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Sulfur cycle in the typical meadow *Calamagrostis angustifolia* wetland ecosystem in the Sanjiang Plain, Northeast China

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Abstract

The sulfur cycle and its compartmental distribution within an atmosphere-plant-soil system was studied using a compartment model in the typical meadow *Calamagrostis angustifolia* wetland in the Sanjiang Plain Northeast China. The results showed that in the typical meadow *C. angustifolia* wetland ecosystem, soil was the main storage compartment and current hinge of sulfur in which 98.4% sulfur was accumulated, while only 1.6% sulfur was accumulated in the plant compartment. In the plant subsystem, roots and litters were the main storage compartment of sulfur and they remained 83.5% of the total plant sulfur. The calculations of sulfur turnover through the compartments of the typical meadow *C. angustifolia* wetland ecosystem demonstrated that the above-ground component took up 0.99 gS/m^2 from the root, of which 0.16 gS/m^2 was translocated to the roots and 0.83 gS/m^2 to the litter. The roots took in 1.05 gS/m^2 from the soil, subsequent translocation back to the soil accounted for 1.31 gS/m^2, while there was 1.84 gS/m^2 in the litter and the net transfer of sulfur to the soil was more than 0.44 $gS/(m^2\cdot a)$. The emission of H_2S from the typical meadow *C. angustifolia* wetland ecosystem to the atmosphere was 1.83 $mgS/(m^2\cdot a)$, while carbonyl sulfide (COS) was absorbed by the typical meadow *C. angustifolia* wetland ecosystem from the atmosphere at the rate of 1.76 $mgS/(m^2\cdot a)$. The input of sulfur by the rainfall to the ecosystem was 4.85 mgS/m^2 during the growing season. The difference between input and output was 4.78 mgS/m^2, which indicated that sulfur was accumulated in the ecosystem and may cause wetland acidify in the future.

Key words: the Sanjiang Plain; typical meadow *Calamagrostis angustifolia* wetland; ecosystem; sulfur cycle

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Introduction

The nutrient cycling within an ecosystem includes not only input and output of organic matter, but also the interaction between the plant community and its environment (Hüttle and Schaaf, 1995; Vitousek, 1984). Sulfur cycle is one of the most complex cycles because oxidation of sulfur varies between S^{2-} and S^{6+} (Yang *et al*., 1996). There has been increasing interest in understanding the sulfur cycle in wetland ecosystems because high inputs of organic matter into wetland soils, along with oxic surface and anoxic subsurface zones, potentially allow sulfur to play a critical role in the biogeochemistry of wetlands (Giblin and Wieder, 1992). Many studies have reported the sulfur cycle in different wetland types, such as salt marsh, freshwater marsh and peat, and so on (Mandernack *et al*., 2000; Thamdrup *et al*., 1994; Spratt *et al*., 1990; Luther and Church, 1988; Wieder and Land, 1988), while in China only Zhang (1996) reported the accumulation and cycle of sulfur in mangrove ecosystem.

The Sanjiang Plain is one of the biggest regions in China, which is widely distributed with various kinds of wetland, the *Calamagrostis angutifolia* wetland which takes up 34.45% of the total wetland area in Sanjiang Plain Northeast China, is one of the main wetland types, with typical meadow *C. angustifolia* wetland (TMC) and marsh meadow *C. angustifolia* wetland (MMC) as the typical types (He, 2000). The two types of wetland are located in different water gradients, and they are both sensitive to the changes of water conditions. Yet in recent years, the MMC began to evolve into TMC because of the changes of climate and disturbs of human activities. To date, the information about the sulfur cycle in the *C. angutifolia* wetland is still limited. Hao *et al*. (2004) reported the distribution of sulfur in the *C. angutifolia* wetland in the Sanjiang Plain, Northeast China. To better understand wetland sulfur cycle, TMC ecosystem was selected as the research object in this article. The atmosphere-plant-soil system was divided into five compartments (including atmosphere, above-ground living body, root, litter and soil) using the compartment model. The sulfur storage dynamics and sulfur turnover among compartments were also studied. Finally, the sulfur cycling compartment model of atmosphere-plant-soil system was established and the status of sulfur balance was evaluated.

