Available online at www.sciencedirect.com
ScienceDirect
Journal of Environmental Sciences 19(2007) 986–995
JOURNAL OF ENVIRONMENTAL SCIENCES
ISSN 1001-0742
CN 11-2629/X
www.jesc.ac.cn

# Nitrogen cycling of atmosphere-plant-soil system in the typical *Calamagrostis angustifolia* wetland in the Sanjiang Plain, Northeast China

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Received 18 October 2006; revised 21 December 2006; accepted 17 January 2007

**Abstract**

The nitrogen (N) distribution and cycling of atmosphere-plant-soil system in the typical meadow *Calamagrostis angustifolia* wetland (TMCW) and marsh meadow *Calamagrostis angustifolia* wetland (MMCW) in the Sanjiang plain were studied by a compartment model. The results showed that the N wet deposition amount was 0.757 gN/(m$^2$·a), and total inorganic N (TIN) was the main body (0.640 gN/(m$^2$·a)). The ammonia volatilization amounts of TMCW and MMCW soils in growing season were 0.635 and 0.687 gN/m$^2$, and the denitrification gaseous lost amounts were 0.617 and 0.405 gN/m$^2$, respectively. In plant subsystem, the N was mainly stored in root and litter. Soil organic N was the main N storage of the two plant-soil systems and the proportions of it were 93.98% and 92.16%, respectively. The calculation results of N turnovers among compartments of TMCW and MMCW showed that the uptake amounts of root were 23.02 and 28.18 gN/(m$^2$·a) and the values of aboveground were 11.31 and 6.08 gN/(m$^2$·a), the re-translocation amounts from aboveground to root were 5.96 and 2.70 gN/(m$^2$·a), the translocation amounts from aboveground living body to litter were 5.35 and 3.38 gN/(m$^2$·a), the translocation amounts from litter to soil were larger than 1.55 and 3.01 gN/(m$^2$·a), the translocation amounts from root to soil were 14.90 and 13.17 gN/(m$^2$·a), and the soil (0–15 cm) N net mineralization amounts were 1.94 and 0.55 gN/(m$^2$·a), respectively. The study of N balance indicated that the two plant-soil systems might be situated in the status of lacking N, and the status might induce the degradation of *C. angustifolia* wetland.

**Key words**: compartment model; nitrogen cycling; *Calamagrostis angustifolia*; wetland ecosystem; Sanjiang Plain

## Introduction

Nitrogen (N) is one of the most limited elements that affect the photosynthesis and primary production process of plant in terrestrial ecosystem (Mooney *et al*., 1987). The N in soil mainly existed in the form of organic N and inorganic N. Inorganic N can be utilized directly by plant, and it mainly existed in the form of ammonium nitrogen ($NH_4^+$-N) and nitrate nitrogen ($NO_3^-$-N). In general, the content of inorganic N in wetland soil is much lower, and it is often the most limited nutrient which directly affects the productivity of wetland ecosystem (Mistch and Gosselin, 2000). At present, the studies related to N cycling in wetland were widely reported by researches (Woodmansee *et al*., 1978; Hayes, 1985; Yoneyamad *et al*., 1993; Middelburg and Joop, 1998), some researchers also adopted $^{15}$N technique to study the movement, transformation and fate of N (McKinney *et al*., 2001; Nordbakken *et al*., 2003; Ulrike *et al*., 2004). In general, these researches mostly focused on a certain process of N cycling without systemic and synthetic study. Comparatively, the domestic studies mainly concentrated on paddy field (Cai and Zhu, 1995; Tian *et al*., 2001; Song *et al*., 2004), and limited information was available on the N cycling of natural marsh wetland. Compartment model is a common method, which has been widely and successfully applied in current researches, to study the elements cycling of ecosystem (Reuss and Innis, 1977; Wallace *et al*., 1978; Li and Redmann, 1992; Mandernack *et al*., 2000). Presently, the domestic researches on compartment model of elements cycling mostly concentrated on grassland ecosystem (Zhang *et al*., 1990; Huang, 1993; Zhang and Cao, 1999; Li *et al*., 2003) and forest ecosystem (Liu and Yu, 2005; Wu *et al*., 2006), and the information about N cycling of natural marsh wetland ecosystem was scarce.

In this article, the *Calamagrostis angutifolia* wetland in the Sanjiang Plain (Northeast China) was selected as study object, and the N cycling status were systemic and synthetic illustrated. The atmosphere-plant-soil system of wetland was firstly divided into five N compartments (including atmosphere, aboveground living body, root, litter and soil), and then, the N storage dynamics and N

Project supported by the Knowledge Innovation Foundation of Chinese Academy of Sciences (KZCX2-YW-309, KZCX3-SW-332) and the National Natural Science Foundation of China (No. 920211003).
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turnovers among compartments were studied. Finally, the N cycling compartment model of atmosphere-plant-soil system was established and the status of N balance was evaluated.

## 1 Study site and methods

### 1.1 Study site

The experiment was carried out in experimental field at Ecological Experiment Station of Mire Wetland in the Sanjiang Plain, the Chinese Academy of Sciences (latitude 47°35′N; longitude 133°31′E), located in the northeast of Heilongjiang Province in China. The experimental field is located in river terrain between Bielahong River and Nongjiang River. It is at 55.4–57.0 m elevation and the total area is about 100 $hm^2$. The site is of typical continental monsoon climate, summer is warm and rainy while winter is long-term cold. Annual average temperature is 1.9°C and the valid cumulative temperature is about 2300°C. The distribution of precipitation is odds in a year. The annual average precipitation is about 600 mm, and approximate sixty percent of it focuses on between June and September. The physiognomy type of experimental field is depressional wetland which is the most typical distribution in the Sanjiang Plain. The depressional wetland is relatively closed which mainly received N deposition and lost by gaseous forms ($NH_3$, $N_2O$, $N_2$ etc.). In addition, the depressional wetland is separated by embankments or ditches with around due to human activities, and there almost no N imported by runoff or exported by leaching due to the high content of clay (46.8%–71.9%) in soil (Sun *et al*., 2006). From the center to the outside, the vegetations of depressional wetland are circularly distributed with *Carex pseudocuraica*, *Carex lasiocarpa* and *C. angustifolia*, etc. The soils are predominantly humus marsh soil and meadow marsh soil (Zhang, 1988). *C. angutifolia* wetland is the main wetland type in the Sanjiang Plain (accounts for 34.45% of total area of wetland), which includes typical meadow *C. angustifolia* wetland (TMCW, no hydrous) and marsh meadow *C. angustifolia* wetland (MMCW, seasonal hydrous) (He, 2000). The two types of *C. angustifolia* wetlands are located in different water gradients, which are sensitive to the changes of water conditions.

