzer (Elementar Vario Micro, German) and TP content by molybdate-ascorbic acid colorimetry (digested by H_2SO_4-H_2O_2). In addition, the NH_4^+-N and NO_3^--N contents in soil were determined by sequence flow analyzer (San^{++} SKALAR, Netherlands).

2.2.6 Calculation of N stock and turnover

The N biological cycle characteristics of *S. salsa* wetland ecosystem can be expressed by absorption coefficient (A), utilization coefficient (U) and cycle coefficient (C), and the calculation was based on equations (7)–(9) (Chen and Lindley, 1983):

$$A = PAN / SN \quad (7)$$

$$U = PAN / PSN \quad (8)$$

$$C = PRN / PAN \quad (9)$$

where PAN is the N absorption amount of plant (g/(m^2·yr)); PSN is the N standing crop of plant (g/m^2); PRN is the N return amount of plant (g/(m^2·yr)); and SN is the N stock in soil (0–60 cm, g/m^2).

According to the calculation method of Li and Redmann (1992), the N stocks in plant compartments (N_n, g/m^2) and the N turnovers among plant compartments (F_a, g/(m^2·yr)) were calculated by equations (10) and (11):

$$N_n = C_n B_n \quad (10)$$

$$F_a = C_a B_a \quad (11)$$

where C_n is the N content of compartment (mg/kg); B_n is the biomass of compartment (g/m^2); C_a is the N content as aboveground biomass reaches maximum value (mg/kg); and B_a is the maximum aboveground biomass (g/m^2).

Litter N stock in aboveground dead plant (F_{da}, g/m^2), the N translocation amount from aboveground part to root (F_{rt}, g/(m^2·yr)), and the N uptake amount of root (F_r, g/(m^2·yr)) were calculated by equations (12)–(14):

$$F_{da} = C_d B_a \quad (12)$$

$$F_{rt} = F_a - F_{da} \quad (13)$$

$$F_r = F_a - F_{rt} + \Delta N_u \quad (14)$$

where C_d is the N content of aboveground dead plant (mg/kg); B_a is the amount of aboveground dead plant (g/m^2); and ΔN_u is the net N increment of root in growing season (g/m^2).

The N translocation amounts from litter to soil (F_s, g/(m^2·yr)) and from root to soil (F_T, g/(m^2·yr)) were calculated by equations (15)–(17):

$$F_s = F_l - F_y \quad (15)$$

$$F_T = T \times B_{max} \times C_{max} \quad (16)$$

$$T = P_m / B_{max} \quad (17)$$

where F_l is composed of F_{da} and F_p; F_p is the N stock in

un-decomposed litter previously accumulated *in situ* (g/m^2); F_y is the N stock in un-decomposed litter after a period of time (g/m^2); T is the turnover rate of root (%); P_m is the deficit of maximum biomass and minimum biomass of root (g/m^2); B_{max} is the maximum root biomass (g/m^2); and C_{max} is the N content as root biomass reaches maximum value (mg/kg).

2.3 Statistical analysis

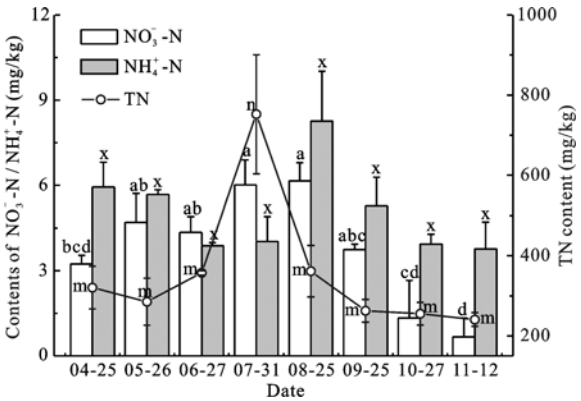
The samples were presented as means over the replications, with standard error (SE). The analysis of variance (ANOVA) tests (SPSS for windows 11.0) was employed to determine if the samples differed significantly ($p < 0.05$).

3 Results and Discussion

3.1 N dynamics, distribution and stock in soil

3.1.1 Seasonal dynamics of N in topsoil

Both the NO_3^--N and TN contents in the topsoil had significant seasonal variations ($p < 0.01$), while the variation of NH_4^+-N content was not significant ($p > 0.05$) (Fig. 1). Although the changes of NO_3^--N and NH_4^+-N contents from April to August were just the opposite, they all reached the maximum value in August (6.16 ± 0.64 mg/kg and 8.27 ± 1.76 mg/kg, respectively). After that, both of them changed consistently, with the minimum value (0.68 ± 0.67 mg/kg and 3.78 ± 0.95 mg/kg, respectively) being observed in November. Similar to the change of NO_3^--N contents, the TN contents generally increased rapidly before July and decreased abruptly from July to November, and the maximum value (752.07 ± 148.86 mg/kg) and minimum value (240.84 ± 17.27 mg/kg) occurred in July and November, respectively. The seasonal changes of NO_3^--N and NH_4^+-N contents were probably related to the mineralization, physical movement, plant absorption, and the ebb and flow of tide in different periods (Mou, 2010), while TN contents mainly depended on the distribution of soil organic matter and the effect of tide. The results showed that the N stock in the topsoil (0–15 cm) in growing season was 32.05–100.07 g/m^2, and the inorganic N and organic N were 0.59–1.92 g/m^2 and 31.45–98.74 g/m^2, respectively.



TN, total nitrogen; NH_4^+-N, ammonium nitrogen; NO_3^--N, nitrate nitrogen
Values are means (± SE, $n = 10$); bars or dots with different letters (a, b, c for NO_3^--N; m, n for TN) are significantly different at the level of $p < 0.05$; bars with same letters (x for NH_4^+-N) are not significantly different at the level of $p < 0.05$

Fig. 1 Seasonal dynamics of TN, NH_4^+-N and NO_3^--N contents in topsoil (0–15 cm) of *Suaeda salsa* wetland