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1 Material and methods

1.1 Site description

The experimental site is located at the Sanjiang Mire Wetland Experimental Station, Chinese Academy of Sciences (47°35′N, 133°31′E), in Tongjiang City of Heilongjiang Province, China. The average above sea level is 56 m, mean annual precipitation is about 600 mm, and mean annual temperature is 1.9°C. The types of vegetation vary from *C. angustifolia* to *Carex lasiocarpa* with standing water depth increases significantly. The standing water depth ranged from 0 to 20 cm in *C. lasiocarpa*, 0 to 15 cm in *Carex meyeruana*, and 0 to 5 cm in *C. angustifolia* marshes. The water and soil in marshes are completely frozen from late October to the next April, and begin to melt in late April, and the highest temperature occurs in July. The experiments were all carried out in the typical meadow *C. angustifolia* wetland, of which the soil main properties are as follows: soil layer 0–20 cm; organic matter 5.16%; total sulfur 518.81 mg/kg; total nitrogen 2,286.09 mg/kg; porosity 63.01%; pH 5.61.

1.2 Sampling and study methods

The above-ground biomass and standing litter biomass were collected with the harvest per half month from May to September, 2005, meanwhile the below-ground biomass was collected with the digging method. Each plot size was 50 cm × 50 cm. Litter decomposition was studied using litterbags with an inside area of 20 cm × 20 cm made of nylon (0.5 mm × 0.5 mm mesh) from May 2004 to September 2005. Soil samples were also collected per month from May to September, 2005, with sampling depth 0–20 cm, and the soil bulk densities were measured at the same time. All the samples had three replicates.

The plant sulfur pools (S_n) and sulfur turnover among plant compartments (F_a) were calculated by the following equations (Li *et al.*, 2000).

$$S_n = C_n B_n \tag{1}$$

$$F_a = C_a B_a \tag{2}$$

The soil sulfur pools were calculated using the following formula (Zhang *et al.*, 2000).

$$S_n = C_n V S_v \tag{3}$$

Standing litter sulfur storage (F_{da}), the sulfur re-translocation amount from above-ground part to root (F_{rt}) and the sulfur uptake amount of root (F_r) were calculated by Eqs. (4)–(6):

$$F_{da} = C_d B_a \tag{4}$$

$$F_{rt} = F_a - F_{da} \tag{5}$$

$$F_r = F_a - F_{rt} + \Delta S_u \tag{6}$$

where, C_d is the content of sulfur in dead plant above-ground part; B_a is the amount of above-ground part; F_a and F_{rt} have been mentioned above; ΔS_u is the net increment of underground biomass in growing season.

The existent amounts of litter (X_{st}) and weightlessness rate (R) of litter were calculated by Eqs.(7)–(8) (Liu *et al.*, 2000):

$$X_{st} = x/(1 - e^{-k}) \tag{7}$$

$$R = (W_1 - W_2)/W_1 \times 100\% \tag{8}$$

where, e^{-k} is the residual rate of litter (%); W_1, W_2 are litter weights (g) for the times of t_1 and t_2 (d), respectively.

The sulfur translocation amounts from litter to soil (F_s) and from root to soil (F_T) were calculated by Eqs. (9)–(11):

$$F_s = F_l - F_y \tag{9}$$

$$F_T = T \times B_{max} \times C_{max} \tag{10}$$

$$T = P_m / B_{max} \tag{11}$$

where, F_l is composed of F_{da} and F_p, F_{da} is the same as above mentioned, F_p is the sulfur storage in litter standing crop; F_y is the sulfur storage in undecomposed litter; T is the turnover rate of root (Dahlman *et al.*, 1965); P_m is the deficit of maximum biomass and minimum biomass of root; B_{max} is the maximum biomass of root; C_{max} is the sulfur content as root biomass achieves maximum.

The atmosphere precipitation was collected from May to September 2005, and the sulfur wet deposition amount (gS/m^2) was calculated by Eq.(12) (Li *et al.*, 2000).

$$\text{Sulfur deposition amount} = \sum (C_i \times 10^{-6} \times V_i)/\mathrm{A}) \times 1000 \tag{12}$$

where, C_i is the SO_4^{2-} concentration (mg/L); V_i is the precipitation volume (L); A is the cross sectional area of collector (0.0314 m^2).