### 1.2 Study methods

The atmosphere precipitation was collected *in situ* (Liu *et al*., 2003) from July 2004 to June 2005, and the N wet deposition amount (kgN/$hm^2$) was calculated by Eq. (1) (Li *et al*., 2000):

$$\text{N wet deposition amount} = \sum_{i=1}^{n} (C_i \times 10^{-6} \times V_i/A) \times 10000 \tag{1}$$

where, $C_i$ is $N$ concentration (mg/L); $V_i$ is precipitation volume (L); $A$ is the cross sectional area of collector (0.0314 $m^2$).

Ammonia ($NH_3$) volatilization was determined by venting method (Wang *et al*., 2002) from May to October in 2005. Three $NH_3$ capture equipments were placed in different sites of each plot (TMCW and MMCW). The sampling frequency was 4–7 d which was based on the volatilization amount determined by venting method. The $NH_3$ volatilization rate (kgN/($hm^2$·d)) was calculated by Eq. (2):

$$NH_3 \text{ volatilization rate } = (M/(A \times t)) \times 10^{-2} \tag{2}$$

where, $M$ is $NH_3$ volatilization amount captured by single equipment (mg); $A$ is the cross sectional area of capture equipment ($m^2$); $t$ is capture time (d).

Denitrification gaseous lost amount was measured using acetylene ($C_2H_2$) inhibition method on intact soil columns (Aulakh *et al*., 1992) from May to October in 2005. Two experimental treatments (let $C_2H_2$ in, not let $C_2H_2$ in) was laid at each plot (TMCW and MMCW), and each treatment included three replications. The incubation frequency was about 15 d and the incubation period was 24 h. The nitrous oxide ($N_2O$) concentrations in the gas samples were determined with GC (Shimadzu GC-14A equipped with ECD detector), and the emission amount (kgN/$hm^2$) was calculated by Eq. (3) (Ding *et al*., 2004):

$$N_2O \text{ emission amount} = M \times 1.25 \times 10^{-9} \times (V_1 - V_2)/S \times 10 \tag{3}$$

where, $M$ is $N_2O$ concentration ($m^3/m^3$); $V_1$, $V_2$ are the effective volumes of incubation bucket and soil column ($cm^3$), respectively; $S$ is the sectional area of soil column ($cm^2$). The estimation of denitrification gaseous lost amount was based on numerical integration method.

The N net mineralization was studied by PVC tube closed-top incubation method (Raison *et al*., 1987) from July 2004 to June 2005, and the incubation depth of soil was 15 cm. The experiment included five incubation phases (with different incubation days), and in each incubation phase, ten replications were laid at each plot (TMCW and MMCW) using diagonal belt transect method. In addition, six soil samples (0–15 cm) were collected at each plot in each incubation phase to study the dynamics of N in soil. The N net mineralization rates ($R_{min}$, mgN/(kg·d)) and net mineralization amount ($W$, kgN/$hm^2$) were calculated by Eqs. (4) and (5):

$$R_{min} = (C_1 - C_0)/(T_1 - T_0) \tag{4}$$

$$W = W_v \times V \times R_{min} \times t/1000 \tag{5}$$

where, $C_0$, $C_1$ are the contents of inorganic N in soil before and after incubation (mg/kg), respectively; $W_v$ is the soil bulk density (g/$cm^3$); $V$ is the soil volume per hectare (soil depth: 15 cm); $t$ is incubation time (d).

Litter biomass, aboveground biomass and belowground biomass (sampling depth: 50 cm) were determined by quadrat method (50 cm × 50 cm, three replications) at each plot (TMCW and MMCW) from May to October in 2005, and the determination frequency was about 15 d. The aboveground samples were separated into stem, leaf and vagina after they were transported to the laboratory.

Litter decomposition was studied by bag technique (Bocock, 1964) from May 2004 to September 2005. The mesh size of bag was 0.5 mm × 0.5 mm, which facilitates most soil fauna entering into litter bag and prevents the debris from being lost. The bags were placed in subplots within each plot (TMCW and MMCW). The experiment included nine sampling times (with different intervals), and in each sampling date, three litter bags were collected from each plot to determine the average weightlessness rate. The standing crop ($X_{st}$) and weightlessness rate ($R$) of litter were calculated by Eqs. (6) and (7) (Liu *et al.*, 2000):

$$X_{st} = x/(1-\beta) \tag{6}$$

$$R = ((W_1 - W_2)/W_1) \times 100\% \tag{7}$$

where, β is the residual rate of litter (%); $x$ is the annual average production of litter; $W_1$, $W_2$ are litter weights (g) for the times of $t_1$ and $t_2$ (d), respectively.

The N contents of water, soil and plant were all determined by conventional methods (The Committee of Agro-chemistry of the Chinese Society of Soil Science, 1983). Based on the research of Li and Redmann (1992), the N storage of plant compartments ($N_n$) and N turnovers among plant compartments ($F_a$) were calculated by Eqs. (8) and (9):

$$N_n = C_n B_n \tag{8}$$

$$F_a = C_a B_a \tag{9}$$

where, $C_n$ is the N content of compartment; $B_n$ is the biomass of compartment; $C_a$ is the N content as aboveground biomass achieves maximum; $B_a$ is the maximum aboveground biomass.

Litter N storage ($F_{da}$), the N re-translocation amount from aboveground to root ($F_{rt}$) and the N uptake amount of root ($F_r$) were calculated by Eqs. (10), (11) and (12):

$$F_{da} = C_d B_a \tag{10}$$

$$F_{rt} = F_a - F_{da} \tag{11}$$

$$F_r = F_a - F_{rt} + \Delta N_u \tag{12}$$

Where, $C_d$ is the N content of aboveground dead plant; $B_a$ is the amount of aboveground dead plant; $F_a$ and $F_{rt}$ are the same as above-mentioned meaning; $\Delta N_u$ is the N net increment of belowground biomass in growing season.

The N translocation amounts from litter to soil ($F_s$) and from root to soil ($F_T$) were calculated by Eqs. (13), (14) and (15):

$$F_s = F_l - F_y \tag{13}$$

$$F_T = T \times B_{max} \times C_{max} \tag{14}$$

$$T = P_m / B_{max} \tag{15}$$

where, $F_l$ is composed of $F_{da}$ and $F_p$, $F_{da}$ is the same as above-mentioned meaning, $F_p$ is the N storage of litter standing crop; $F_y$ is the N storage of undecomposed litter after a period of time. $T$ is the turnover rate of root (Dahlman and Kucera, 1965); $P_m$ is the deficit of maximum biomass and minimum biomass of root; $B_{max}$ is the maximum root biomass; $C_{max}$ is the N content as root biomass achieves maximum.