3.1.2 Vertical distribution of N in soil

Significantly and similarly vertical distribution of NO_3^--N, NH_4^+-N and TN contents were observed in the soil profile (Fig. 2). There was an obvious peak at the depth of 10–20 cm, and the values were 1.36 ± 0.47 mg/kg, 3.62 ± 0.15 mg/kg and 597.33 ± 20.64 mg/kg, respectively. At the depth of 30–60 cm, the NO_3^--N contents increased appreciably, while NH_4^+-N and TN contents increased significantly. The N stocks in different soil layers decreased at the depth of 0–30 cm and increased significantly in 30–60 cm. The vertical changes of NO_3^--N, NH_4^+-N, TN contents and N stock generally depended on the spatial heterogeneity of soil organic matter (Mou, 2010) and the effect of soil water condition change (Verhoeven *et al.*, 1994), and the minimum value appeared at the depth of 20–30 cm might be related to the low N contents in sediment which was mostly derived from soil parent material in the Loess Plateau. Liu and Shao (2010) found that the TN contents in wild grassland in the Loess Plateau were generally high in the topsoil (0–20 cm, 311.3 ± 164.4 g/kg), while decreased greatly at the depth of 20–40 cm (159.7 ± 16.7 g/kg). From 40 cm to 800 cm, the TN contents had little changes and the values ranged from 84.3 ± 29.5 g/kg to 146.4 ± 46.6 g/kg. Therefore, if the parent material deposited in the intertidal zone of the Huanghe River estuary mostly derived from 20–800 cm loess, the low N values might occur in some soil layers. The results in this study showed that the total N stock in soil (0–60 cm) in August 2008 was 363.90 g/m^2, and the inorganic N and organic N were 2.70 g/m^2 and 361.20 g/m^2, respectively.

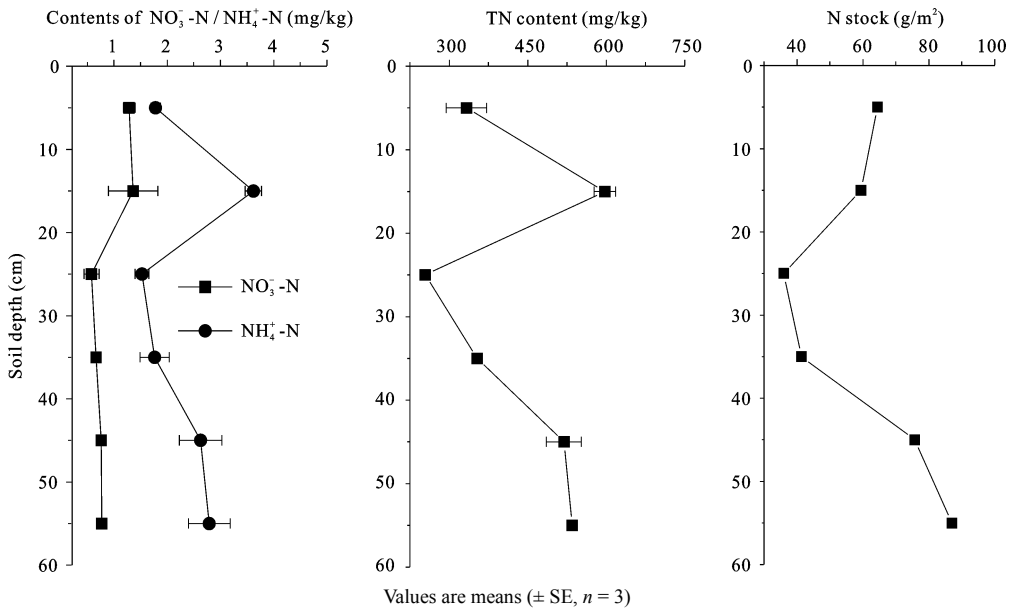
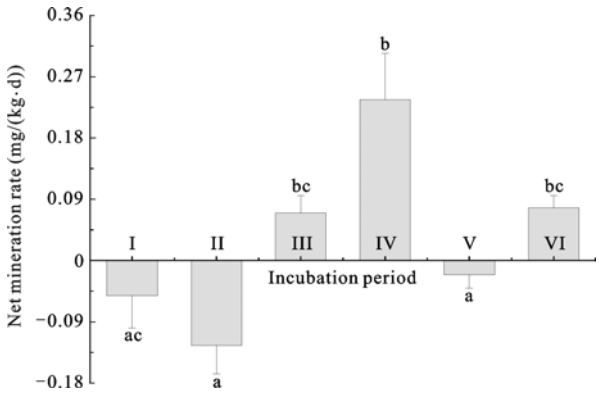


Fig. 2 Vertical distribution of TN, NH_4^+-N, NO_3^--N contents and N stock in soil profile of *S. salsa* wetland

3.1.3 Net N mineralization in topsoil

The net N mineralization rates (NNMRs) in the topsoil in different incubation periods were significantly different ($p < 0.01$) (Fig. 3). The NNMRs in the I, II and V incubation periods were negative (–0.052 ± 0.048 mg/(kg·d), –0.125 ± 0.042 mg/(kg·d) and –0.021 ± 0.020 mg/(kg·d), respectively), while in other periods (III, IV and VI) the values were positive (0.070 ± 0.025 mg/(kg·d), 0.236 ± 0.068 mg/(kg·d), 0.077 ± 0.018 mg/(kg·d), respectively). In general, the inorganic N produced by mineralization still remained after being immobilized by microbes and soil animals. The maximum NNMR was observed in summer, while the minimum value was observed in spring, indicating that hydrothermal condition might have significant effects on mineralization. Sierra (1997) found that temperature and moisture had significant interaction. In summer, the hydrothermal status in the topsoil was optimal for the survival and reproduction of microbes (Pérez *et al*., 1998), which generally enhanced mineralization rate. However, the temperature in spring was very low, and the high moisture in soil caused by the tide might have disadvantageous effects on mineralization. In addition, the poor aeration status resulting from high moisture might also enhance denitrification (Nadelhoffer *et al*., 1985), which could induce significant N loss (N_2, N_2O) of soil. The results from this study showed that the net N mineralization amount in the topsoil (0–15 cm) in growing season was 1.190 g/m^2.



