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Research Article

Responses of Carbon Dynamics to Nitrogen Deposition in Typical Freshwater Wetland of Sanjiang Plain

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The effects of nitrogen deposition (N-deposition) on the carbon dynamics in typical *Calamagrostis angustifolia* wetland of Sanjiang Plain were studied by a pot-culture experiment during two continuous plant growing seasons. Elevated atmospheric N-deposition caused significant increases in the aboveground net primary production and root biomass; moreover, a preferential partition of carbon to root was also observed. Different soil carbon fractions gained due to elevated N-deposition and their response intensities followed the sequence of labile carbon > dissolved organic carbon > microbial biomass carbon, and the interaction between N-deposition and flooded condition facilitated the release of different carbon fractions. Positive correlations were found between CO_2 and CH_4 fluxes and liable carbon contents with N-deposition, and flooded condition also tended to facilitate CH_4 fluxes and to inhibit the CO_2 fluxes with N-deposition. The increases in soil carbon fractions occurring in the nitrogen treatments were significantly correlated with increases in root, aboveground parts, total biomass, and their carbon uptake. Our results suggested that N-deposition could enhance the contents of active carbon fractions in soil system and carbon accumulation in plant of the freshwater wetlands.

1. Introduction

Interest in the impacts of nitrogen deposition (N-deposition) on ecosystem processes has increased in recent years because of the concerns that global change may alter their frequency and intensity [1]. Human activities, such as fossil fuel burning and land conversion, have elevated the atmospheric N-deposition, which has been shown to impact ecosystem production, diversity, and carbon cycling in consistent ways [2, 3]. N-deposition is habitual at middle and high latitudes, and the effects of N-deposition on forest ecosystems have been widely studied in humid regions [4, 5], but rarely in northern wetland ecosystems. Most studies found that N-deposition could stimulate the release of soil active carbon fractions and then increase the storage of carbon [6, 7]. However, the effects varied greatly with the duration, frequency, and intensity of N-deposition, edaphic characteristics, and other factors such as vegetation type and soil water content [8, 9]. The potential effects of N-deposition may include significant changes in the release and storage of active carbon, such as microbial biomass carbon, dissolved organic carbon, and labile carbon [10, 11]. Moreover, the study of active and labile carbon fractions can serve as a clue for soil organic carbon dynamics on a long-term exposure to elevated level of N-deposition.

In recent decades, nitrogen oxide exhausted from the fuel combustion and ammonia volatilized from the agricultural fertilization have increased the nitrogen concentration in the atmosphere. It was reported that the emission of reactive N has increased from $14\,\mathrm{Tg\,N\,yr^{-1}}$ in 1961 to $68\,\mathrm{Tg\,N\,yr^{-1}}$ in 2000 and is expected to reach $105\,\mathrm{Tg\,N\,yr^{-1}}$ in 2030 in Asia [12]. In the wetland of Sanjiang Plain, northeast China, N-deposition was measured at $7.6\,\mathrm{kg\,hm^{-2}\,yr^{-1}}$ during 2004-2005 [13]. The wetland in this region is always considered to be an important sink of carbon, and nitrogen is found to be a limited factor for the wetland plant and soil system [14]. Thus it is critical to address the effects of increasing N-deposition on the carbon dynamics in freshwater wetland, especially in northern China, where industry and agriculture have been increasing rapidly. Therefore this study was an attempt to quantify the variations of biomass and its carbon partitioning in different parts of plant and soil carbon changes under changes of N-deposition levels and water conditions.

Specifically, the objectives were to (1) perform a detailed examination of biomass and carbon partition in plant and its influence factors; (2) elucidate the wetland soil carbon dynamics with variations of N-deposition and water level; and (3) establish relationships between carbon fractions, carbon emission, and plant parameters.

2. Materials and Methods

2.1. Study Area and Soil Characterization. The Sanjiang Plain (43°49′55″~48°27′40″N, 129°11′20″~135°05′26″E) is a river basin illuviated by Heilong river, Songhua river, and Usuri river, which is the largest concentrative distribution area for freshwater marshes in northeast China. The experimental site is located at the Sanjiang Marsh Wetland Ecological Experimental Station, Chinese Academy of Sciences (47°35′N, 133°31′E). The average elevation of the study area is about 55.4–57.9 m with a gradient of 1/5000. The annual mean air temperature is 1.6–1.9°C and the highest and lowest temperatures occur in July and January, respectively. The average annual precipitation is 565–600 mm, of which more than 60% takes place from June to August, and the average annual evaporation is about 542–580 mm. Water and soil in the marsh are completely frozen from October to April and begin to thaw in late April. The vegetation types of natural wetland vary from *Calamagrostis angustifolia* (*C. angustifolia*) to *Carex lasiocarpa* as the standing water level increases. The type of soil here is meadow soil with 39.32% clay and 54.32% silt, and the average contents of total organic carbon and nitrogen are about 39.66 $\mathrm{g\,kg^{-1}}$ and 10.41 $\mathrm{g\,kg^{-1}}$, respectively.