### 1.3 Statistical analysis

The samples were presented as means over the replications, with standard deviation (SD). 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 exchange characteristics and fluxes in atmosphere-soil system

#### 2.1.1 Characteristics of N wet deposition and estimation of N wet deposition amount

The deposition amounts of different N forms were calculated by Eq. (1) according to the growing season (from 20 April to 30 September) and non-growing season (from 1 October to 20 April of the next year) of plant in the Sanjiang Plain (Table 1). The results showed that the growing season was an important period for total nitrogen (TN) deposition, and total inorganic N (TIN) was the main body (0.640 gN/(m$^2$·a)). The study of TN composition indicated that the deposition amount of TIN in growing season and non-growing season were 0.422 and 0.068 gN/(m$^2$·a), and the values of total organic N (TON) were 0.218 and 0.049 gN/(m$^2$·a), respectively. These showed that the growing season was also an important period for TIN and TON deposition. The study of TIN composition indicated that the deposition amounts of different N forms in growing season were much higher than those in non-growing season except nitrite nitrogen ($NO_2^-$-N). The values of $NH_4^+$-N and $NO_3^-$-N in growing season were 1.84 and 2.26 folds

**Table 1 Nitrogen wet deposition amount in growing season, non-growing season and whole year**

| Items | | $NH_4^+$-N | $NO_3^-$-N | $NO_2^-$-N | TIN | TON | TN |
|---|---|---|---|---|---|---|---|
| Non-growing season | Deposition amount (gN/m$^2$) | 0.140 | 0.070 | 0.008 | 0.218 | 0.049 | 0.267 |
| | Percent of non-growing season (%) | 52.43 | 26.22 | 3.00 | 81.65 | 18.35 | 100 |
| | Percent of whole year (%) | 18.49 | 9.25 | 1.06 | 28.80 | 6.47 | 35.27 |
| Growing season | Deposition amount(gN/m$^2$) | 0.258 | 0.158 | 0.007 | 0.422 | 0.068 | 0.490 |
| | Percent of growing season (%) | 52.65 | 32.24 | 1.43 | 86.12 | 13.88 | 100 |
| | Percent of whole year (%) | 34.08 | 20.87 | 0.92 | 55.75 | 8.98 | 64.73 |
| Whole year | Deposition amount (gN/m$^2$) | 0.398 | 0.228 | 0.015 | 0.640 | 0.117 | 0.757 |
| | Percent of whole year (%) | 52.58 | 30.12 | 1.98 | 84.54 | 15.46 | 100 |
| Ratio | Growing season/non-growing season | 1.84 | 2.26 | 0.88 | 1.94 | 1.39 | 1.84 |

TIN: total inorganic nitrogen; TON: total organic nitrogen; TN: total nitrogen.

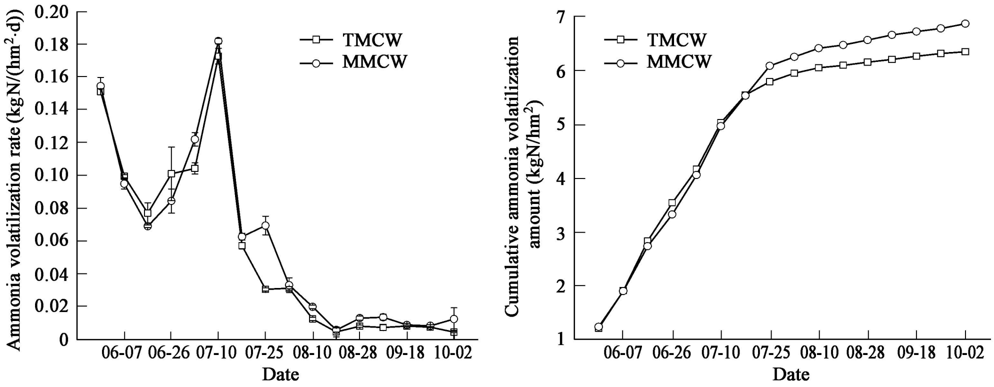


Fig. 1 Ammonia volatilization characteristics and cumulative ammonia volatilization amounts of wetland soils in growing season. Values are means (±SD, $n$=3); TMCW: typical meadow *Calamagrostis angustifolia* wetland; MMCW: marsh meadow *Calamagrostis angustifolia* wetland.

of those in non-growing season, respectively. In general, the TN wet deposition amount was 0.757 gN/(m$^2$·a), and TIN/TON ratio was 5.47. $NH_4^+$-N and $NO_3^-$-N were the main body of TIN, and their deposition amounts (0.398 and 0.228 gN/(m$^2$·a)) accounted for 52.58% and 30.12% of the TN wet deposition amount, respectively.

### 2.1.2 Characteristics of $NH_3$ volatilization and estimation of volatilization amount

The results of $NH_3$ volatilization experiment showed that the change characteristics of $NH_3$ volatilization rates of TMCW and MMCW soils in growing season were basically the same (Fig.1), with two peaks and a valley before the middle ten days of July. The first peak was appeared on 31 May, and the values were 0.151±0.003 kgN/(hm$^2$·d) for TMCW soil and 0.155±0.009 kgN/(hm$^2$·d) for MMCW soil. The second peak was appeared on July 10th, and the values were 0.173±0.008 and 0.182±0.003 kgN/(hm$^2$·d), respectively. The valley was appeared on 14 June, and the lower values were 0.077±0.011 and 0.069±0.001 kgN/(hm$^2$·d), respectively. After the middle 10 d of July, the changes of $NH_3$ volatilization rates of TMCW and MMCW soils, as a whole, declined, and became smooth after 18 August which indicated that the soils still could keep lower $NH_3$ volatilization rates (the means were 0.007±0.002 and 0.010±0.003 kgN/(hm$^2$·d), respectively) even at the end of growing season as the temperature was much lower. Comparatively, the $NH_3$ volatilization rates of MMCW soil were relatively high, with an average value being 1.35±0.53 (±SD, $n$=16) folds of TMCW soil, but there was no significant difference between them ($p$>0.05). The change characteristics of cumulative $NH_3$ volatilization amounts were also the same, i.e., they increased rapidly before the middle 10 d of July, and the values were relative proximity, then the values increased slowly and had significant differentiations. Further analysis indicated that the changes of cumulative $NH_3$ volatilization amounts between them had no significant difference ($p$>0.05). The estimation results showed that the total $NH_3$ volatilization amounts of TMCW and MMCW soils in growing season were 0.635 gN/m$^2$ and 0.687 gN/m$^2$, respectively, and the latter had a slightly higher value.