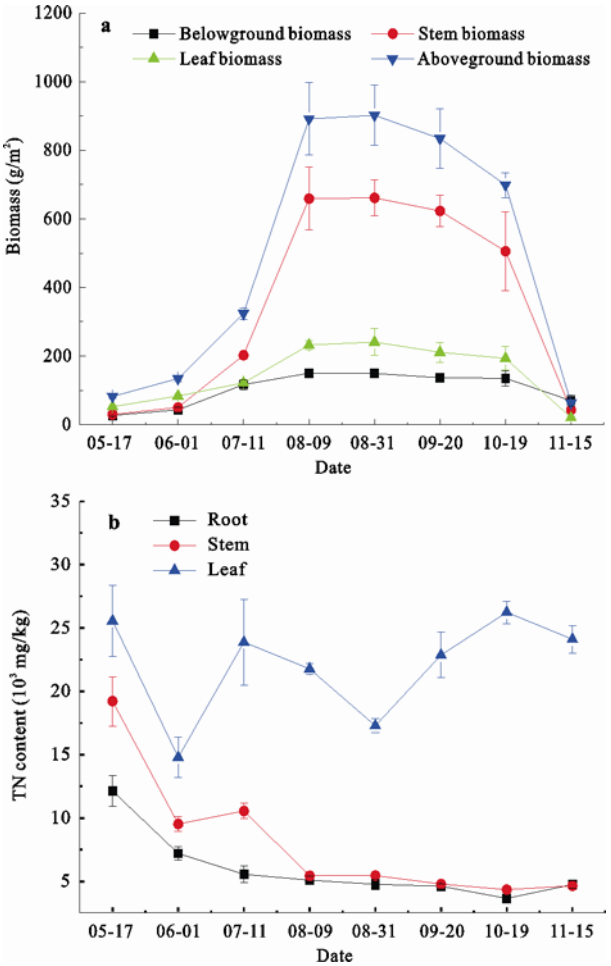
Values are means (± SE, n = 10); bars with different letters were significantly different at the level of $p < 0.05$

Fig. 3 Net N mineralization rate in tidal wetland soil (0–15 cm)

3.2 N dynamics, stock and turnover in plant

3.2.1 Dynamics of plant biomass and N content

The results of aboveground biomass and belowground biomass of *S. salsa* showed significant seasonal changes (Fig. 4a). Both of them increased with the improvement of hydrothermal condition since May 17, and reached the maximum values on August 31 (902.08 ± 87.57 g/m^2) and August 9 (149.87 ± 4.84 g/m^2), respectively. After that, they decreased gradually with the coming of autumn, and the minimum values (63.00 ± 5.88 g/m^2 and 69.74 ± 15.78 g/m^2, respectively) were observed on November 15. The seasonal changes of stem and leaf biomass were similar to aboveground biomass, and the maximum values (661.22 ± 51.98 g/m^2 and 240.86 ±



Values are means (± SE, n = 5 for biomass, n = 3 for TN content)

Fig. 4 Seasonal dynamics of biomass (a) and TN content (b) in different parts of *S. salsa*

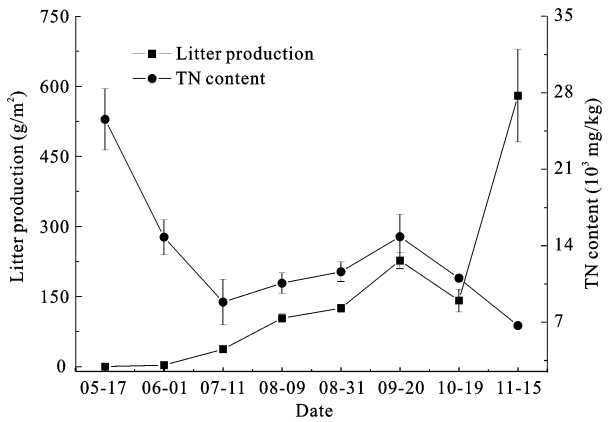
38.57 g/m^2, respectively) also occurred on August 31. The TN contents in root and stem of *S. salsa* generally decreased in growing season (Fig. 4b), and reached the minimum values (3641.36 ± 110.02 mg/kg and 4339.11 ± 177.16 mg/kg, respectively) on October 19. Comparatively, the TN contents in leaf fluctuated significantly, which mainly depended on the dilute effect caused by the increase of biomass (Sun, 2007). In general, the TN contents in leaf were much higher than those in root and stem, indicating that leaf was the main N accumulation organ. Tessier and Raynal (2003) found that N/P ratio was an effective indicator to estimate nutrient limitation and N saturation. Koerselman and Meuleman (1996) thought that the growth of wetland plants 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. The relationship was applied to discussing the nutrient limitation of *S. salsa*, and the results showed that the average of N/P ratio (9.87 ± 1.23) was less than 14 (Table 1), indicating that the *S. salsa* might be limited by N. In addition, the N/P ratios in different parts changed significantly in growing season (Table 1), which mainly depended on the nutrient absorption status of *S. salsa* and the nutrient supply status of soil in different periods. The results in the present study showed that the N stock in root, stem and leaf of *S. salsa* were 0.313–0.762 g/m^2, 0.198–3.560 g/m^2 and 0.492–5.070 g/m^2, respectively. The N uptake amounts of aboveground part and root were 7.764 g/m^2 and 4.332 g/m^2, respectively. The N translocation amounts from aboveground part to root and from root to soil were 3.881 g/m^2 and 0.626 g/m^2, respectively.

3.2.2 Dynamics of litter production and N content in litter

The litter production and the TN content in litter are show in Fig. 5. The litter production was low on May 17 and the value was 0.34 ± 0.01g/m^2. After that, the values increased at all times except for a significant decrease observed on October 19, and reached the maximum value (579.90 ± 98.91 g/m^2) on November 15. Actually, the *S. salsa* produced lots of litter at the end of growing season, and the low litter production determined on October 19 might be related to the low litter standing crop resulting from the strong scouring action of tide. The TN content in litter was high on May 17, and the value was 25561.80 ± 2804.14 mg/kg. After that, the TN contents generally decreased although some fluctuations

Table 1 Dynamics of N/P ratio in different parts of *Suaeda salsa*

Items	Date								Mean value (± SE)
	05–17	06–01	07–11	08–09	08–31	09–20	10–19	11–15	
Root	9.13	7.31	8.74	5.71	5.66	5.28	8.86	15.05	8.22 ± 1.12
Stem	11.07	7.89	11.78	5.03	4.68	4.96	11.68	16.54	9.20 ± 1.51
Leaf	16.93	17.19	20.58	22.31	12.54	7.05	4.97	11.53	14.14 ± 2.19
Plant	13.53	10.97	14.02	8.64	6.82	5.93	5.91	13.12	9.87 ± 1.23



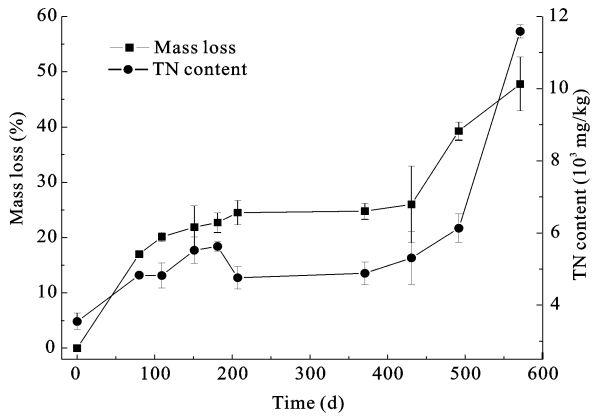
Values are means (± SE, n = 5 for litter production, n = 3 for TN content)

Fig. 5 Seasonal dynamics of litter production and TN content in litter

occurred from August 9 to October 19, and the minimum value (6695.66 ± 167.86 mg/kg) occurred on November 15. The results showed that the N stock in litter was 0.009–3.883 g/m^2, and the N translocation amount from aboveground living body to litter was 3.883 g/m^2.