The emission flux of sulfur gases at each site were measured using the method of closed chamber (Kanda and Minami, 1992). The concentrations of H_2S and COS were determined as described in detail by Li *et al.* (2006). And emission fluxes were calculated using the following equation:

$$F = \frac{MPT_0}{V_0 P_0 T} H \frac{dc}{dt} \tag{13}$$

where, F is gas emission flux (μg/(m^2·h)); M is gas mass of mol (H_2S: 34.08; COS: 60.07), P_0, T_0, and V_0 are 1,013.25 hPa, 273.15 K and 22.41 L/mol; H is height of sampling box; P is air pressure of sampling site; T is absolute temperature; dc/dt is slope of concentration of gas and time.

2 Results and discussion

2.1 Seasonal changes of biomass and sulfur content in plant

The above-ground biomass and below-ground biomass of *C. angustifolia* in TMC both had significantly seasonal changes (Fig.1a). The above-ground biomass increased with the improvement of hydrothermal condition since April and reached the maximum values on 29 July

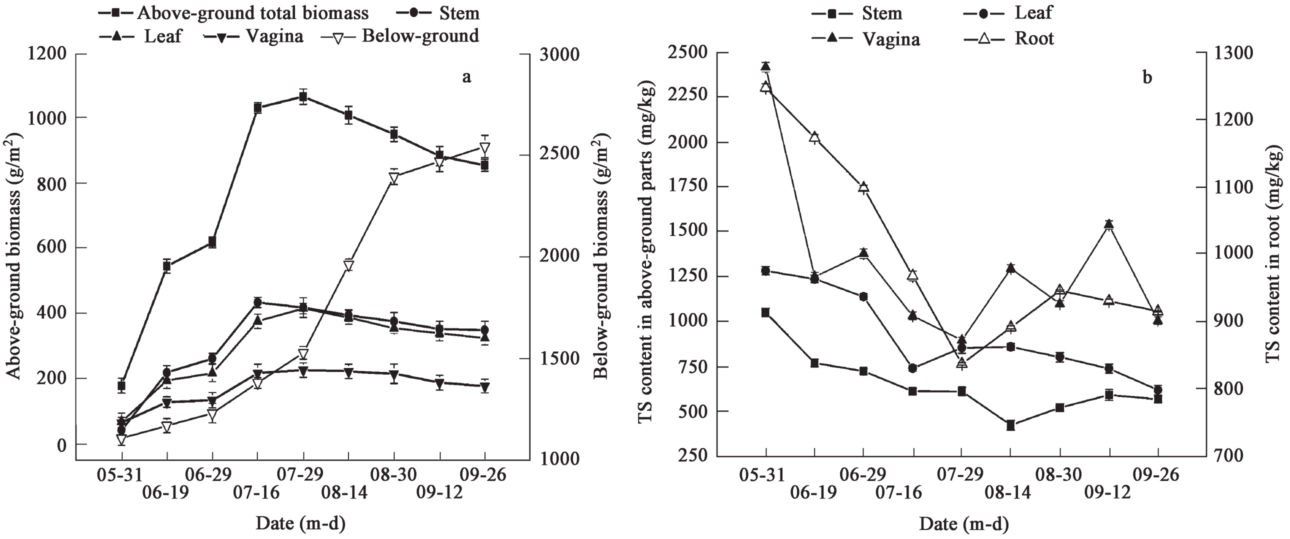

Fig. 1 Seasonal dynamics of biomass (a) and sulfur contents (b) in each part of *Calamagrostis angustifolia*.

(1,066.86 g/m^2), which was consistent with previous work (Ma *et al*., 1993). Later it began to decline with the autumn coming and reached the minimum values (856.30 g/m^2) on 26 September. The seasonal changes of stem, vagina and leaf biomass of *C. angustifolia* were the same as the above-ground biomass, and the maximum values were 435.34, 417.55, and 228.96 g/m^2, respectively. The below-ground biomass increased at all times and reached the maximum values (2,542.03 g/m^2) on 26 September.