### 2.1.3 Characteristics of denitrification gaseous loss and estimation of lost amount

The study of denitrification gaseous loss showed that the change characteristics of denitrification gaseous lost rates of TMCW and MMCW soils in growing season were different (Fig.2). The ranges of their values were 0.024–0.127 and 0.021–0.043 kgN/(hm$^2$·d), the seasonal means were 0.046 and 0.029 kgN/(hm$^2$·d), and the coefficient of variation were 75.03% and 23.41%, respectively. In general, the denitrification gaseous lost rates of TMCW soil appeared two peaks on 28 June (0.100 kgN/(hm$^2$·d)) and 14 August (0.127 kgN/(hm$^2$·d)), respectively, and the minimum value (0.024 kgN/(hm$^2$·d)) was observed on 4 August. In other periods, the values changed between 0.025 and 0.044 kgN/(hm$^2$·d), and had no great fluctuations. In contrast with that, the denitrification gaseous lost rates of MMCW soil changed smoothly except one obvious peak was observed on 29 August (0.043 kgN/(hm$^2$·d)), and the values, in other periods, changed between 0.021 and 0.034 kgN/(hm$^2$·d). Comparatively, the denitrification gaseous lost rates of TMCW soil were relatively high with an average value being 1.67±1.56 (±SD, $n$=11) folds of TMCW soil, but there was no significant difference between them ($p$>0.05). The estimation results showed that

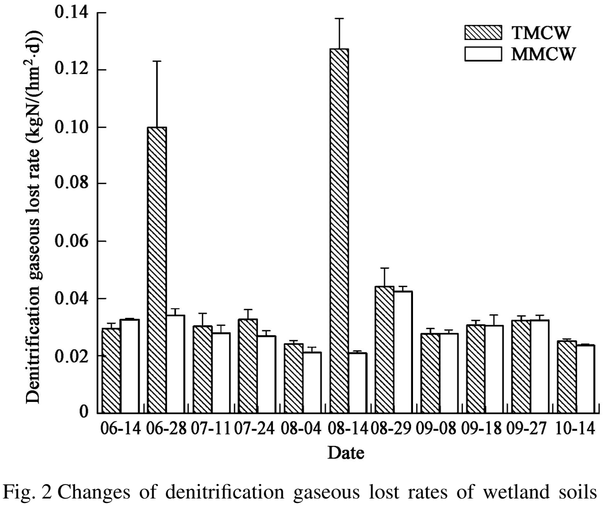


Fig. 2 Changes of denitrification gaseous lost rates of wetland soils in growing season. Values are means (±SD, $n$=3).

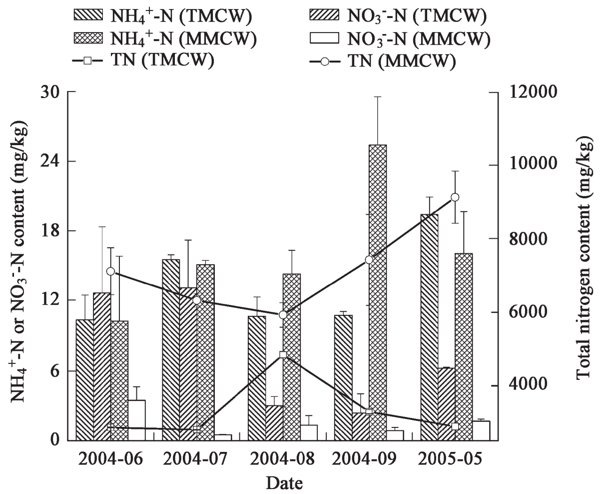


Fig. 3 Dynamics of TN, $NH_4^+$-N, $NO_3^-$-N contents in different wetland soils (0–15 cm). Values are means (±SD, *n*=6).

the denitrification gaseous lost amounts of TMCW and MMCW soils in growing season were 0.617 and 0.405 $gN/m^2$, respectively, and the former had a much higher value.

## 2.2 N dynamics, storages, and turnovers in plant-soil system

### 2.2.1 N dynamics and storages in soil

The changes of total nitrogen (TN), ammonia nitrogen ($NH_4^+$-N) and nitrate nitrogen ($NO_3^-$-N) contents in TMCW and MMCW soils (0–15 cm) are shown in Fig.3. The results showed that the contents of different N forms among months had significantly seasonal dynamics. Both the changes of TN contents in TMCW and MMCW soils presented the shape of "V", but the trends were just adverse. In August, the former achieved the maximum value (4845±1415 mg/kg) and the latter achieved the minimum value (5930±330 mg/kg). But in May, the former achieved the lower value (2894±150 mg/kg) and the latter achieved the maximum value (9138±710 mg/kg). In general, the changes of $NH_4^+$-N and $NO_3^-$-N contents in TMCW soil were basically the same. The $NH_4^+$-N contents in May (19.44±1.55 mg/kg) or July (15.58±0.43 mg/kg) were much higher than those in other months. Whereas, the $NO_3^-$-N contents were much higher in June or July, and the values were 12.69±5.70 and 13.14±4.13 mg/kg, respectively. Comparatively, the changes of $NH_4^+$-N and $NO_3^-$-N contents in MMCW soil were not consistent. The $NH_4^+$-N contents changed smoothly except one obvious peak (25.45±4.14 mg/kg) was observed in September, and the values, in other months, changed between 10.31 and 16.11 mg/kg. The $NO_3^-$-N contents achieved the maximum value in June (3.50±1.15 mg/kg), and had no great fluctuations in other months. Overall, the TN contents in MMCW soil were much higher than those in TMCW soil, and the difference between them was significant ($p$<0.01). Moreover, the $NH_4^+$-N contents in TMCW and MMCW soils, in general, were relatively high, with average values being 3.09±1.39 ($n$=4) and 16.37±12.32 ($n$=5) folds of $NO_3^-$-N contents, respectively. Further analysis indicated that the difference between them in TMCW soil was not significant ($p$>0.05), but in MMCW soil, the significant difference was existed ($p$<0.05). The calculation results showed that the N storage in TMCW and MMCW soils (0–15cm) were 510.51–881.20 and 442.81–639.61 $g/m^2$, and the inorganic N and organic N storage were 2.40–5.23, 505.31–879.32 $g/m^2$ and 0.97–1.84, 413.92–638.41 $g/m^2$, respectively.