2.2. Experimental Design. The experiments were conducted in *C. angustifolia* wetland ecosystem under four levels of N-deposition and two water conditions. In May of 2008, 10 cm height seedlings of *C. angustifolia* were selected as the test plant. All the treatments were applied to *C. angustifolia* meadow marsh soil transferred in layers from natural meadow marsh sites. According to the field density, 21 seedlings were grown in a pot (30 cm diameter, 40 cm height) with 10 kg weight soil. Nitrogen (N) treatment was applied to experimental pots under nonflooded (NF) and flooded (FD) conditions. According to the report by Sun et al. [15] that the total N-deposition amount in a year is 7.57 $\mathrm{kg\,hm^2}$, of which the ratio of inorganic and organic nitrogen is 5.47. The NH_4^+–N and NO_3^-–N are the main body of inorganic nitrogen whose proportion is 1.75 : 1, whereas N was applied mainly as NH_4Cl at 0 (distilled water only, N0), 1(N1), 3(N3), and 5 $\mathrm{g\,N\,m^{-2}\,yr^{-1}}$ (N5). Simulated N-depositions were made every 10–15 days during the growing season with NH_4Cl aqueous solution (purity 99.5%) in the form of spraying since early June from 2008 to 2009 (0.5 L water per pot a year), which is being divided into six times a year. During the whole experiment, the pot-culture experiment fields were sheltered with plastic cloth in the case of raining to prevent nitrogen from outflow.

2.3. Plant and Soil Sampling. Plant and soil parameters were recorded through destructive sampling in June, July, August, and September of 2008 and 2009. Dry matter yields (70°C in a hot air oven till constant weight) of stem and leaf (aboveground) and root were recorded, and their carbon contents were measured. Soil samples were collected from the topsoil (0–15 cm) of each pot. Four cores (2.54 cm diameter × 15 cm deep) were taken at each pot. The four soil cores from each pot were mixed to get one composite sample and delivered to laboratory immediately. Each composite sample was passed through a 4 mm sieve, and any visible living plant material (e.g., roots) was manually removed from the sieved soil. The CH_4 and CO_2 flux from marsh soil were taken through the revised static opaque chamber technique once or twice a week from June to September during the experiment periods. The sampling time was 30 min in the sunny morning after ten o'clock, and samples were collected with an injector with a 60 mL capacity, once in every 10 min [16] and determined within 12 h.

2.4. Determination. The soil that passed through 2 mm sieve and preserved at −4°C was used in the analysis of microbial biomass carbon (MBC) by fumigation-extraction method [17] and of dissolved organic carbon (DOC) by water extraction method [18]. Air dried soil samples (2 mm sieved) were used for determining the labile carbon (LBC) using 0.333 M $KMnO_4$ oxidization method [19]. Organic carbon (OC) was measured by potassium dichromate-sulfuric method, and total nitrogen (TN) was measured by the Kjeldahl method after digesting with sulfuric acid. The concentrations of CH_4 and CO_2 were measured with a gas chromatograph (Agilent 4890) equipped with a flame ionization detector (FID) [16].

2.5. Statistical Analysis. All treatments were replicated three times in the experiments and the values were the averages of determined results of the two years at the same period. The means and standard errors were calculated by the Microsoft Office Excel 2006. Multiple and stepwise regressions were performed to explore the extents of association of various carbon fractions (DOC, MBC, and LBC) with plant biomass and carbon assimilation parameters. When a significant difference was observed between treatments ($P < 0.05$ or $P < 0.01$), multiple comparisons were made using the LSD test. SPSS 11.5 (SPSS Inc., Chicago, IL, USA) software package was used.

3. Results

3.1. Biomass and Carbon Partition in Plant. Among N-deposition treatments, the aboveground net primary productivity (ANPP) was increased significantly at either 3 or 5 $\mathrm{g\,N\,m^{-2}\,yr^{-1}}$ level, especially under the flooded treatment (Table 1). The average increases in ANPP rates of the three N-deposition treatments were 5.83%, 13.99%, and 23.16% and 7.10%, 13.86%, and 22.83% under UF and FD conditions when compared with the control treatment. Particularly, N-deposition had significantly stimulated the accumulation of root biomass ($P < 0.05$), with the maximum increases 45.01% and 28.65% under UF and FD conditions, respectively, and the partition of root biomass was also increased with the

Table 1: The accumulation of biomass and carbon in *C. angustifolia* under N-deposition.