3.2.3 Dynamics of litter decomposition and N content in litter

The mass loss of *S. salsa* litter increased at all times during decomposition (Fig. 6). In general, the mass lost rapidly from April to November in 2008 (from 0 d to 207 d), accounting for 51.29% of the total loss in the experiment, which mainly depended on the moderate hydrothermal condition in growing season. From November 2008 to April 2009 (from 207 d to 371 d), the mass lost slowly due to the low temperature, and the mass loss only increased 0.28%. Since April 26, 2009 (371 d), the mass loss rapidly increased again, and after 571 d, the mass loss reached 47.78%. The TN contents in *S. salsa* litter increased rapidly from 0 d to 181 d, and then decreased until November 15, 2008 (207 d). After that, the TN contents rapidly increased again, and reached the maximum value on November 12, 2009 (571 d).



Values are means (± SE, n = 3)

Fig. 6 Dynamics of mass loss and TN content during litter decomposition

The changes of C/N ratios in litter were just opposite to those of TN contents (Table 2), and they had significant negative correlation (R = –0.910, 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 the conclusion reported by Köchy and Wilson (1997). The TN contents in litter during decomposition were 134.01%–326.28% of the initial value, indicating that N accumulated in the litter at all times. The increase of N in *S. salsa* litter might be ascribed to the N immobilization by microbes from the N sources (such as tidewater and topsoil) in decomposition environment. Similar results also were concluded by Gessner (2000) who found that the increase of TN content in *P. australis* litter was mainly related to the external biological immobilization from lake water. The results from this research showed that the decomposition rate of *S. salsa* litter was 0.3780 g/(g·yr), the N standing crop of litter was far less than 8.75 g/m^2, and the annual N return amount from litter to soil was –0.125 g/m^2 (Table 3), indicating that the litter immobilized N from the decomposition environment in the whole year. With increasing decomposition time, the N immobilized from the decomposition environment would increase simultaneously, and the actual annual N immobilization amount would be more than 0.125 g/m^2. Because the N immobilized in the litter could be easily

Table 2 Dynamics of C/N ratio in *S. salsa* litter during decomposition

Sampling date	Decomposition time (d)	C/N (Mean ± SE, n = 3)
2008-04-21	0	115.76 ± 7.85
2008-07-11	80	87.68 ± 1.85
2008-08-09	109	86.50 ± 6.48
2008-09-20	151	76.92 ± 4.28
2008-10-20	181	72.89 ± 0.71
2008-11-15	207	89.11 ± 7.58
2009-04-26	371	80.32 ± 7.41
2009-06-25	431	68.91 ± 12.37
2009-08-25	492	68.60 ± 4.11
2009-11-12	571	22.48 ± 0.39

or gradually carried away by the tide, the *S. salsa* wetland was situated in the status of lacking N, which indicated that N might be an important limiting nutrient. This result was consistent with the conclusion mentioned previously.

3.3 N allocation and cycle in plant-soil system

3.3.1 N allocation in plant-soil system

The results of N allocation in compartments of plant-soil system in *S. salsa* wetland showed that aboveground living body was the main N stock of plant subsystem with the mean value of 5.103 g/m^2, accounting for 71.35% of the total N stock of plant subsystem (Table 4). In plant-soil system, the N stock of plant subsystem was very low, accounting for only 1.92% of the total N stock. Soil organic N was the main N stock of plant-soil system and the proportion of it was 97.35%. In contrast, soil inorganic N accounted for only 0.73%, indicating that the available N in *S. salsa* wetland soil was very low. The high proportion of organic N indicated that organic N played the function of circulation hinge in N cycle process, which could prevent the N from being lost easily. On the other hand, the low available N stock indicated that the supply of effective N was very limited.

3.3.2 N cycle characteristics in plant-soil system

The N absorption, utilization and cycle coefficients of *S. salsa* were 0.0145, 0.3844 and 0.7108, respectively (Table 5). The absorption and utilization coefficients of different plants along the latitudinal gradient had no significant variations. However, the cycle coefficient presented regular change, and the values of different plants (*Kandelia candel*, *Bruguiera sexangula*, *Rhizophora stylosa*, *P. australis*, *Spartina alterniflora* and *Scirpus mariqueter*) were generally high (0.40–0.76) along the latitudinal gradient (19°51′–31°14′N), while those of *Calamagrostis angustifolia*, *Carex lasiocarpa* and *P. australis* were relative low (0.084–0.317) in mid-latitude region (44°55′–47°35′N) (Table 5), and it was related to the regular changes of heat status, water condition and precipitation along the latitudinal gradient which had great influences on the litter decomposition and nutrient recycle. Although temperature, water and precipitation might have some effects on the growth of different plants, the N absorption and utilization of them, to a great extent, were more related to their kinds, growth rhythm and eco-physiology characteristics, and the nutrient supply status in habitat (Sun, 2007). In this paper, the study site in the Huanghe River estuary is located in mid-latitude region (37°45′57″N), and the N absorption, utilization and cycle coefficients of *S. salsa* generally accorded with above-mentioned variations. However, the N absorption and utilization coefficients of *S. salsa* was very lower compared with other plants along the latitudinal gradient, while the cycle coefficient was much higher (Table 5), indicating that the N absorbed by *S. salsa* was much lower compared with the N stock in soil, and the lower N was mostly unutilized by the plant. Moreover, the high cycle coefficient indicated that the N in plant-soil system of *S. salsa* had strong mobility and high cycle rate. Because water and salinity are the most typical environmental factors in the Huanghe River estuary, the low N absorption and utilization capacity of *S. salsa* might be significantly affected by the intense inundation and high salinity conditions. In general, water condition has significant effect on the N absorption and utilization status of plants (Wang *et al*., 2004), and high water conditions inhibit N absorption and utilization through diluting N nutrient