### 2.2.2 N net mineralization in soil

The study of N net mineralization showed that the mineralization rates of TMCW soil (0–15 cm) were positive in incubation period except the phases from July to August in 2004 (–0.24±0.05 mgN/(kg·d)) and from May to June in 2005 (–0.14±0.04 mgN/(kg·d)), and the maximum value (0.28±0.06 mgN/(kg·d)) was observed in the phase from August to October in 2004 (Fig.4). Comparatively, the values of MMCW soil were positive in incubation period except the phases from October 2004 to May 2005 (−0.03±0.01 mgN/(kg·d)) and from May to June in 2005 (–0.15±0.04 mgN/(kg·d)), and the maximum value was also observed in the phase from August to October in 2004 (0.34±0.07 mgN/(kg·d)) (Fig.4). These indicated that the inorganic N produced by mineralization was still remained in most phases after the immobilization of microbes and soil animals. In general, the maximum mineralization rates of TMCW and MMCW soils were observed in autumn, while the minimum values were observed at initial and middle stage of rainy season, which was mainly correlated with the abundant precipitation in the two periods. The bad ventilate status in soils caused by abundant precipitation could induce the denitrification to be enhanced, which might consume a lot of $NO_3^-$-N. Further analysis indicated that the mineralization rates of TMCW and MMCW soils in different phases had significant difference ($p$<0.01). The calculation results showed that the N net mineralization amounts of TMCW and MMCW soils (0–15 cm) were 1.941 and 0.551 $g/(m^2·a)$, respectively.

### 2.2.3 Dynamics of aboveground biomass, belowground biomass of plant

The aboveground biomass of *C. angustifolia* in TMCW and MMCW had significantly seasonal dynamics (Fig.5).

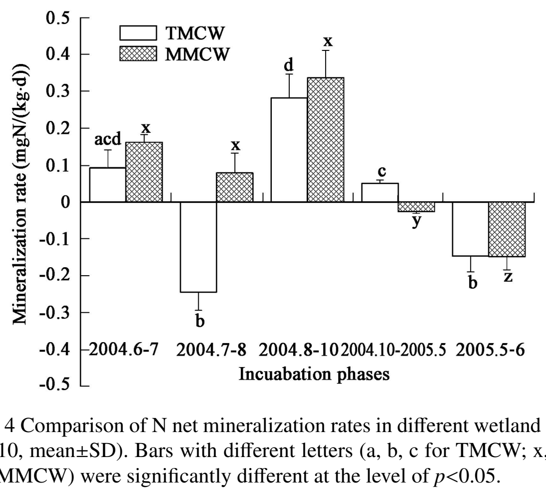


Fig. 4 Comparison of N net mineralization rates in different wetland soils ($n$=10, mean±SD). Bars with different letters (a, b, c for TMCW; x, y, z for MMCW) were significantly different at the level of $p$<0.05.

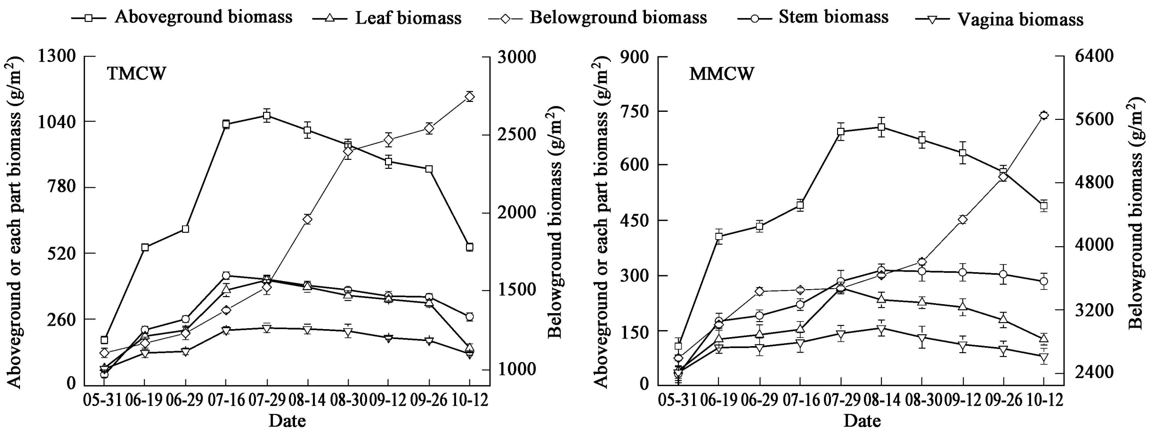


Fig. 5 Seasonal dynamics of *C. angustifolia* biomass in the two types of wetland communities. Values are means (±SD, $n$=3).

Both of them increased since 20 April as the improvement of hydrothermal condition, and the maximum values were observed on 29 July (1066.86 g/m$^2$) and 14 August (706.71 g/m$^2$), respectively. Since then, the aboveground biomass declined gradually as the coming of autumn, and the minimum values (547.33 and 491.91 g/m$^2$) were observed on 12 October. In general, the changes of *C. angustifolia* aboveground biomass in TMCW and MMCW were basically the same. The values in TMCW were much higher than those in MMCW (1.11–2.09 folds), and the difference between them was significant ($p$<0.05). The changes of leaf, vagina and stem biomass of *C. angustifolia* in TMCW and MMCW were also basically the same, and the maximum values (417.55, 228.96, 435.34 g/m$^2$ and 267.01, 157.45, 314.87 g/m$^2$, respectively) were observed on between 14 July and 14 August. Comparatively, the leaf, vagina and stem biomass of *C. angustifolia* in TMCW were much higher than those in MMCW, and the values of leaf and vagina between them were significantly different ($p$<0.05). The *C. angustifolia* belowground biomass in TMCW and MMCW also had significantly seasonal dynamics. They increased at all times and achieved the maximum values (2744.73 and 5658.07 g/m$^2$) on 12 October. Comparatively, the belowground biomasses in MMCW were much higher than those in TMCW (1.59–2.78 folds), and the difference between them was significant ($p$<0.01).