Part	N level	UF		FD	
		Biomass ($g{\cdot}m^{-2}$)	C content ($g{\cdot}kg^{-1}$)	Biomass ($g{\cdot}m^{-2}$)	C content ($g{\cdot}kg^{-1}$)
Aboveground	N0	131.21 ± 15.78^{a}	584.40 ± 25.15^{a}	$1\,173.87 \pm 17.32^{a}$	542.61 ± 16.56^{a}
	N1	138.85 ± 16.22^{a}	555.68 ± 11.45^{ab}	$1\,186.22 \pm 18.68^{a}$	526.06 ± 15.44^{ab}
	N3	149.55 ± 19.12^{a}	533.48 ± 9.45^{b}	$1\,197.97 \pm 15.76^{a}$	518.03 ± 18.59^{b}
	N5	161.58 ± 19.58^{a}	515.84 ± 13.26^{b}	213.57 ± 15.63^{a}	504.85 ± 15.37^{b}
Root	N0	115.25 ± 10.18^{a}	506.83 ± 5.02^{a}	114.93 ± 15.45^{a}	468.79 ± 7.68^{a}
	N1	129.07 ± 10.09^{a}	508.59 ± 4.73^{a}	138.46 ± 16.63^{a}	487.60 ± 7.73^{a}
	N3	135.75 ± 14.50^{ab}	523.36 ± 5.99^{ab}	144.69 ± 18.89^{a}	505.93 ± 4.53^{ab}
	N5	167.00 ± 32.19^{b}	548.37 ± 5.81^{b}	178.91 ± 17.88^{a}	533.44 ± 3.63^{b}
Total	N0	246.46 ± 22.43^{a}	568.79 ± 13.61^{a}	288.81 ± 27.53^{a}	540.19 ± 9.28^{a}
	N1	267.92 ± 22.41^{a}	537.03 ± 6.77^{a}	324.68 ± 35.81^{a}	516.11 ± 9.25^{a}
	N3	285.31 ± 32.43^{ab}	520.33 ± 4.79^{ab}	342.66 ± 56.76^{ab}	500.02 ± 10.79^{ab}
	N5	328.58 ± 48.21^{b}	511.29 ± 3.14^{b}	392.48 ± 52.46^{b}	483.54 ± 9.81^{b}

Notes: different letters meant significant difference ($P < 0.05$).

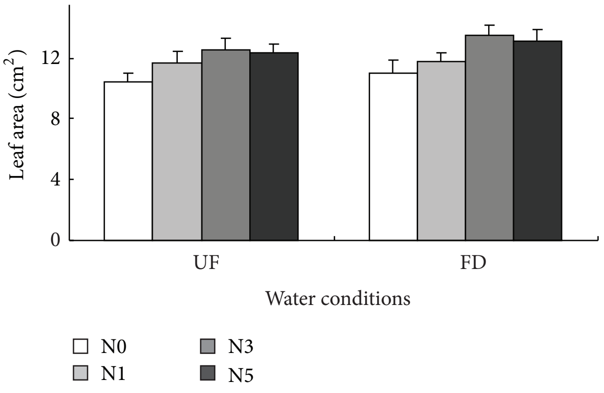

Figure 1: Effects of N-deposition on the leaf area of *C. angustifolia*.

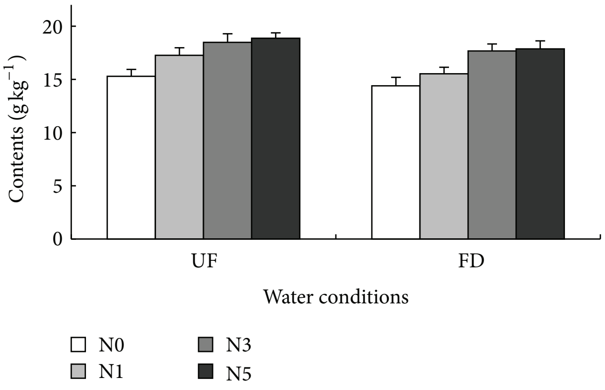

Figure 2: Effects of N-deposition on the leaf N content of *C. angustifolia*.

increasing N-deposition. The biomass in root approximately accounted for 11.99%–44.90% and 20.47%–55.67% of the total biomass under UF and FD conditions, respectively.