Table 3 N standing crop and returning amount of *S. salsa* litter

Annual input amount (g/m^2)	Decomposition rate (g/(g·yr))	Litter standing crop (g/m^2)	Average N content (mg/kg)	N standing crop (g/m^2)	Annual N return amount (g/m^2)
579.90	0.3780	<< 1534.13*	5701.21	<< 8.75*	> 0.125(–)**

Notes: *, far less than the value; **, slightly more than the value; the minus (–) represented N immobilization

Table 4 N allocation among compartments of plant-soil system in *S. salsa* wetland

	Root*	Aboveground living body*		Litter*	Plant subsystem	Soil (0–60 cm)**		Plant-soil system
		Stem	Leaf			Organic N	Inorganic N	
N stock (g/m^2)	0.526 ± 0.065	1.967 ± 0.495	3.136 ± 0.671	1.523 ± 0.554	7.152	361.20	2.70	371.05
Percent (%)	7.35^a	27.50^a	43.85^a	21.29^a	1.92^b	97.35^b	0.73^b	100.00^b

Notes: *, values are means (± SE, n = 8); **, values are determined in August 2008; a, percent of plant subsystem; b, percent of plant-soil system

Table 5 N absorption, utilization and cycle coefficients of plants in different wetland/marsh ecosystems in China

Location	Geographical location	Site	Plant	Absorption coefficient	Utilization coefficient	Cycle coefficient	References
Sanjiang Plain	47°35′17″N, 133°31′35″E	Honghe	*Calamagrostis angustifolia* a*	0.017	0.634	0.317	Sun *et al*., 2009
			Calamagrostis angustifolia b**	0.015	0.548	0.200	Sun *et al*., 2009
		Honghe	*Carex lasiocarpa*	0.415	0.926	0.115	He and Zhao, 2001
Songliao Plain	44°55′–45°09′N, 122°05′–122°35′E	Erbaifangzi	*Phragmites australis*	0.018	0.402	0.084	Bai *et al*., 2010
		Fulaowenpao	*P. australis*	0.017	0.373	0.121	Bai *et al*., 2010
Huanghe River estuary	37°45′57″N, 119°09′41″E	Dawenliu	*Suaeda salsa*	0.0145	0.3844	0.7108	This study
Changjiang (Yangtze) River estuary	31°06′20″–31°14′00″N, 121°53′06″–122°04′33″E	Shangsha	*P. australis*	0.0472	0.63	0.73	Liu and Yang, 2008
		Shangsha	*Spartina alterniflora*	0.0219	0.96	0.76	Yang *et al*., 2009a
		Shangsha	*Scirpus mariqueter*	0.0703	0.96	0.62	Yang *et al*., 2009b
		Zhongsha	*P. australis*	0.1123	0.82	0.73	Liu and Yang, 2008
		Zhongsha	*S. alterniflora*	0.0259	0.72	0.66	Yang *et al*., 2009a
		Zhongsha	*S. mariqueter*	0.0218	0.27	0.74	Yang *et al*., 2009b
		Xiasha	*P. australis*	0.0237	0.80	0.61	Liu and Yang, 2008
		Xiasha	*S. alterniflora*	0.0250	0.88	0.74	Yang *et al*., 2009a
		Xiasha	*S. mariqueter*	0.0061	0.51	0.40	Yang *et al*., 2009b
Jiulong River estuary	24°26′10″–24°27′38″N, 117°54′12″–117°55′31″E	Longhai	*Kandelia candel*	–	–	0.607***	Lin, 2001
Shatian Peninsula	21°28′22″–21°37′00″N, 109°37′00″–109°47′00″E	Shatian	*Bruguiera sexangula*	–	–	0.605***	Lin, 2001
Hainan Island	19°51′–20°01′N, 110°32′–110°37′E	Dongzhaigang	*Rhizophora stylosa*	–	–	0.457***	Lin, 2001

Notes: a*, typical meadow *C. angustifolia*; b**, marsh meadow *C. angustifolia*; ***, coefficients were calculated according to the dates in reference

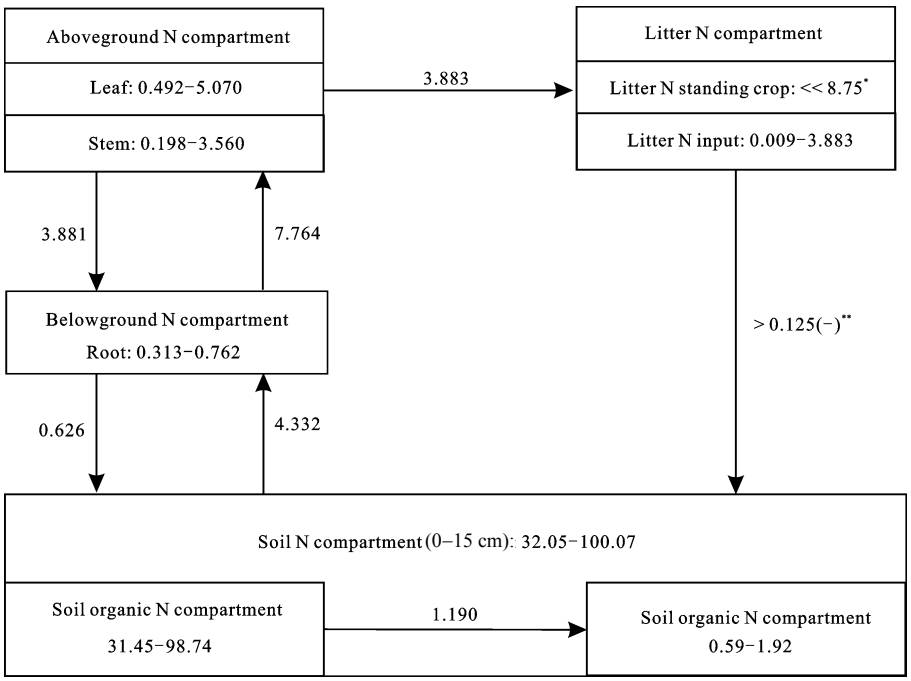
(Luxmoore and Millington, 1971) and affecting the physical movement of inorganic N (NH_4^+ -N and NO_3^- -N) in wetland soil (Sun and Liu, 2007b). As NH_4^+ -N and NO_3^- -N are mainly derived from mineralization and nitrification, the N absorption and utilization status of plants, to a great extent, depends on the N transformation in soil. Li and Huang (2008) found 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 the N absorption and utilization of plants. Mashhday *et al*. (1982) thought that salinity significantly affected the N absorption of wheat and triticale, and the N utilization efficiency decreased gradually with increasing salinity. Paramita *et al*. (2007) even found that the photosynthetic N-use efficiency of mangroves was significantly affected by salinity.