### 2.2.4 N dynamics, storages and turnovers in plant

The TN contents in leaf, vagina and stem of *C. angustifolia* in TMCW and MMCW declined gradually as the lapse of time, and the minimum values were observed at the end of growing season (Fig.6). Compared with the latter, the changes of TN contents of the former fluctuated greatly, and the reason was mainly correlated with the dilute effect caused by the increase of aboveground biomass. The aboveground biomass of the former increased much faster than that of the latter. Therefore, the dilute effect of the former was much higher than that of the latter. Further analysis showed that the changes of TN contents in leaf, vagina and stem of *C. angustifolia* in TMCW or MMCW had no significant difference ($p$>0.05). Comparatively, the TN contents in leaf were much higher than those of vagina or stem, which indicated that the leaf was the main N storage of aboveground plant. In general, the changes of TN contents in *C. angustifolia* root in TMCW and MMCW were basically the same, with one obvious peak on 29 June and 29 July, respectively (Fig.6). In contrast with that, the maximum aboveground biomass were observed on 29 July and 14 August, respectively (Fig.5), which indicated that the root must accumulate enough N nutrient before the coming of growth midseason to meet the need of growth. Since then, the TN contents in root declined due to the

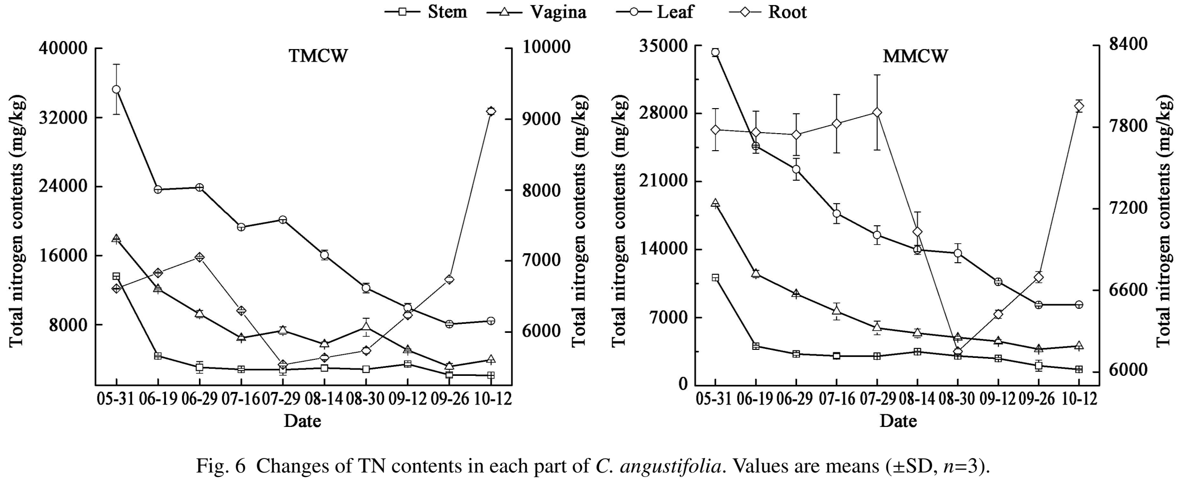


Fig. 6 Changes of TN contents in each part of *C. angustifolia*. Values are means (±SD, $n$=3).

N nutrients were largely transferred from belowground to aboveground, and the minimum values were observed on 29 July and 30 August, respectively. After 29 July or 30 August, the TN contents in root increased rapidly due to the translocation of N nutrient from aboveground to belowground as the senescence of aboveground parts, and the maximum values were observed at the end of growing season. Further analysis indicated that the changes of TN contents in *C. angustifolia* root in TMCW and MMCW had no significant difference ($p$>0.05). The calculation results showed that the N storage in root, stem, leaf and vagina of *C. angustifolia* in TMCW and MMCW were 7.34–25.01, 0.59–1.22, 1.26–8.40, 0.49–1.67 g/m$^2$ and 20.21–45.01, 0.35–1.09, 1.06–4.13, 0.33–1.20 g/m$^2$, respectively. The N uptake amounts of aboveground were 11.31 and 6.08 g/(m$^2$·a), the N uptake amounts of root were 23.02 and 28.18 g/(m$^2$·a), the N re-translocation amounts from aboveground to root were 5.96 and 2.70 g/(m$^2$·a), and the N translocation amounts from root to soil were 14.90 and 13.17 g/(m$^2$·a), respectively.

### 2.2.5 Dynamics of litter production and N content

The changes of litter productions and TN contents in *C. angustifolia* growth process in TMCW and MMCW are showed in Fig.7. The results indicated that the litter productions were lower at initial stage, and the values were 8.61±2.00 and 10.64±1.47 g/m$^2$, respectively. Since then, the productions increased at all times, and the maximum values (960.71±52.17 and 640.68±141.83 g/m$^2$) were observed at final stage. The change characteristics of TN contents in litters were just adverse to those of litter productions. At initial stage, the TN contents in litters were the highest, and the values were 15062.5±105.2 and 10301.8±98.2 mg/kg, respectively. Although the TN contents in litters fluctuated greatly, they declined, as a whole, with the lapse of time. The litter productions of the former were much higher than those of the latter (1.16–3.44 folds), but there was no significant difference between them ($p$>0.05). Moreover, the TN contents in *C. angustifolia* litters in the two types of wetlands also had no significant difference ($p$>0.05). The calculation results showed that the N translocation amounts from aboveground living body to litter were 5.35 and 3.38 g/(m$^2$·a), the N storage in standing dead stem, leaf and vagina were 0.59, 1.26, 0.49 g/(m$^2$·a) and 0.35, 1.06, 0.33 g/(m$^2$·a), and the cumulative N storage in litter-fall were 3.01 and 1.64 g/(m$^2$·a), respectively.

### 2.2.6 Dynamics of weightlessness rate and N content in litter decomposition process

The changes of weightlessness rates and TN contents in *C. angustifolia* litter decomposition process in TMCW and MMCW are shown in Fig.8. The results indicated that the change characteristics of weightlessness rates were basically the same, and the seasonality was significant. At initial stage (0–30 d), the litters decomposed slowly due to the worse hydrothermal condition and the lower microbial decomposition capacity. Then, the weightlessness rates increased rapidly with the improvement of hydrothermal condition. At the end of growing season (90–120 d), the weightlessness rates increased slowly due to the lower temperature. Since June of the next year (360 d), the weightlessness rates increased rapidly again. In general, the weightlessness rates of *C. angustifolia* litters in TMCW and MMCW increased at all times as the lapse of time, and the values, after 480 d, were 30.62% and 33.72%, respectively. The TN contents in *C. angustifolia* litters in TMCW and MMCW varied in flexuosity in decomposition process, which was mainly controlled by C/N ratios. The correlation analysis indicated that the C/N ratios had significantly negative correlations with TN contents ($p$<0.01), and the correlation coefficients were −0.981 and −0.970 ($n$=10), respectively. The study of the ratios between TN contents in different phases and initial TN content showed that the *C. angustifolia* litter in TMCW lost N from 0 to 390 d (the lost rates fluctuated from 3.67% to 30.55%), and accumulated N from 390 d to 480 d. In contrast with that, the *C. angustifolia* litter in MMCW lost N from 0 to 450 d (the lost rates fluctuated from 8.47% to 30.92%), and accumulated N from 450 to 480 d. The calculation results showed that the litter standing crops were 4.00 and 2.77 kg/m$^2$, and the N storages in litter were 15.80 and 9.47 g/m$^2$, respectively. In addition, the N translocation amounts from litter to soil would be larger than 1.55 and 3.01 g/(m$^2$·a) as the increase of decomposition time and the accumulation of litters.