The aboveground and root carbon contents responded differently to N-deposition (Table 1). In particular, N addition decreased the aboveground carbon contents by 4.91%–11.73% and 3.05%–6.96% under UF and FD conditions, respectively. Contrarily, N-deposition increased the root carbon content by 0.94%–8.99% and 4.44–15.71% under UF and FD conditions, respectively, causing the preferential carbon allocation in root ($P < 0.05$).

3.2. Leaf Area and N Content. Leaf area and its N content in *C. angustifolia* also responded to N-deposition to different degrees as shown in Figure 1. Generally, the leaf area index (LAI) values under all three N treatments were higher than that of control, although in the 5 $g\,N\,m^{-2}\,yr^{-1}$ N treatment the increasing extent declined a little. The trends were also the same for leaf N content (Figure 2), in which increase rates of 14.14%, 19.86%, and 31.31% were detected for the three N treatments, respectively. There was significant correlation between ANPP and leaf area ($P < 0.01$), of which the stepwise regression is ANPP = 59.60 LAI − 222.57, $R^2 = 0.827$, $n = 30$. Moreover, the leaf N content was also significantly correlated with leaf area ($P < 0.01$).

3.3. Different Carbon Fractions in Soil. Soil different carbon fractions revealed significant increases with the increasing N-deposition under different water conditions ($P < 0.05$) (Figures 3, 4, and 5). When averaged over the growing season, MBC contents were increased gradually with the increasing N-deposition, and the increase rates were 16.30%–27.14% and 5.12%–17.76% under UF and FD conditions, respectively. Similarly, with the increasing N-deposition, DOC and LBC contents increased by 5.86%–23.34% and 2.01%–31.91% under UF and FD conditions, respectively.

The soil carbon fractions had significant seasonal changes under different N-deposition and water conditions. Maximum carbon variations were observed under N-deposition of 5 $g\,N\,m^{-2}\,yr^{-1}$ as shown in Table 2. No significant difference in the average content of MBC had been observed between June and July; however, from August remarkable increase in MBC content was observed and reached its maximum in

Table 2: The contents of wetland soil carbon fractions under N-deposition (mg·kg^{-1}).

Carbon fractions	Month	UF		FD	
		N0	N5	N0	N5
MBC	Jun.	166.7 ± 21.69	254.7 ± 26.28	204.0 ± 55.22	226.4 ± 23.27
	Jul.	178.9 ± 10.53	212.3 ± 10.72	178.9 ± 10.53	193.0 ± 12.28
	Aug.	242.1 ± 18.98	264.9 ± 23.83	215.8 ± 10.26	259.6 ± 18.68
	Sept.	268.4 ± 32.87	310.5 ± 17.94	258.4 ± 24.12	294.7 ± 12.91
DOC	Jun.	118.0 ± 0.61	199.2 ± 2.99	177.8 ± 0.61	196.9 ± 1.17
	Jul.	409.8 ± 6.25	439.1 ± 7.78	453.8 ± 7.63	481.8 ± 7.99
	Aug.	198.6 ± 3.12	229.2 ± 3.89	219.5 ± 3.81	249.5 ± 3.99
	Sept.	362.5 ± 5.62	398.4 ± 7.01	401.1 ± 6.87	439.9 ± 7.19
LBC	Jun.	546.7 ± 81.16	919.6 ± 46.23	813.6 ± 27.50	1330.6 ± 50.10
	Jul.	4513.2 ± 168.20	4184.8 ± 386.62	4481.4 ± 68.76	3902.9 ± 557.64
	Aug.	4246.2 ± 597.41	4559.8 ± 223.90	4100.0 ± 39.70	4839.5 ± 136.11
	Sept.	3381.7 ± 261.11	5420.1 ± 323.51	5447.6 ± 56.50	6104.4 ± 101.62

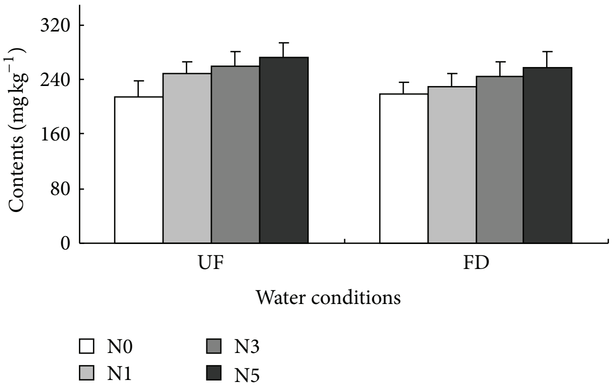

Figure 3: Effects of N-deposition on the wetland soil MBC.

