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Four years of free-air CO_2 enrichment enhance soil C concentrations in a Chinese wheat field

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Abstract

Elevated atmospheric CO_2 can influence soil C dynamics in agroecosystems. The effects of free-air CO_2 enrichment (FACE) and N fertilization on soil organic C (C_{org}), dissolved organic C (DOC), microbial biomass C (C_{mic}) and soil basal respiration (SBR) were investigated in a Chinese wheat field after expose to elevated CO_2 for four full years. The results indicated that elevated CO_2 has stimulative effects on soil C concentrations regardless of N fertilization. Following the elevated CO_2, the concentrations of C_{org} and SBR were increased at wheat jointing stage, and those of DOC and C_{mic} were enhanced obviously across the wheat jointing stage and the fallow period after wheat harvest. On the other hand, N fertilization did not significantly affect the content of soil C. Significant correlations were found among DOC, C_{mic}, and SBR in this study.

Key words: dissolved organic C; free air CO_2 enrichment; microbial biomass C; N fertilization; soil basal respiration; soil organic C

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Introduction

With increasing global industrialization, the concentration of atmospheric CO_2 has increased by 32% in last 250 years (Nowak *et al*., 2004), which have significant effects on the C cycling in terrestrial ecosystems (van Groenigen *et al*., 2006; Prior *et al*., 2008). Understanding the response of soil C dynamics to high atmospheric CO_2 concentrations is critical for evaluating the potential for soil C sequestration on time scales of decades to centuries (Pendall *et al*., 2001).

Since free-air CO_2 enrichment (FACE) exposure systems nearly completely overcome the problem of microclimatic artifacts during exposure (Erbs and Fangmeier, 2006), most recent studies focused on the effects of elevated CO_2 on soil C and N dynamics by means of FACE technology. The studies indicated that elevated CO_2 increased the concentrations of total organic C, microbial biomass C (C_{mic}) and stimulated soil respiration in cropland, grassland and forest ecosystems (Pendall *et al*., 2001; Dijkstra *et al*., 2005; Moscatelli *et al*., 2005; Prior *et al*., 2008). Using meta-analytic techniques, van Groenigen *et al*. (2006) studied the effect of elevated CO_2 on soil C dynamics between several levels of ecosystem management, and concluded that soil organic C (C_{org}), soluble C, C_{mic} and microbial respiration at elevated CO_2 increased by 4.1%, 9.4%, 8.5% and 18.0%, respectively, compared to those at ambient. So far, there is little information about the effect of elevated CO_2 and N fertilization on soil C dynamics of rice-wheat rotation ecosystems.

Therefore, the aim of this study was to investigate the responses of C_{org}, dissolved organic C (DOC) and C_{mic} to free-air CO_2 enrichment and N fertilization in the wheat growing season of a rice-wheat rotation ecosystems (transplanting rice in mid-June and harvest in October, then sowing wheat in early November and harvest in early June in the following year), which has been fumigated with elevated atmospheric CO_2 for four full years.

1 Materials and methods

1.1 Experimental site and design

The experimental site is located in a suburb of Jiangdu in Jiangsu of China (32°35′N, 119°42′E). The soil at the study site is Shajiang-Aquic Cambosols, with 18.4 g/kg total C, 1.5 g/kg total N, pH (H_2O) 7.2 (Yang *et al*., 2009), 13.7% clay and bulk density 1.16 g/cm^3. A randomized complete block design was established with two levels of target atmospheric CO_2 concentration over the rice-wheat rotation system. It consisted of three replicate rings for the elevated CO_2 (hereinafter referred to as FACE) and three for the ambient CO_2 (hereinafter referred to as ambient). The atmospheric CO_2 of each FACE ring was

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enriched by 200 μmol CO_2/mol on average the ambient (370 μmol CO_2/mol). In each FACE and ambient plot, two levels of N fertilization were applied in each sub-plot, and ammonium-based nitrogen fertilizer was applied in wheat season at the rates of 350 and 174 kg N/ha (Li *et al*., 2009). The FACE experiment including four different treatments was established in 2004. Our study was conducted during the wheat growing season of 2008.