3.3.3 Establishment of N biological cycle model and assessment of N cycle status

Based on the above-mentioned studies, the compartment model on the allocation and circulation of N in the plant-soil system of *S. salsa* wetland was established, and the quantitative relationships among compartments were analyzed (Fig. 7). According to the compartment model, it was concluded that the N in *S. salsa* wetland was a very important limiting factor, and the ecosystem was situated in unstable and vulnerable status. There were several probable reasons.

(1) The *S. salsa* wetland was an open ecosystem, which was frequently affected by the tide. As analyzed previously, the N stock in topsoil (0–15 cm) in growing season was 32.05–100.07 g/m^2, much lower than that of freshwater marsh, grassland and forest soils (Table 6), indicating that the N supply capacity of topsoil was very low. The net mineralization N in topsoil in growing season also was very lower (1.190 g/m^2) compared with that of 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* wetland might inhibit the N transformation in soil as mentioned previously, which also reflected that the supply of available N in soil was very limited. In addition, the poor aeration status resulting from high moisture might enhance denitrification, which could induce significant N loss (N_2, N_2O) of soil.

(2) Litter decomposition was generally regarded as an effective path for nutrient return, however, our study drew an opposite result. In this study, although quite a



Numerals in panes were the N stocks of compartments (g/m^2); numerals above arrowhead were the N turnovers among compartments (g/(m^2·yr))
*, far less than the value; **, slightly more than the value; the minus (–) represents N immobilization

Fig. 7 N biological cycle compartment model of plant-soil system in *S. salsa* wetland

Table 6 Comparison of N stock and net N mineralization amount in marsh, grassland and forest soils

Type	Location	Method	Plant		N stock (g/m^2)	Net mineralization N ($g/(m^2 \cdot yr)$)	Reference
Marsh ecosystem	Sanjiang Plain	m	*Calamagrostis angustifolia*	a*	422.69	1.941	Sun and Liu, 2007c
		m		b**	383.78	0.551	
	Huanghe River estuary	m	*Suaeda salsa*		32.05–100.07	1.190***	This study
Grassland ecosystem	Songnen Plain	m	*Leymus chinensis*		–	3.11	Li *et al*., 2003
Forest ecosystem	Dongling Mountain	m	*Pinus tabulaeformis*		327.59	2.27	Su *et al*., 2001
		m	*P. tabulaeformis/ Quercus wutaishanica*		261.10	5.55	
	Connecticut, USA	n	*Pinus strobus*		–	8.4	Brinkley and Valentine, 1991

Notes: a*, typical meadow *C. angustifolia*; b**, marsh meadow *C. angustifolia*; ***, net mineralization N in growing season; m, PVC tube closed-top incubation; n, resin cores

few litters produced in growing season could be gradually carried away or redistributed in tidal wetland due to the tide, part of them could still accumulate or decompose *in situ* in *S. salsa* community. As mentioned previously, the litter immobilized N from the decomposition environment at all times during decomposition, and these litters also could be easily or gradually carried away by the tide, indicating that the litter in *S. salsa* wetland ecosystem acted as an important N loss source.

(3) As mentioned above, the N absorption and utilization capacity of *S. salsa* was very low and intense inundation or high salinity conditions might inhibit the capacity, indicating that the *S. salsa* was very limited by N. This result was consistent with the conclusion drawn by the study on N/P ratios in *S. salsa*.

(4) Based on the analysis above, the available N was very limited in the plant-soil system of *S. salsa* wetland, and the ecosystem was situated in N loss status. In addition, the N in the plant-soil system of *S. salsa* wetland had high N cycle rate and strong mobility, indicating that the N loss rate might be accelerated simultaneously.

Mistch and Gosselin (2000) found that N is often the most limiting nutrient in wetlands, and the N cycle status not only affects the structure and function of wetlands, but also, to some extent, influences the stabilization and health of ecosystems. Taken in this sense, the current *S. salsa* wetland was situated in unstable and vulnerable status. However, the *S. salsa* was seemingly well adapted to the low-nutrient status and vulnerable habitat, and the N quantitative relationships determined in the compartment model might provide some scientific bases for us to reveal the special adaptive strategy of *S. salsa* to the vulnerable habitat in the following studies.

4 Conclusions

In this paper, we established the N biological cycle compartment model of *S. salsa* wetland in the Huanghe River estuary, and assessed the N cycle status of ecosystem. Results have demonstrated that: 1) the N uptake amount of aboveground part and root were 7.764 g/m^2 and 4.332 g/m^2, respectively, and the N translocation amounts from aboveground part to root and from root to soil were 3.881 g/m^2 and 0.626 g/m^2, respectively. The N translocation amount from aboveground living body to litter was 3.883 g/m^2, the annual N return amount from litter to soil was more than 0.125(–) g/m^2, and the net N mineralization amount in topsoil (0–15 cm) in growing season was 1.190 g/m^2; 2) the N in *S. salsa* wetland was a very important limiting factor, and the ecosystem was situated in unstable and vulnerable status. However, the *S. salsa* was seemingly well adapted to the low-nutrient status and vulnerable habitat. Because our study does not discuss the transformation and turnover mechanisms of N in different compartments of *S. salsa* wetland which are beneficial to understand the N biological cycle status and the ecological process of ecosystem deeply, further related studies are still needed in the future.

References

Ahmad S, Li C F, Dai G Z *et al*., 2009. Greenhouse gas emission from direct seeding paddy field under different rice tillage systems in central China. *Soil & Tillage Research*, 106(1): 54–61. doi: 10.1016/j.still.2009.09.005

Bai Junhong, Wang Qinggai, Gao Haifeng *et al*., 2010. Dynamic changes of nitrogen contents and nitrogen cycling in *Phragmites australis* of Xianghai marsh wetland. *Wetland Science*, 8(2): 164–167. (in Chinese)

Boyer K E, Fong P, 2005. Macroalgal-mediated transfers of water column nitrogen to intertidal sediments and salt marsh plants.