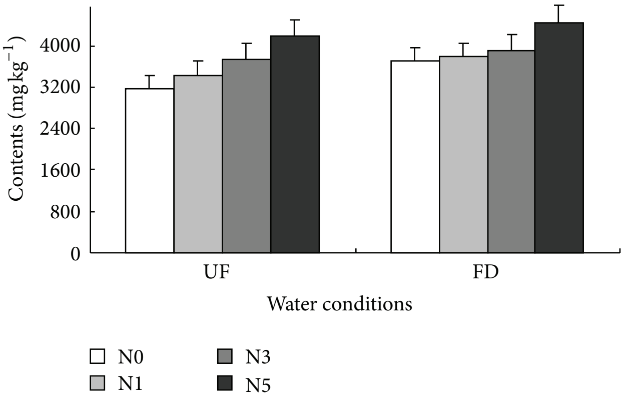

Figure 5: Effects of N-deposition on the wetland soil LBC.

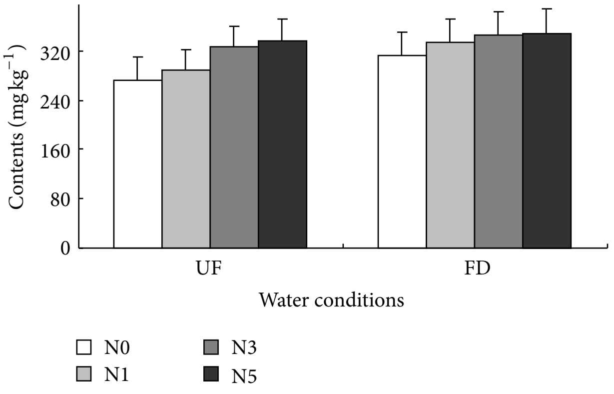

Figure 4: Effects of N-deposition on the wetland soil DOC.

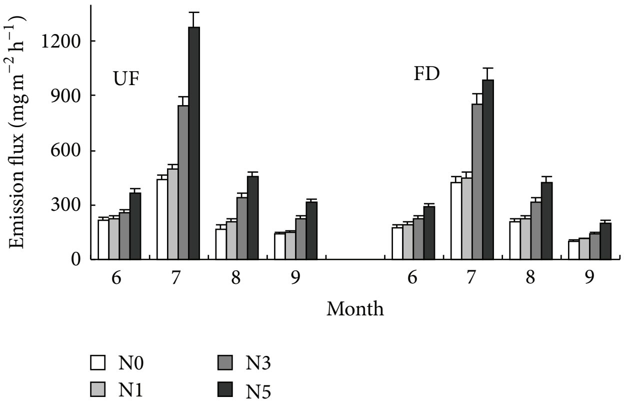

Figure 6: Effects of N-deposition on the wetland CO_2 emission.

September. The average content of LBC increased as the mature stage of *C. angustifolia* and reached its maximum in September. The seasonal dynamic of DOC was even more significant, which was higher in July and September and lower in June and August. N-deposition had significantly stimulated the release of MBC, especially in June ($P < 0.05$), and enhanced its seasonal change in return.

3.4. CO_2 and CH_4 Fluxes. N-deposition significantly facilitated CO_2 emission and its fluxes varied during the growing season, which reached the maximum at the *C. angustifolia* heading stage (July) as shown in Figure 6. During the growing season, the average increase of CO_2 fluxes was 3.70%–20.32%, 19.77%–100.92%, and 70.48%–193.08% with the N increasing

Table 3: The correlation of carbon fractions with plant parameters.

Variables	Formula	R^2
MBC	$MBC = 3.456A + 0.638B - 122.074$	0.361
DOC	$DOC = 30.519E - 41.171F + 29.904$	0.291
LBC	$LBC = 0.205C - 0.132D + 5.402$	0.694

A: root biomass, B: root carbon, C: total biomass, D: proportion of root biomass, E: aboveground biomass, F: aboveground carbon. $P < 0.05$.