Figure 1b shows the changes of TS contents in stem, leaf, vagina and root. The TS contents in the stem, leaf and vagina of *C. angustifolia* declined as a whole dring the grown season. The maximum value was in May 2005, later they changed fluctuantly mainly because of the dilute effect caused by the increase of above-ground biomass. Comparatively, the TS contents in leaf were higher than those in vagina or stem, because leaf was tender and sulfur distributes preferentially to the tender part. While the TS contents in roots changed fluctuantly during the grown season, and it declined from 31 May to 29 July due to the translocation of sulfur from roots to above-ground and the minimum values achieved on 29 July. Since then it increased from 29 July to 30 August due to the senescence of above-ground organs and the translocation of sulfur from above-ground to roots, and it declined again from 30 August to 26 September because the amounts of translocation of sulfur from above-ground to roots decreased as a result of the death of plant. The calculation results showed that the sulfur storage in the root, stem, leaf and vagina of *C. angustifolia* were 1.28–2.33 g/m^2, 0.05–0.27 g/m^2, 0.17–0.53 g/m^2, and 0.09–0.20 g/m^2 respectively. The sulfur uptake amounts of above-ground and roots were 0.99 and 1.05 g/m^2, respectively. The sulfur re-translocation amounts from the above-ground to roots and from roots to soil were 0.16 and 1.31 g/m^2, respectively.

2.2 Seasonal changes of standing litter biomass and sulfur content in standing litter

The changes of standing litter biomass and TS contents of *C. angustifolia* were shown in Fig.2. The standing litter biomass was lower at the initial stage and the value was 8.61 g/m^2, later it increased all the time and reached the maximum value (547.33 g/m^2) at the final stage. Whereas, the TS content in the standing litter was higher at the initial stage and the value was (2,231.77 mg/kg), later although the TS content in the standing litter fluctuated greatly, it declined as a whole, which was consistent with the work reported by Wang *et al*. (2000). And the calculation results showed that the storage amount of sulfur in the standing litter was 0.51 g/m^2 and the transformation amount of sulfur from the above-ground living body to the standing litter was 0.83 g/m^2.

2.3 Changes of litter decomposition and sulfur content in the remaining litter

The changes of *C. angustifolia* litter decomposition showed an alternate change of fast-slow (Fig.3). The decomposition rate of litter was faster from May to October 2004, and it became lower from November to April in the next year, which was correlated with the native climate. The weightlessness rate of the litter was 29.13% after 480 d decomposition.

The TS content in the litter changed fluctuantly during

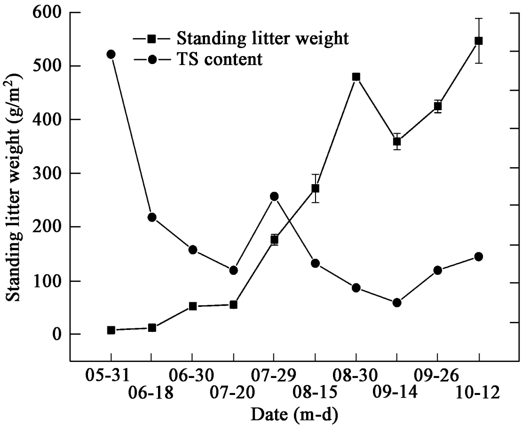

Fig. 2 Changes of standing litter biomass and total sulfur (TS) content in standing litter in 2005.

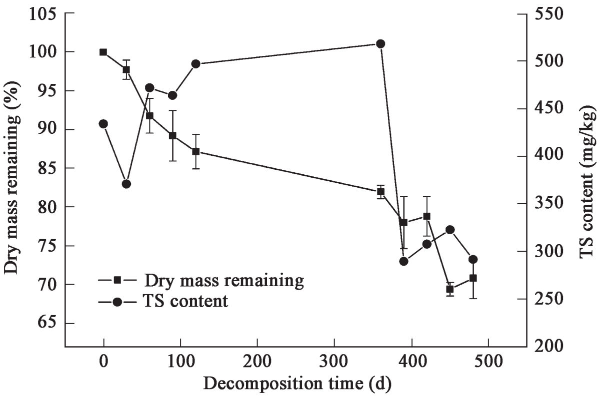

Fig. 3 Changes of dry mass remaining and total sulfur (TS) content in *Calamagrostis angustifolia* litter in 2004.

the decomposition, which was mainly affected by the ratio of C/S in the litter. The ratio of TS content in the remaining litter and initial litter showed that the sulfur in the litter was released during the first 60 d and the period between 390–420 d, while the exogenous sulfur was immobilized during other decomposition periods. The calculation results showed that the sulfur storage in litter was 1.33 g/m^2 and the sulfur return amount from the litter to soil was 0.44 g/m^2.