1.2 Soil sampling and analysis

Soil samples were collected from 0–15 cm depth in each plot on March 18 at wheat jointing stage (JS) and on June 8 during the fallow period after wheat harvest (FP) in 2008. Each soil sample pooled from five soil cores (2.5 cm diameter) was stored in individual plastic bag. Thereafter, two sub-samples were prepared. One sub-sample was air-dried and then passed through a 2-mm sieve for soil pH, C_{org} and total N measurements, the other was kept at 4°C until the analysis of DOC, C_{mic} and soil basal respiration (SBR). C_{org} and total N contents were determined by an Element Analyzer (Elementar, Vario EL III, Germany). Soil pH was measured at a 1:2.5 (*W/V*) ratio of soil to distilled water. C_{mic} was determined according to chloroform-fumigation-extraction (CFE) method (Vance *et al*., 1987). The fumigated and non-fumigated soils were extracted with 0.5 mol/L K_2SO_4 and the extracts were analyzed for C using an automated TOC analyzer (Multi N/C 3000, Analytik Jena AG, Germany). C_{mic} was determined based on the difference between C extracted from fumigated and unfumigated soil samples, using a conversion factor (K_e) of 0.45. Basal respiration was determined by placing 30 g of field moist soil in a 50 mL beaker and incubating the sample for 10 d in the dark at 25°C in a 1 L airtight sealed jar with 10 mL of 1 mol/L NaOH. The CO_2-C evolved was determined after 2, 5 and 10 d by titration (Anderson, 1982). Basal respiration rate was calculated based on cumulative CO_2 evolution over the 10-d period.

Two two-way ANOVA were applied separately for the two sampling dates to test the effects of elevated atmospheric CO_2 and N fertilization on soil C. Statistical analyses were performed using SPSS statistical software (SPSS Inc., Chicago, USA). Differences with P < 0.05 were considered significant.

2 Results and discussion

2.1 Soil organic carbon

Soil organic C is not only one of important indicators of soil fertility, but its sequestration also plays an important role in alleviating increasing atmospheric CO_2 concentrations (Post *et al*., 2004). In our study, significant elevated CO_2 effects on C_{org} were only found at JS (P < 0.01), and no significant effect of N fertilization was observed during two periods (Table 1). The values of C:N ratio of the soil were significantly higher under FACE than under ambient at JS (P < 0.05), but significantly lower under high nitrogen (HN) than under low nitrogen (LN) in both periods (P < 0.05) (Table 1). Under LN and HN, C_{org} increased by 11.4% and 9.8% at elevated CO_2, respectively (Fig. 1). The result was consistent with previous study by Prior *et al*. (2008), in which C_{org} at the 5–10 cm depth under dry treatment increased significantly by 11.8% at elevated CO_2 in an American sorghum field.

C_{org} was negatively correlated with pH (r = –0.469, P < 0.05), and positively with soil C:N ratio (r = 0.771, P < 0.01). The obtained results indicated that soil C_{org} and pH were synchronously affected by the elevated CO_2 at JS. An elevated CO_2 can increase soil C_{org} content mainly via increasing plant photosynthesis, production and allocation of photosynthate to below ground components, and thus increasing C input into soils (Xie *et al*., 2005) and reducing soil pH by increasing CO_2 partial pressure in soil solution (Wang *et al*., 2008) or by enhancing plant root exudates containing certain acid substances especially organic acids (Diaz *et al*., 1993; Berntson and Bazzaz, 1996).