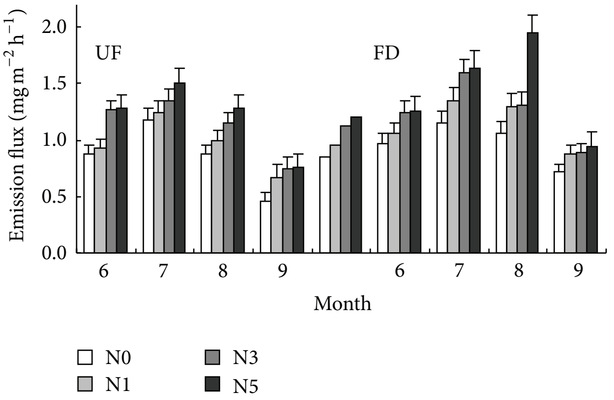

Figure 7: Effects of N-deposition on the wetland CH_4 emission.

N-deposition under UF condition, while those of CO_2 fluxes were 5.78%–11.73%, 26.46%–103.62%, and 61.38%–134.09% under FD condition. CO_2 fluxes were decreased from August to September and the increase rates of CO_2 flux made by N-deposition were also slowed down obviously. As the same seasonal rule of CO_2 emission, CH_4 emission fluxes from N treatments were also obviously higher than those of the control under different water conditions ($P < 0.05$) (Figure 7). The average increase rates of CH_4 fluxes were 5.95%–49.12%, 14.43%–64.60%, and 27.67%–69.03% with the increasing N-deposition under UF condition, while those of CH_4 fluxes were 9.25%–21.65%, 22.51%–38.79%, and 30.53%–83.49% under FD condition. Hence, the increase rates of CH_4 flux under FD condition were higher than those of UF condition when compared with increase rates of CO_2 flux.

3.5. Correlating Carbon Fractions with Plant Parameters. Stepwise regression analysis was carried out with the respective carbon fractions as dependable variables, to explore their dependence on various plant parameters (Table 3). No commonality of factors was observed among the carbon fractions. MBC depended directly on root biomass and carbon content ($R = 0.601$, $P < 0.05$). DOC was positively correlated with the aboveground biomass and its carbon content ($R = 0.540$, $P < 0.05$). Predictability of LBC was highest ($R = 0.833$, $P < 0.05$) and the values were found to be positively correlated with total biomass and negatively correlated with root biomass. Carbon fractions were also correlated with each other, and the content of LBC was significantly correlated with DOC and MBC ($R = 0.785$, $P < 0.05$), while MBC showed negative correlations with DOC ($R = 0.599$, $P < 0.05$). The CO_2 emission (E_{CO_2}) was significantly correlated with MBC and DOC ($E_{CO_2} = 5.052\ MBC + 0.980\ DOC - 1184.98$, $R^2 = 0.805$, $P < 0.05$), and CH_4 emission (E_{CH_4}) was also significantly correlated with MBC and DOC ($E_{CH_4} = 0.002\ MBC + 0.006\ DOC - 1.123$, $R^2 = 0.872$, $P < 0.05$).

4. Discussion

Different nitrogen deposition types will demonstrate different effects to the ecosystem; thus many studies have attempted to elucidate the effects of rate of N-deposition types on soil organic matter decomposition, but the effects of the dominant N form have been seldom addressed [20]. In fertilization experiments, N is usually applied as NH_4NO_3 [21]. Yet, the ratio of ammonium (NH_4^+) to nitrate (NO_3^-) ranges from 1 : 4 to 3 : 1 and shows spatial heterogeneity. Ammonium is dominant when fertilizer inputs are high, while nitrate is actively generated when combustion of fossil fuels occurs [20]. As NH_4^+ and NO_3^- have different biochemical characteristics (e.g., biological preference and ionic charge), the abundant ion may determine the direction of organic matter mineralization. For example, NH_4^+ is preferred to NO_3^- by microorganisms due to the low energy cost, implying stimulated decomposition with NH_4^+ additions [22]. In line with this, microbial respiration increased in a corn-rye rotation field after NH_4^+ treatment [23]. In our research region, Sun et al. [15] reported that the total N-deposition amount in a year is 7.57 kg hm^2, and the ratio of inorganic and organic nitrogen is 5.47. Moreover, NH_4^+–N and NO_3^-–N are the main body of inorganic nitrogen, and the ratio of them is 1.75. This is mainly due to that the regions have experienced an intensive reclamation over the past 50 years with the population growth and migration. Most of the virgin marshland has been converted, resulting in the increase of cultivated land from about 8.2×10^5 hm^2 in 1949 to 5.24×10^6 hm^2 at present [24] and subsequently causing the extensive utilization of fertilizer. Therefore NH_4^+–N deposition has the preferential ecological effect to the soil carbon transformation.