2.4 Seasonal changes of total sulfur and inorganic sulfur in soil

The changes of total sulfur and inorganic sulfur in TMC soil (0–20 cm) are shown in Fig.4. The contents of total sulfur and inorganic sulfur both had significantly seasonal variation. The content of total sulfur in the soil declined from May to August 2005 and reached the minimum value (437.61 mg/kg), which was caused by the uptake of *C. angustifolia*, then it began to increase from August to September and reached maximum value (529.19 mg/kg), later it declined again.

The content of inorganic sulfur in the soil also declined from May to August which was related with the uptake of plant, and it increased slowly from the early August to the later September, which may be caused by the decreased uptake of plant due to senescence and the input of SO_4^{2-} by the rainfall increased due to the increase of rainfall. The range of the content of inorganic sulfur in soil (0–20 cm) was 35.82–45.31 mg/kg. The calculation results showed that the TS storage in soil (0–20 cm) were 238.22–288.01 gS/m^2, and the storage of inorganic and organic sulfur were 16.17–5.96 gS/m^2 and 222.05–262.05 gS/m^2, respectively.

2.5 Characteristics of sulfur wet deposition and estimation of sulfur wet deposition amount

Sulfur monthly deposition amount from May to September, 2005 is shown in Fig.5. Sulfur monthly deposition amount was lower in May, which was related with the increased volatile amount of ammonia caused by agricultural fertilization. Then it increased from May to July, and reached the peak value in July, which was correlated with the location and wind of the study area. Later it began to decrease until September. The calculation results showed that the sulfur deposition amount was 4.85 mgS/m^2 in the grown season.

2.6 Seasonal variations of H_2S and COS emission fluxes

Figure 6 shows the H_2S and COS emission fluxes in TMC. The emission of H_2S in TMC ranged from 0.00 to 0.68 μgS/(m^2·h) where 0.00 expressed values lower than the detection limit in this paper. And the averaged emission was 0.14 μgS/(m^2·h) which was lower than the previous values in Louisiana Coast freshwater marsh (Delaune *et al*., 2002; Castro and Dierberg, 1987). H_2S emission rate increased gradually during May and July, and reached peak value in July, because the low soil redox potential (Eh) and high temperature in July. High temperature can promote microorganism activities, the organic matter was quickly metabolized and thus increased the sulfur gases emission (Goldan *et al*., 1987; Yang *et al*., 1996). Low Eh can increase the rate of dissimilatory sulfate reduction (Istvan and Delaune, 1995) which can enhance the production of H_2S. During August and September, emission flux changes had no obvious rules, but lower than those in July, probably because of the low temperature and high Eh in that time. The COS emission flux in TMC ranged from –1.68 to 0.8 μgS/(m^2·h), and the averaged emission

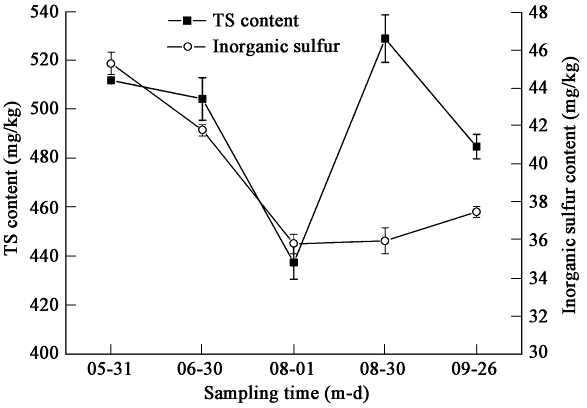

Fig. 4 Seasonal changes of total sulfur (TS) and inorganic sulfur in soil (0–20 cm) of typical meadow *Calamagrostis angustifolia* wetland wetland (TMC) in 2005.