Table 1 Soil C dynamics under ambient or elevated CO_2 of two nitrogen levels at the wheat jointing stage (JS) and the fallow period after wheat harvest (FP)

Period	Indicator	Low nitrogen (LN)		High nitrogen (HN)		Effect		
		Ambient	FACE	Ambient	FACE	C	N	C×N
JS	pH	6.89 ± 0.06	6.47 ± 0.07	6.55 ± 0.05	6.26 ± 0.16	**	**	ns
	C_{org} (mg/g)	11.13 ± 0.31	12.60 ± 0.50	11.07 ± 0.47	12.27 ± 0.32	**	ns	ns
	Total N (mg/g)	1.22 ± 0.07	1.24 ± 0.06	1.32 ± 0.04	1.35 ± 0.04	ns	**	ns
	C:N	9.17 ± 0.71	10.20 ± 0.78	8.33 ± 0.15	9.10 ± 0.36	*	**	ns
	DOC (μg/g)	120.62 ± 9.49	149.27 ± 2.28	118.56 ± 12.99	146.66 ± 9.13	**	ns	ns
	C_{mic} (μg/g)	268.60 ± 28.38	329.38 ± 19.82	254.28 ± 21.42	344.15 ± 51.35	**	ns	ns
	SBR (μg CO_2/(g·d))	5.30 ± 0.97	6.57 ± 0.54	5.20 ± 0.93	6.56 ± 0.45	*	ns	ns
FP	pH	6.68 ± 0.15	6.31 ± 0.05	6.33 ± 0.02	6.21 ± 0.07	**	**	*
	C_{org} (mg/g)	11.13 ± 0.81	12.20 ± 0.60	11.13 ± 0.89	12.10 ± 1.02	ns	ns	ns
	Total N (mg/g)	1.17 ± 0.02	1.21 ± 0.03	1.31 ± 0.02	1.31 ± 0.03	ns	**	ns
	C:N	9.50 ± 0.80	10.13 ± 0.67	8.50 ± 0.61	9.23 ± 0.67	ns	*	ns
	DOC (μg/g)	222.54 ± 30.14	281.04 ± 22.82	205.36 ± 16.98	286.15 ± 23.25	**	ns	ns
	C_{mic} (μg/g)	686.99 ± 30.45	796.36 ± 19.82	684.17 ± 25.91	808.85 ± 70.19	**	ns	ns
	SBR (μg CO_2/(g·d))	16.61 ± 3.02	16.49 ± 0.87	16.62 ± 2.72	16.63 ± 1.08	ns	ns	ns

C_{org}: soil organic C; DOC: dissolved organic C; C_{mic}: microbial biomass C; C_{mic}/C_{org}: microbial quotient; SBR: soil basal respiration. C: effect of elevated CO_2; N: N fertilization effect; C×N: the interactions of elevated CO_2 and N fertilization.
Data are expressed as mean ± SD.
**P < 0.01; *P < 0.05; ns: non-significant (P > 0.05).

2.2 Soil dissolved organic C

Soil dissolved organic C (DOC) is thought to be an important labile C fraction since it is the main energy source for soil microorganisms and a primary source of mineralizable N, P and S, and it commonly responds rapidly to environmental changes (Zhang *et al*., 2007). In this study, significant elevated CO_2 effects on DOC were found at both JS and FP ($P < 0.01$), but no significant N fertilization effect was observed. Under LN and HN, DOC increased significantly by 25.0% and 31.5% at elevated CO_2, respectively (Fig. 1). With larger change magnitude than total organic C, the DOC tended to be more sensitive to elevated CO_2. These positive effects were lower than that determined by Kang *et al*. (2001) who observed 49.1% increase of DOC at elevated CO_2 in a peatland of north Wales. The differences may be caused by the different soil types, crop species and CO_2 exposure duration.

The continuous elevated CO_2 will possibly lead to significant effects on DOC. Newton *et al*. (1994) found considerably more root biomass at elevated CO_2. Other observations (van Ginkel *et al*., 1996) further confirmed that more root material input might increase the process of assimilatory under elevated CO_2. Soil with an actively growing root system and a highly active soil microbial biomass may stimulate DOC. Hussain *et al*. (1999) found that N supply of 120 kg N/ha is sufficient for growth and development of wheat. Therefore, the two N levels, 350 and 174 kg N/ha, designed as normal and low N supply in our experiments, are practically super-optimal for local wheat growth and development. No significant N fertilization effect on DOC (Fig. 1) may be due to that N nutrient is practically excessive for growth and development of wheat under normal N supply.