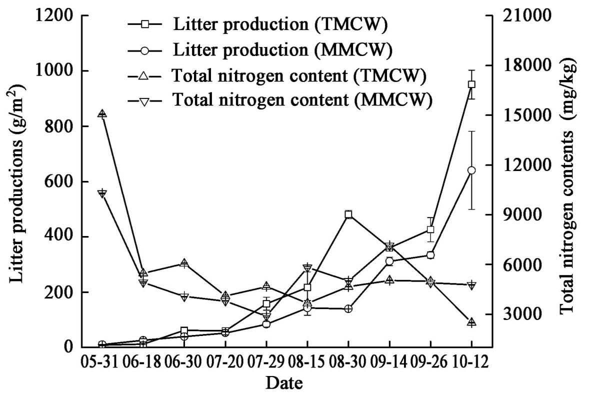


Fig. 7 Changes of litter productions and TN contents. Values are means (±SD, $n$=3).

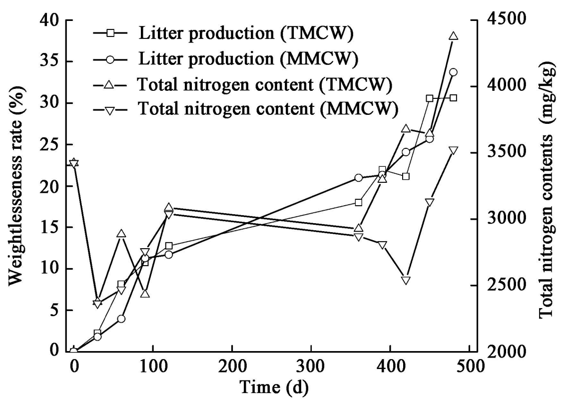


Fig. 8 Changes of litter weightlessness rates and TN contents. Values are means (±SD, $n$=3).

### 2.3 N distribution in compartments of plant-soil system

The study of N distribution in compartments of plant-soil system in TMCW and MMCW showed that root and litter were the main N storage of plant subsystems (Table 2), and the values were 28.16 and 37.41 g/($m^2$·a), accounting for 80.65% and 90.30% of the total N storages of plant subsystems, respectively. The *C. angustifolia* litter N storage in TMCW was higher than that in MMCW, while the root N storage in TMCW was lower than that in MMCW. In the two plant-soil systems, the N storages of plant subsystems only accounted for 5.43% and 7.61% of the total N storages. Soil organic N was the main N storage of the two plant-soil systems and the proportions of it were 93.98% and 92.16%, respectively. In contrast with that, soil inorganic N only accounted for 0.59% and 0.23%, which indicated that the available N in soils in TMCW and MMCW were very low. In general, the organic N played the function of circulation hinge in N cycling process, which could prevent the N from being lost easily. On the other hand, the lower available N storage indicated that the supply of soil effective N was limited.

### 2.4 Establishment of compartment model and calculation of N balance

Based on the above-mentioned studies, the compartment model on the distribution and circulation of N in atmosphere-plant-soil system of *C. angustifolia* wetland was established (Fig.9). In order to calculate the N balance of atmosphere-plant-soil system, some presumptions were established and explained. Firstly, the plant-soil system of depressional wetland was regarded as a whole, and it mainly received N deposition and lost by N gaseous forms. Meanwhile, the plant-soil system was separated by embankments or ditches with around due to human activities, and there almost no N imported by runoff or exported by leaching outlined previously. Therefore, the N in runoff or leaching water was neglected in our study. Secondly, the dry deposition and biological fixation were also important N input ways. Because the input amounts of the two processes were not determined, the N input amount of plant-soil system should be far larger than 0.757 gN/($m^2$·a). Finally, because wetland soils still could keep lower $NH_3$ volatilization rate at the end of growing season as the temperature was much lower, the annual

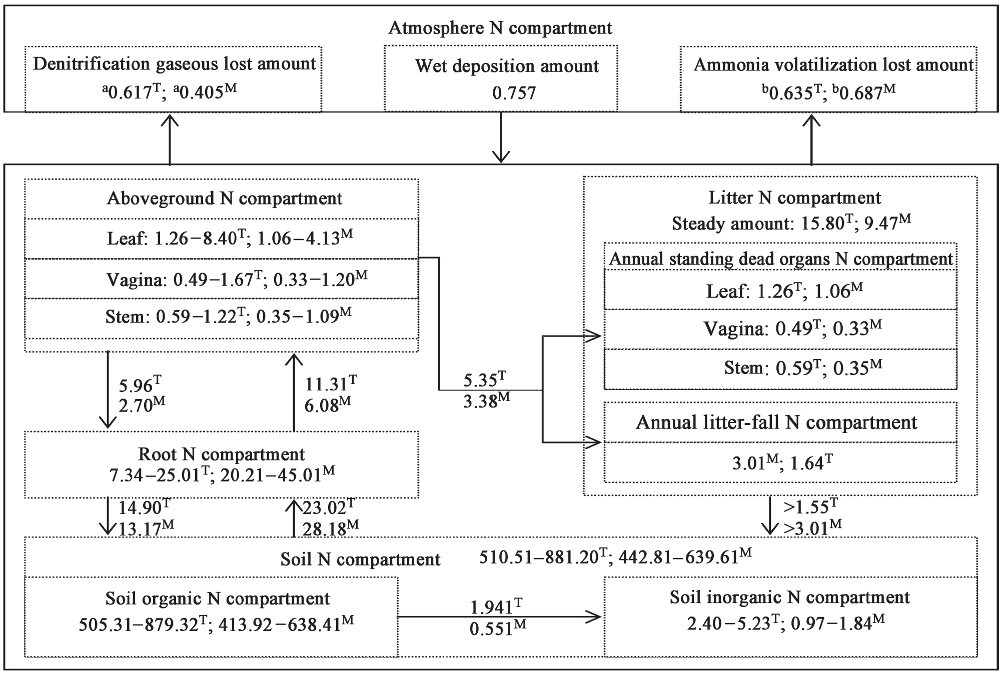


Fig. 9 N cycling compartment model of atmosphere-plant-soil system in *C. angustifolia* wetland. Numerals in panes were the N storages of compartments (gN/$m^2$). Numerals above arrowhead were the N turnovers among compartments (gN/($m^2$·a)). [a] Denitrification gaseous lost amount in growing season (gN/$m^2$); [b] ammonia volatilization lost amount in growing season (gN/$m^2$); [T] TMCW; [M] MMCW.