Journal of Experimental Marine Biology and Ecology, 321(1): 59–69. doi: 10.1016/j.jembe. 2005.01.005

Brinkley D, Valentine D, 1991. Fifty-year biogeochemical effects of green ash, white pine, and Norway spruce in a replicated experiment. *Forest Ecology and Management*, 40(1–2): 13–25. doi: 10.1016/0378-1127(91)90088-D

Chen Lingzhi, Lindley D K, 1983. Nutrient elements cycling in *Pteridium aquilinum* grassland ecosystem of Hampsfe, England. *Acta Ecologica Sinica*, 25(1): 67–74. (in Chinese)

Cui B S, Yang Q C, Yang Z F *et al.*, 2009. Evaluating the ecological performance of wetland restoration in the Yellow River Delta, China. *Ecological Engineering*, 35(7): 1090–1103. doi: 10.1016/j.ecoleng.2009.03.022

Eriksson P G, Svensson J M, Carrer G M, 2003. Temporal changes and spatial variation of soil oxygen consumption, nitrification, and denitrification rates in a tidal salt marsh of the Lagoon of Venice, Italy. *Estuarine Coastal and Shelf Science*, 58(4): 861–871. doi: 10.1016/j.ecss.2003.07.002

Fair J M, Heikoop J M, 2006. Stable isotope dynamics of nitrogen sewage effluent uptake in a semi-arid wetland. *Environmental Pollution*, 140(3): 500–505. doi: 10.1016/j.envpol.2005.08.005

Gessner M O, 2000. Breakdown and nutrient dynamics of submerged *Phragmites* shoots in the littoral zone of a temperate hardwater lake. *Aquatic Botany*, 66(1): 9–20. doi: 10.1016/S0304-3770(99)00022-4

Gu Fengtian, 1999. Research in exploiting the green series of edibles-*Suaeda salsa*. *Journal of Binzhou Education College*, 5(3): 43–48. (in Chinese)

Han N, Shao Q, Lu C M *et al.*, 2005. The leaf tonoplast V-H^+-ATPase activity of a C_3 halophyte *Suaeda salsa* is enhanced by salt stress in a Ca-dependent mode. *Journal of Plant Physiology*, 162(3): 267–274. doi: 10.1016/j.jplph.2004.07.016

He Chiquan, Zhao Kuiyi, 2001. The accumulation, allocation and biological cycle of the nutrient elements in *Carex lasiocarpa* wetland. *Acta Ecologica Sinica*, 21(12): 2074–2080. (in Chinese)

Köchy M, Wilson S D, 1997. Litter decomposition and nitrogen dynamics in Aspen forest and mixed-grass prairie. *Ecology*, 78(3): 732–739.

Koerselman W, Meuleman A F M, 1996. The vegetation N : P ratio: A new tool to detect the nature of nutrient limitation. *Journal of Applied Ecology*, 33(6): 1441–1450.

Li Jianbing, Huang Guanhua, 2008. Pilot study of salinity (NaCl) affecting nitrogen transformation in silt loam soil. *Research of Environmental Sciences*, 21(5): 98–103. (in Chinese)

Li Y S, Redmann R E, 1992. Nitrogen budget of *Agropyron dasystachyum* in Canadian mixed prairie. *American Midland Naturalist*, 128(1): 61–71.

Li Yuzhong, Wang Qingsuo, Zhong Xiuli *et al.*, 2003. N internal cycling in *Leymus chinensis* grassland vegetation-soil system. *Acta Phytoecologica Sinica*, 27(2): 177–182. (in Chinese)

Lin Peng, 2001. A review on the mangrove research in China. *Journal of Xiamen University* (*Natural Science*), 40(2): 592–603. (in Chinese)

Liu Change, Yang Yongxing, 2008. Characteristics of N, P and K cycling in *Phragmites australis* wetland ecosystem in Jiuduansha shoal of Shanghai. *Chinese Journal of Ecology*, 27(3): 418–424. (in Chinese)

Liu J S, Li X H, 2008. Sulfur cycle in the typical meadow *Calamagrostis angustifolia* wetland ecosystem in the Sanjiang Plain, Northeast China. *Journal of Environmental Science*, 20(4): 470–475. doi: 10.1016/S1001-0742(08)62081-1

Liu Jingshuang, Sun Xueli, Yu Junbao, 2000. Nitrogen content variation in litters of *Deyeuxia angustifolia* and *Carex lasiocarpa* in Sanjiang Plain. *Chinese Journal of Applied Ecology*, 11(6): 898–902. (in Chinese)

Liu J S, Yu J B, 2005. Element cycling in the dominant plant community in the Alpine tundra zone of Changbai Mountains, China. *Journal of Environmental Science*, 17(3): 521–525.

Liu Zhipeng, Shao Mingan, 2010. Vertical variations of soil moisture and total nitrogen in small catchment on Loess Plateau. *Transactions of the Chinese Society of Agricultural Engineering*, 26(5): 71–76. (in Chinese)

Luxmoore R J, Millington R J, 1971. Growth of perennial ryegrass (*Lolium perenne* L.) in relation to water nitrogen, and light intensity II. Effects on dry weight production transpiration and nitrogen uptake. *Plant and Soil*, 34(1): 561–574. doi: 10.1007/BF01372813

Mashhday A S, Sayed H I, Heakal M S, 1982. Effect of soil salinity and water stresses on growth and content of nitrogen, chloride and phosphate of wheat and triticale. *Plant and Soil*, 68(2): 207–216. doi: 10.1007/BF02373706

Mistch W J, Gosselin J G, 2000. *Wetlands*. New York: Van Nostrand Reinhold Company Inc, 89–125.

Mooney H A, Vitousek P M, Matson P A, 1987. Exchange of materials between terrestrial ecosystems and the atmosphere. *Science*, 238(4829): 926–932. doi: 10.1126/science.238.4829.926

Mou Xiaojie, 2010. *Study on the Nitrogen Biological Cycling Characteristics and Cycling Model of Tidal Wetland Ecosystem in Yellow River Estuary*. Beijing: Graduate University of Chinese Academy of Sciences. (in Chinese)

Nadelhoffer K J, Aber J D, Melillo J M, 1985. Fine roots, net primary production, and soil nitrogen availability: A new hypothesis. *Ecology*, 66(4): 1377–1399. doi: 10.2307/1939190

Naidoo G, 2009. Differential effects of nitrogen and phosphorus enrichment on growth of dwarf *Avicennia marina* mangroves. *Aquatic Botany*, 90(2): 184–190. doi: 10.1016/j.aquabot.2008.10.001

Olson J S, 1963. Energy storage and the balance of products and decomposers in ecological systems. *Ecology*, 44(2): 322–331. doi: 10.2307/1932179