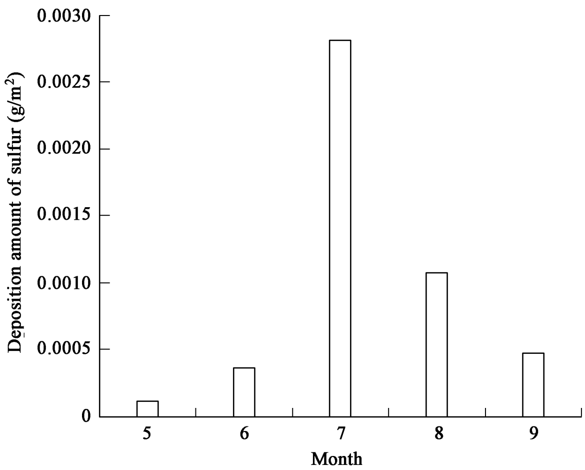

Fig. 5 Change of month deposition amounts of sulfur during growing season in 2005.

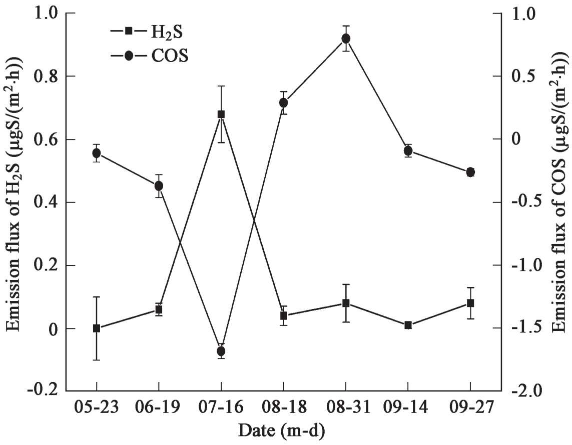

Fig. 6 Seasonal variation of H_2S and carbonyl sulfide (COS) emission fluxes.

was –0.20 μgS/(m^2·h). During May and July, the emission rate of the COS decreased. Moreover, the absorbed peak was observed in July, probably due to the rapid growth of *C. angustifolia* in July and high metabolism rate of COS (Brown *et al*., 1986). During August and September, COS emission flux increased due to the small influence by the matured and dying plants. The estimation results showed that the emission amounts of H_2S and COS were 1.83 and –1.76 mgS/m^2, respectively.

Table 1 Allocation of sulfur among compartments of plant-soil system

	Total sulfur (g/m^2)	Proportion (%)
Above-ground-living body		
Stem	0.19	4.5
Leaf	0.36	8.4
Vagina	0.15	3.6
Root	1.72	40.3
Litter	1.84	43.2
Plant system	**4.26**	**1.6**
Soil (0–60 cm)		
Inorganic sulfur	23.18	8.4
Organic sulfur	247.88	90.0
Plant-soil system	**275.32**	**100**

2.7 Sulfur distribution and cycling in *C. angustifolia* wetland ecosystem

The study of sulfur distribution in the compartments of plant-soil system in TMC ecosystem (Table 1) shows that organic sulfur was the main form of sulfur storage in soil and its proportion in the plant-soil system was 90%. In contrast with that, inorganic sulfur in soil only accounted for 8.4%, which indicated that sulfur storage in soil had important function in the sulfur cycle of ecosystem and it was the main storage and current hinge of sulfur. Comparatively, sulfur storage in the plant was much lower and its proportion in the plant-soil system was only 1.6%. In the plant subsystem, the root and the litter were the main storage of sulfur and they kept 83.5% of the total sulfur in plant.

On the basis of the above results, the compartment model on the distribution and circulation of sulfur in atmosphere-soil-plant system of TMC ecosystem was established (Fig.7). According to the compartment model, the sulfur balance in TMC was calculated in Table 2. The results showed that the input of sulfur was higher than the output of sulfur in TMC ecosystem, and the minimum difference between input and output was 4.78 mgS/m^2 (Table 2), which indicated that sulfur was accumulated in the TMC ecosystem. Sulfur was one of the necessary nutrient elements to the plant, however, the more sulfur accumulated in the ecosystem, the more the growth of plant would be restrained, the productivity of ecosystem would also be depressed, moreover the wetland would face acidification in the future if sulfur were accumulated too much.