2.3 Soil microbial biomass C

Soil microbes play a key role in recycling of plant nutrients, maintenance of soil structure, detoxification of noxious chemicals, and the control of plant pests and plant growth (Elsgaard *et al*., 2001; Filip, 2002). Many studies have reported that changes in soil microbial biomass and activity gave early indication of environmental change (Livia and Frank, 2006). An understanding of microbial biomass and activity in response to belowground processes induced by elevated CO_2 is thus crucial to predict the long-term response of ecosystems to climatic changes (Moscatelli *et al*., 2005). According to our results, C_{mic} showed a similar trend with DOC during the study period. Under LN and HN, C_{mic} increased significantly by 19.3% and 26.8% at elevated CO_2, respectively (Fig. 1). These results were in accordance with those of Moscatelli *et al*. (2005), who reported that in an Italian poplar plantation soil C_{mic} increased by a 16% under elevated CO_2.

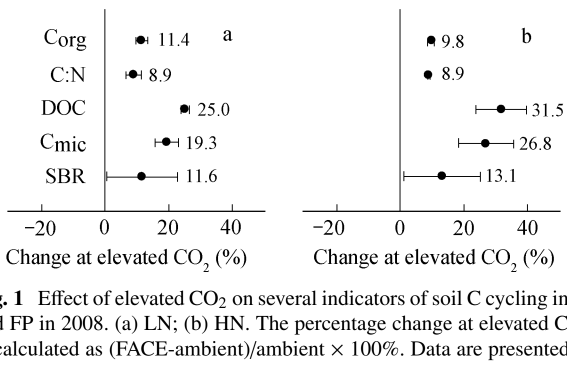

Fig. 1 Effect of elevated CO_2 on several indicators of soil C cycling in JS and FP in 2008. (a) LN; (b) HN. The percentage change at elevated CO_2 is calculated as (FACE-ambient)/ambient × 100%. Data are presented as mean ± SE.

Significant elevated CO_2 effect on SBR was observed at JS ($P < 0.01$), but not at FP. No significant N fertilization effect on SBR was observed during the wheat growing season. Under LN and HN, SBR increased by 11.6% and 13.1% at elevated CO_2, respectively (Fig. 1). These results were lower than those observed by Pendall *et al*. (2001), who found that FACE increased soil respiration rate by 38% during the peak of wheat growth in USA in 1997.

The main reason for above results might be that elevated CO_2 can significantly increase root biomass and root tissue turnover, thereby increase the flux of energy and nutrients available for microbial biosynthesis (Zak *et al*., 2000). As reported by Körner and Arnone (1992), elevated CO_2 may stimulate microbial biomass production because of increasing C input into the rhizosphere, which will enhance the decomposition of soil organic matter, with a positive feedback on plant growth by releasing the necessary nutrients. Bernhardt *et al*. (2006) also found that elevated CO_2 increase the C allocation rate to the roots, which led to the activity of soil microorganisms and enhance SBR significantly.

C_{mic} was positively correlated with SBR (r = 0.887, $P < 0.01$) and DOC (r = 0.941, $P < 0.01$) which was in line with those of Sowerby *et al*. (2000), who reported that the increase in microbial biomass was responsible for the increase in respiration of soils exposed to elevated CO_2 concentration. DOC was proposed as an indicator of the C available to soil microorganisms (Smolander and Kitunen, 2002). The close relationship between C_{mic} and DOC was reported by many researchers, such as Zhang *et al*. (2007), who observed that C_{mic} was positively correlated with DOC with a correlation coefficient of 0.99 under an abandoned cultivated wetland in Northeast China.

3 Conclusions

Results from this study demonstrated that elevated CO_2 significantly increased C_{org} and stimulated SBR at wheat jointing stage after a 4-year exposure. Elevated CO_2 significantly enhanced the concentrations of DOC and C_{mic} at wheat jointing stage and during the fallow period after wheat harvest. The N fertilization exhibited no significant effect on soil C dynamics during the study period. These results suggested that elevated CO_2 has stimulative effects on soil C concentrations regardless of N fertilization.

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