Increases in ANPP under simulated atmospheric N-deposition have already been reported [25, 26] and were observed in our field experiment. Measurements of leaf area and leaf N content demonstrated significant changes in response to N-deposition, and there was significant correlation between ANPP and leaf area ($P < 0.01$); thus, an increase in leaf area might be the factor driving the increase in ANPP for the N-deposition treatment. The roots, while metabolically active, could contribute to the active carbon fractions like DOC (through exudation and secretion) and MBC (indirectly through greater supply of substrates in rhizosphere)

[11]. The increase of biomass and carbon sequestration caused by N-deposition had been verified in many researches, which had attracted extensive attention. As shown in the results of many N addition researches [27], the input of N would improve the net primary productivity of plant, which prior to that other nutrients become limiting factors. Jiang et al. [28] had found that the biomass of weed (total biomass, aboveground biomass, and root biomass) was increased under N-deposition treatment, which was also true for freshwater wetland plants, and certain level of N addition could enhance the carbon accumulation in plant.

The effects of N-deposition on the allocation of biomass and carbon in plant had already been investigated [29], of which results showed that the leaf-weight ratio of seedlings of *Schima superba* and *Cryptocarya* was higher under higher N treatment, which indicated that the biomass allocated to branches and stems increased under higher N-deposition, while the ratio of biomass allocated to root was decreased with the increasing N-deposition. Generally, it was believed that soil carbon distribution had positive correlations with the utilization rate of mineral N [30], and higher nitrogen addition would ensure the increasing of root biomass. However, different species showed different responses to simulated N-deposition. For instance, the root biomass of *Veronica didyma* decreased significantly ($P < 0.05$), while no obvious effect of N-deposition had been found in the root of *Poa annua* and *Amaranthus spinosus*, and the root biomass of *Lolium perenne* and other seven species all increased significantly ($P < 0.05$). Our results showed that the root biomass of *C. angustifolia* was significantly enhanced by N-deposition ($P < 0.05$) and the increased apportioning of biomass to root was of major significance.

Increases in soil active carbon fractions due to elevation in nitrogen addition had been reported by several works [31, 32] and were ascribed to the increases in nitrogen utilization rate and microbial activity, where a positive correlation between soil active carbon fractions and precipitation was observed ($R = 0.677$, $P < 0.001$) [32]. The DOC is primarily associated with low molecular-weight water-soluble carbohydrates and amino acids [33]. This fraction can be expected to leak more from the young root cells without secondary cell wall. Hence, the DOC pool increased in size as the plant growth and carbon allocation of root were enhanced by N-deposition in July and then decreased as the root matured. Nitrogen addition could also increase the contents of soil light fraction organic carbon and dissolved organic carbon, which implied that nitrogen addition would have critical functions in the management of soil active carbon fractions [32]. The MBC is a measure of carbon associated with living microbes and exhibited great seasonal change. Increased availability of nutrient simulated by N-deposition had improved the plant growth in summer and intensified the competition of nutrient between plant and microbes, which imposed great restriction on the growth of microbes and caused MBC decrease when compared with the corresponding values under control treatment, while, in autumn the nutrient fixed by microbes increased with the increase of litter under N-deposition, which led to significant increase of MBC. For instance, it had been found that the application of nitrogen addition could increase the content of MBC by 9.6%, and there were significant correlations between the contents of microbial carbon, labile carbon, mineralized carbon, and nitrogen contents [34]. As the liabilities of active carbon fractions, the changes of these fractions are expected to impart short- to medium-term effect on soil C-sequestration [32].

The response of soil carbon fractions to N-deposition was basically consistent under different water conditions [8, 9]. Except that MBC declined under flooded condition, the releases of other carbon fractions were all enhanced, which implied that the growth of microbes was constrained under flooded condition. The effect of water condition on the release of soil different carbon fractions in our studies was also observed; the contents of DOC and LBC were higher under flooded condition, of which the increase extents followed the sequence of DOC (11.39%) > LBC (19.70%). The carbon fractions increase rates of the study soil followed the order of MBC (16.68%) > LBC (13.94%) > DOC (12.76%). However, the order was not seemingly following the sequence of the decreasing liability of carbon fractions as described by Kant et al. [35], which meant that the response of active carbon fractions to the N-deposition elevation would depend on their relative liabilities. The results indicated that N-deposition had significantly enhanced the contents of soil active carbon fractions, which might be directly correlated to the increase of the root carbon allocation. Therefore, it could be concluded that some differences must exist between the sensitivities of soil active carbon fractions to the elevated atmospheric N-deposition, as well as water levels and vegetation and soil types.