**Table 2 Nitrogen distribution among compartments of plant-soil system[a]**

| Item | Root | Aboveground living body | | | Litter | Plant subsystem | Soil (0–15cm) | | Plant-soil system |
|---|---|---|---|---|---|---|---|---|---|
| | | Stem | Leaf | Vagina | | | Organic N | Inorganic N | |
| Nitrogen storage (g/$m^2$) | $12.36^{T}$ | $0.96^{T}$ | $4.59^{T}$ | $1.21^{T}$ | $15.80^{T}$ | $34.92^{T}$ | $604.41^{T}$ | $3.80^{T}$ | $643.13^{T}$ |
| | $27.94^{M}$ | $0.72^{M}$ | $2.57^{M}$ | $0.73^{M}$ | $9.47^{M}$ | $41.43^{M}$ | $501.90^{M}$ | $1.25^{M}$ | $544.58^{M}$ |
| Percent (%) | $^{b}35.40^{T}$ | $^{b}2.75^{T}$ | $^{b}13.14^{T}$ | $^{b}3.47^{T}$ | $^{b}45.25^{T}$ | $^{c}5.43^{T}$ | $^{c}93.98^{T}$ | $^{c}0.59^{T}$ | $^{c}100^{T}$ |
| | $^{b}67.44^{M}$ | $^{b}1.74^{M}$ | $^{b}6.20^{M}$ | $^{b}1.76^{M}$ | $^{b}22.86^{M}$ | $^{c}7.61^{M}$ | $^{c}92.16^{M}$ | $^{c}0.23^{M}$ | $^{c}100^{M}$ |

[a] Values are means(±SD), $n$=3 for root, stem, leaf, vagina and litter, $n$=6 for soil organic N and inorganic N; [b] percent of plant subsystem; [c] percent of plant-soil system; [T] TMCW (Typical meadow *Calamagrostis angustifolia* wetland); [M] MMCW (Marsh meadow *Calamagrostis angustifolia* wetland).

**Table 3 Nitrogen balance of atmosphere-plant-soil system in wetland**

| Wetland type | Input | Output | | Total output (g/(m$^2$·a)) | Deficit (g/(m$^2$·a)) |
|---|---|---|---|---|---|
| | Deposition and biological fixation (g/(m$^2$·a)) | Denitrification (g/(m$^2$·a)) | Ammonia volatilization (g/(m$^2$·a)) | | |
| TMCW | >0.757* | <0.617** | >0.635*** | ≈1.252**** | <0.495 |
| MMCW | | <0.405** | >0.687*** | ≈1.092**** | <0.335 |

*Far larger than the value; **slightly lower than the value; ***slightly higher than the value; ****approximate the value.

$NH_3$ volatilization amounts of TMCW and MMCW soils should be slightly higher than 0.635 and 0.687 gN/m$^2$, respectively. Meanwhile, the studies of $N_2O$ flux in *C. angustifolia* wetland in non-growing season indicated that the wetland, on the whole, was a faintish sink of $N_2O$ (Zhang *et al*., 2005). Therefore, the annual denitrification gaseous lost amounts of TMCW and MMCW soils might be slightly lower than 0.617 and 0.405 gN/m$^2$, respectively. Based on above analysis, it was concluded that the total N output might approximate 1.252 and 1.092 gN/m$^2$, respectively.

Based on the above-mentioned presumptions or explanations, the N balance of TMCW and MMCW were calculated in Table 3. The results showed that the maximum N deficits might be 0.495 and 0.335 gN/(m$^2$·a), respectively, which indicated that the two plant-soil systems might be situated in the status of lacking N if the N input amount (through wet or dry deposition and biological fixation) was lower than that of output amount (through gaseous losses of denitrification and $NH_3$ volatilization). Because N is often the most limited elements that affect the photosynthesis and primary production process of wetland plant (Mistch and Gosselin, 2000), the N lacking status in *C. angustifolia* wetlands might have significant effects on the growth of plants, and it even could induce wetland degradation as the N balance was seriously broken. But, in order to get clear conclusions, further studies still needed to be carried out to illustrate the contribution of N dry deposition and biological N fixation, and the annual lost amounts of denitrification and $NH_3$ volatilization.

## 3 Conclusions

The systemic study of N cycling of atmosphere-plant-soil system in TMCW and MMCW indicated that: (1) the N wet deposition amount was 0.757 gN/m$^2$ in a year. The $NH_3$ volatilization amounts in growing season were 0.635 and 0.687 gN/m$^2$, and the denitrification gaseous lost amounts were 0.617 and 0.405 gN/m$^2$, respectively; (2) the N turnovers among compartments of the two plant-soil systems were different. The uptake amounts of root were 23.02 and 28.18 gN/(m$^2$·a) and the values of aboveground were 11.31 and 6.08 gN/(m$^2$·a), the re-translocation amounts from aboveground to root were 5.96 and 2.70 gN/(m$^2$·a), the translocation amounts from aboveground living body to litter were 5.35 and 3.38 gN/(m$^2$·a), the translocation amounts from litter to soil were larger than 1.55 and 3.01 gN/(m$^2$·a), the translocation amounts from root to soil were 14.90 and 13.17 gN/(m$^2$·a), and the soil (0–15 cm) N net mineralization amounts were 1.94 and 0.55 gN/(m$^2$·a), respectively; (3) the N, in plant subsystem, was mainly stored in root and litter. Soil organic N was the main N storage of plant-soil system, which played the function of circulation hinge in N cycling process; (4) the two plant-soil systems might be situated in the status of lacking N, and the status might induce the degradation of *C. angustifolia* wetland.

**Acknowledgements**

The authors would like to thank Zhang Yu-xia and Lou Bo-kun for their analytical supports. The efforts of Yang Ji-song, Zhou Wang-ming, Qin Sheng-jin, Li Xin-hua, Zhao Wei and Dou Jing-xin during the experimental endeavor are gratefully acknowledged.

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