Paramita N, Sauren D, Monoranjan G *et al.*, 2007. Effects of salinity on photosynthesis, leaf anatomy, ion accumulation and photosynthetic nitrogen use efficiency in five Indian mangroves. *Wetlands Ecology and Management*, 15(4): 347–357. doi: 10.1007/s11273-007-9036-8

Pérez C A, Hedin L O, Armesto J J, 1998. Nitrogen mineralization in two unpolluted old-growth forests of contrasting biodiversity and dynamics. *Ecosystems*, 1(4): 361–373. doi: 10.1007/s100219900030

Raison R J, Connell M J, Khanna P K, 1987. Methodology for studying fluxes of soil mineral-N *in situ*. *Soil Biology & Biochemistry*, 19(5): 521–530. doi: 10.1016/0038-0717(87)90094-0

Reuss J O, Innis G S, 1977. A grassland nitrogen flow simulation model. *Ecology*, 58(2): 379–388. doi: 10.2307/ 1935612

Rückauf U, Augustin J, Russow R *et al.*, 2004. Nitrate removal from drained and reflooded fen soils affected by soil N transformation processes and plant uptake. *Soil Biology & Biochemistry*, 36(1): 77–90. doi: 10.1016/j. soilbio.2003.08.021

Sierra J, 1997. Temperature and soil moisture dependence of N mineralization in intact soil cores. *Soil Biology & Biochemistry*, 29(9/10): 1557–1563. doi: 10.1016/S0038-0717(96)00288-X

Su Bo, Han Xingguo, Qu Chunmei *et al*., 2001. Net nitrogen mineralization and nitrification in one pure pine (*Pinus tabulaeformis*) forest and one pine-oak mixed forest in Dongling forest mountainous region. *Acta Phytoecologica Sinica*, 25(2): 195–203. (in Chinese)

Sun Zhigao, 2007. *Study on the Nitrogen Biogeochemical Process of Calamagrostis angustifolia Wetland in the Sanjiang Plain*. Beijing: Graduate University of Chinese Academy of Sciences. (in Chinese)

Sun Zhigao, Liu Jingshuang, Yu Junbao, 2009. Nitrogen accumulation and allocation in *Calamagrostis angustifolia* in different plant communities of Sanjiang Plain. *Chinese Journal of Applied Ecology*, 20(2): 277–284. (in Chinese)

Sun Z G, Liu J S, 2007a. Nitrogen cycling of atmosphere-plant-soil system in the *Calamagrostis angustifolia* wetland in the Sanjiang Plain, Northeast China. *Journal of Environmental Science*, 19(8): 986–995. doi: 10.1016/S1001-0742(07)60161-2

Sun Zhigao, Liu Jingshuang, 2007b. Study on vertical movement of nitrate nitrogen and ammonia nitrogen in typical *Calamagrostis angustifolia* Wetland Soils of Sanjiang Plain. *Journal of Soil and Water Conservation*, 21(6): 25–30. (in Chinese)

Sun Zhigao, Liu Jingshuang, 2007c. Soil nitrogen net mineralization and nitrification in typical *Calamagrostis angustifolia* wetlands in Sanjiang Plain. *Chinese Journal of Applied Ecology*, 18(8): 1771–1777. (in Chinese)

Tessier J T, Raynal D J, 2003. Use of nitrogen to phosphorus ratios in plant tissue as an indicator of nutrient limitation and nitrogen saturation. *Journal of Applied Ecology*, 40(3): 523–534. doi: 10.1046/j.1365- 2664.2003.00820.x

Tian Jiayi, Wang Xiufeng, Cai Xuejun, 2005. *Protection and Restoration Technique of Wetland Ecosystem in Yellow River Delta*. Qingdao: China Ocean University Press. (in Chinese)

Trott L A, Mckinnon A D, Alongi D M *et al*., 2004. Carbon and nitrogen processes in a mangrove creek receiving shrimp farm effluent. *Estuarine Coastal and Shelf Science*, 59(2): 197–207. doi: 10.1016/j.ecss.2003.08.008

van Damme S, Frank D, Micky T *et al*., 2009. Tidal exchange between a freshwater tidal marsh and an impacted estuary: The Scheldt estuary, Belgium. *Estuarine Coastal and Shelf Science*, 85(2): 197–207. doi: 10.1016/j.ecss.2009.08.005

Verhoeven J T A, Whigham D F, Kerkhoven M V, 1994. Comparative study of nutrient-related processes in geographically separated wetlands: Towards a science base for functional assessment procedure. In: Mitsch W J (ed.). *Global Wetlands*: *Old World and New*. Columbus: Elsevier Press.

Wang F Y, Liu R J, Lin X G *et al*., 2004. Arbuscular mycorrhizal status of wild plants in saline-alkaline soils of the Yellow River Delta. *Mycorrhiza*, 14(2): 133–137. doi: 10.1007/s00572-003-0248-3

Wu G, Wei J, Deng H B *et al*., 2006. Nutrient cycling in an Alpine tundra ecosystem on Changbai Mountain, Northeast China. *Applied Soil Ecology*, 32(2): 2087–2092. doi: 10.1016/j.apsoil.2005.06.003

Xu X G, Guo H H, Chen X L *et al*., 2002. A multi-scale study on land use and land cover quality change: The case of the Yellow River Delta in China. *GeoJournal*, 56(3): 177–183. doi: 10.1023/A:1025175409094

Yang S S, Lai C M, Chang H L *et al*., 2009. Estimation of methane and nitrous oxide emissions from paddy fields in Taiwan. *Renewable Energy*, 34(8): 1916–1912. doi: 10.1016/j.renene.2008.12.016

Yang Yongxing, Liu Change, Yang Yang, 2009a. Characteristics of N, P and K cycling in *Spartina alterniflora* wetland ecosystem in Jiuduansha shoal of Yangtze River estuary. *Chinese Journal of Ecology*, 28(2): 223–230. (in Chinese)

Yang Yongxing, Liu Change, Yang Yang, 2009b. Characteristics of N, P and K cycling in *Scirpus mariqueter* wetland ecosystem at Jiuduansha shoal of Yangtze River estuary. *Chinese Journal of Ecology*, 28(10): 1977–1985. (in Chinese)

Zhang L H, Song C C, Wang D X *et al*., 2007. Effects of exogenous nitrogen on freshwater marsh plant growth and N_2O fluxes in Sanjiang Plain, Northeast China. *Atmospheric Environment*, 41(5): 1080–1090. doi: 10.1016/j.atmosenv.2006.09.029