Atmospheric CO_2 assimilated by photosynthesis evolves by ecosystem respiration from metabolic activity of plant and soil microbes. Changes in ecosystem respiration under global changes (i.e., CO_2 and N-deposition elevation) may affect the function of wetland ecosystem as sinks or sources of atmospheric CO_2. A previous study suggested that increases in water and nitrogen supplies significantly stimulated CO_2 emissions by 47%–70% ($P < 0.01$) but did not significantly change CH_4 uptake during the growing season in degraded plots [36]. These conditions generally promoted autotrophic plant respiration including both above- and belowground parts [37] as well as rhizosphere respiration by microbes due to the accelerated decomposition of soil organic matter [38]. Our study showed that ecosystem respiration rates in the freshwater wetland were closely related to both water condition and nitrogen deposition (Figure 6). The highest increase in respiration rate occurred in the treatment with both N-deposition and unflooded condition. In addition, under the synergistic effect of dry-wet cycles or unflooded condition, the N-deposition induced strong CO_2 emission (from July to August) in all N treatments.

Generally, the nitrogen addition could inhibit the uptake of CH_4 in soil [39]. N-deposition accelerated the microbial anaerobic decomposition of organic matter and thus promoted the CH_4 generation. The previous research showed that N-deposition decreased CH_4 oxidation by 15.3% [40, 41], and the decreasing magnitude of CH_4 oxidation was much larger than that of CO_2 emission (15.3% for CH_4 and only 2.33% for CO_2) owing to the fact that methanotroph might be more susceptible to the nitrogen deposition than other soil microbes relating to CO_2 emissions [42]. Our study also showed a similar trend that the average increase in rates of CH_4 was 3.84% higher under the unflooded treatment than that of flooded treatment, which was lower than the increase in CO_2 emission rate. It indicated that flooded condition could inhibit aerobic microbial respiration, leading to higher CH_4 fluxes and lower CO_2 fluxes. The main reasons were that ${NH_4}^+$ is a competitive inhibitor of CH_4 oxidation due to lack of specificity of methanotroph, and osmotic stress caused by added nitrogen salt can suppress the activity of methanotroph [42].

Among all factors associated with soil CO_2 and CH_4 fluxes, DOC could be considered as the primary factor regulating the seasonal variation of soil microbial activity, which, in turn, controls the CO_2 emission from the soil. DOC has been proposed as an indicator of the carbon availability to soil microorganisms [43]. It is assumed that all the dissolved substances are labile and utilized rapidly [18]. So, there is often a reasonably good correlation found between the concentration of DOC and soil CO_2 flux [44]. Simultaneously, N-deposition could increase soil organic matter, which directly increased the substrates for CH_4 production and indirectly decreased the capacity of CH_4 oxidization [40]. In this study, the release of CO_2 emission was significantly correlated with MBC and DOC ($R = 0.897$, $P < 0.05$), while CH_4 emission also was significantly correlated with MBC and DOC ($R = 0.934$, $P < 0.05$). The results also showed that the contents of MBC and LBC attained their peaks at the plant heading stage, which were in accordance with the changes of N-deposition effects on CO_2 and CH_4 fluxes.

5. Conclusion

N-deposition can lead to changes in net primary production and its carbon contents, soil carbon fractions, and carbon gases emission from soil. Furthermore, N-deposition had the potential to increase carbon storage in both the biomass and soil of the *C. angustifolia* wetland ecosystem in Sanjiang Plain, northeast China. The increase in ANPP was likely to be driven by higher rates of photosynthesis from the increase of leaf area, while the stimulation of soil active carbon release under N-deposition treatments appeared to be driven by the increase of root biomass allocation, which would constrain the decomposition of inherent organic carbon and enhanced the storage of soil organic carbon. Different soil carbon fractions were elevated within chronic N-deposition, and the interaction between N-deposition and the flooded condition could facilitate the release of different carbon fractions. N-deposition significantly promoted microbial activity and utilization of carbon substrates, which was the main driver for changes in soil DOC and LBC amount and their composition. The ecosystem respiration rates and CH_4 fluxes in the freshwater wetland were closely related to both water condition and N-deposition, and the flooded condition tended to facilitate CH_4 fluxes and to inhibit the CO_2 fluxes with N-deposition. Overall, these results suggested that although increasing N-deposition would increase the carbon accumulation through plant but adversely could stimulate soil microbial metabolic activity and thus deplete the accumulation of soil organic carbon in the freshwater wetland. Therefore, it is indispensable to get the critical value of N-deposition that would stimulate the fixation of carbon in the management of wetland preventing more emission of carbon gases from the soil.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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