Table 2 Amounts of input and output of sulfur in wetland system (unit: mgS/m^2)

Input of sulfur	Output of sulfur		Deficit between input and output of sulfur
Wet deposition	H_2S	COS	4.78
4.85	1.83	–1.76	

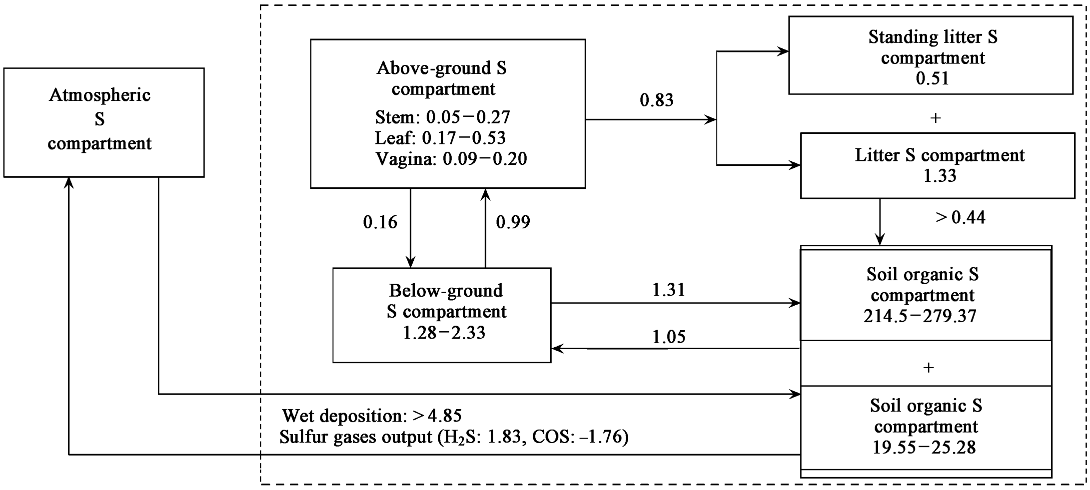

Fig. 7 Sulfur cycle model in typical meadow *Calamagrostis angustifolia* wetland (TMC) ecosystem. Unit: mgS/m^2.

3 Conclusions

The study of sulfur cycle in the TMC ecosystem showed that the soil was the main storage and current hinge of sulfur which accumulated 98.4% of the total sulfur, the organic sulfur in soil was the main body of soil sulfur storage and accounted for 90% sulfur in the plant-soil system , and only 1.6% sulfur was accumulated in the plant storage. In the plant subsystem, the root and litter were the main storage of sulfur and they remained 83.5% of the total plant sulfur. The calculations of sulfur turnover through the compartments of the TMC ecosystem showed that the above-ground component took up 0.99 gS/m^2 and of which 0.16 gS/m^2 was translocated to the root and 0.83 gS/m^2 to the litter. The roots took up 1.05 gS/m^2 from the soil, subsequent translocation back to the soil accounted for 1.31 gS/m^2, while 1.84 gS/m^2 remained in the litter and the net transfer amount of sulfur from the litter to soil was more than 0.44 $gS/(m^2 \cdot a)$. The emission of H_2S from the TMC ecosystem to the atmosphere was 1.83 $mgS/(m^2 \cdot a)$, while COS was absorbed by the TMC ecosystem from the atmosphere and the absorbed amount was 1.76 $mgS/(m^2 \cdot a)$. The input amount of sulfur by rainfall to the ecosystem was 4.85 mgS/m^2 during the growing season. The difference between input and output amount was 4.78 mgS/m^2, which indicated that sulfur was accumulated in the ecosystem and may cause the wetland acidify in the future, effective measures must be taken to prevent the acidification of wetland.

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References

Brown K A, Bell J N B, 1986. Vegetation the missing sink in the Global cycle of carbonyl sulfide (COS). *Atmos Environ*, 20(3): 537–540.

Castro M A, Dierberg F E, 1987. Biogenic hydrogen sulfide emissions from selected Florida wetlands. *Water Air Soil Pollut*, 33: 1–13.

Dahlman R C, Kucera C L, 1965. Root productivity and turnover in native prairie. *Ecology*, 46: 84–89.

Delaune R D, Devai I, Lindau C W, 2002. Flux of reduced sulfur gases along a salinity gradient in Louisiana coastal Marshes. *Estuar Coast Shelf Sci*, 54: 1003–1011.

Goldan P D, Kuster W C, Albritton D L, Fehsenfeld F C, 1987. The measurement of natural sulfur emissions from soil and vegetation: three site in the eastern United States revisited. *J Atmos Chemis*, 5: 439–467.

Giblin A E, Wieder R K, 1992. Sulphur cycling in marine and freshwater wetlands. In: Sulphur Cycle in the Continents, Wetlands, Terrestrial Ecosystems and Associated Water Bodies (Howarth R. V., Stewart J. W. B., Ivanou M. V., eds.). Chichester: John Wiley and Sons Ltd.

Hao Q J, Wang Q C, Wang Y S, 2004. The distribution of sulfur in typical wetland soils in the Sanjiang Plain. *J Soil Sci*, 35(3): 331–335.

He L, 2000. The Sanjiang Plain of China. Heilongjiang, China: Heilongjiang Sciences Technology Press.

Hüttle R F, Schaaf W, 1995. Nutrient supply of forest soils in relation to management and site history. *Plant Soil*, 169: 31–41.

Istvan D, Delaune R D, 1995. Formation of volatile sulfur compounds in salt marsh sediment as influenced by soil redox condition. *Org Geochem*, 23: 283–287.

Kanda K, Minami K, 1992. Measurement of dimethyl sulfide emission from lysimeter paddy field. *Ecoll Bull*, 42: 195–198.

Mandernack K W, Lynch L, Krouse H R, Morgan M D, 2000. Sulfur cycling in wetland peat of the New Jersey Pinelands and its effect on stream water chemistry. *Geochim Cosmochim Acta*, 64(23): 3949–3964.

Li X H, Liu J S, Jia Y Q, 2006. Determination of trace hydrogen sulfide by cryogenic adsorption-thermal desorption gas chromatography. *J Instrumental Anal*, 25(3): 68–69.

Li Y Z, Zhu Y C, Jiang S C, 2000. Nitrogen deposition in *Leymus chinensis* Grassland of Songnen Plain. *Grassland Chin*, 2: 24–27.

Liu J S, Sun X L, Yu J B, 2000. Nitrogen content variation in litters of *Deyeuxia angustifolia* and *Carex lasiocarpa* in Sanjiang Plain. *Chin J Appl Ecol*, 11(6): 898–902.

Luther III G W, Church T M, 1988. Seasonal cycling of sulfur and iron in porewaters of a Delaware salt marsh. *Marine Chem*, 23: 295–309.

Ma K P, Zhou R C, Zhang Y, 1993. Studies on the structure and seasonal dynamics of above-ground biomass of *Calamagrcstis angustifolia* Grassland in Sanjiang Plain. *Grassland Chin*, 2: 27–31.

Spratt H G, Morgan M D, 1990. Sulfur cycling in a cedar dominated freshwater wetland. *Limnol Oceangr*, 35: 1586–1593.

Thamdrup B, Fossing H, Jorgensen B B, 1994. Manganese, iron and sulfur cycling in a coastal marine sediment, Aarhus Bay, Denmark. *Geochim Cosmochim Acta*, 58: 5115–5129.

Vitousek P M, 1984. Litterfall, nutrient cycling and nutrient limitation in tropical forests. *Ecology*, 65: 283–298.

Wang S Y, Yang Y X, 2000. Study on dynamics of litter and seasonal dynamics of phosphorus in decomposed of Deyeuxia angustifolia in Sanjiang Plain. *Grassland Chin*, 6: 6–10.

Wieder R K, Land G E, 1988. Cycling of inorganic and organic sulfur in peat from Big Run Bog, West Virginia. *Biogeochem*, 5: 221–242.

Yang Z, Wang L, 1996. Research and prospect: on the research of emission of volatile sulfur gases. *Adv Environ Sci*, 4: 19–27.

Zhang F Z, Liang H, Zhang H L, Jin X L, 1991. Biogeochemical cycling of nitrogen, phosphorus and sulphur in pinus-tabulaeformis forest ecosystem in Haihe River basin. *Acta Sci Circumst*, 11(2): 131–140.

Zhang R G, 1996. Study on sulfur accumulation and cycling in Mangrove forest in pear River mouth. *Tropic Subtropic Soil Sci*, 5(5): 67–73.