Effects of plant-derived dissolved organic matter (DOM) on soil CO₂ and N₂O emissions and soil carbon and nitrogen sequestrations

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ABSTRACT

Dissolved organic matter (DOM) in soils play an essential role in soil physical, chemical and biological processes, but little information is available on the biodegradability of plant-derived DOM and its effect on soil carbon and nitrogen sequestration in field soils. The objectives of this study were to investigate the impacts of crop residue-derived DOM on soil CO₂ and N₂O emissions, as well as soil carbon and nitrogen sequestration by adding water extracts of maize stalk (i.e., plant-derived DOM) to soils. In this study, wheat was grown in pots under field conditions with treated soils, the soils treatments were: plant-derived DOM (PDOM), urea nitrogen (N), PDOM + urea nitrogen (PDOM + N), as well as a control with no additions to soil (CK). Adding plant-derived DOM to soil increased soil CO₂ and N₂O emissions ($P < 0.05$). During the wheat growing season, the cumulative CO₂-C emission from CK, PDOM, N and PDOM + N was 107 ± 1 , 157 ± 7 , 136 ± 2 and 149 ± 6 g C m⁻², respectively. Meanwhile, the cumulative N₂O-N emission from CK, PDOM, N and PDOM + N was 188 ± 8 , 256 ± 5 , 239 ± 10 and 258 ± 7 mg N m⁻², respectively. Compared with N treatment, DOM addition had little effect on soil N sequestration, but it accelerated the decomposition of native soil organic carbon (SOC) and caused a net loss of SOC. The soil C sequestration decreased about 151 ± 67 and 51 ± 45 g C m⁻² in PDOM and PDOM + N treatments, respectively. The increased microbial biomass and root biomass were responsible for the greater CO₂ emission in DOM-amended soils. Negative correlation between dissolved organic carbon (DOC) content and N₂O flux suggested that the release of N₂O was dependent on the supply of DOC. These results indicated that the supply of plant-derived DOM exacerbated soil CO₂ and N₂O emissions and reduced soil C sequestration. Therefore, agricultural management practices that increase the stability of highly soluble C inputs and/or retard the decomposition of crop residues should be adopted to decrease soil greenhouse gas emission and increase soil C sequestration.

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1. Introduction

Dissolved organic matter (DOM) is readily decomposable and can be preferentially utilized by the microorganisms than the recalcitrant fraction of SOC (Cleveland et al., 2004, 2007; Ghani et al., 2013; Kalbitz et al., 2003). It is estimated that about 3.8×10^9 Mgyr⁻¹ of total crop residues are produced in global agricultural ecosystems (Thangarajan et al., 2013), and large quantities of crop residues are retained in soils every year

(Rochette and Gregorich, 1998). The litter-derived soluble organic carbon accounts for 5–15% of the total C content, which corresponds to 5–25% of the litter biomass (Cleveland et al., 2004). The plant-derived DOM represents a major source of soil DOM (Kalbitz et al., 2000), while adding this kind of soluble organic matter to soil may lead to an increase in microbial activity and subsequently accelerate the turnover of SOC through priming effect (PE) (Derrien et al., 2014; Fontaine et al., 2004; Kuzyakov et al., 2000; Paterson and Sim, 2013). The PE is generally neglected in soil C balance calculation because it is commonly accepted that the PE is temporary leading to small soil C losses (Kuzyakov et al., 2000). However, recent studies have shown that the PE could persist several months after the complete decomposition of added fresh organic matter, and having a marked effect on the final C

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balance (Fontaine et al., 2004, 2011). Some studies, based on positive priming effect, stated that organic amendments were not favorable for soil C sequestration (Ding et al., 2010). This is unjustified since they did not consider the amount of added C remaining in the soil (Kuzaykov, 2010). Although many previous studies have observed that DOM can be rapidly decomposed by microbes (Chantigny, 2003; Kalbitz et al., 2000), a few studies have reported that DOM is comprised of a rapidly decomposable fraction with a turnover rate of <1–5 days (Gregorich et al., 2003; Usselman et al., 2000), and a slowly decomposable fraction with a turnover rate of between 80 days and 9 years (Gregorich et al., 2003; Kalbitz et al., 2003). The slowly mineralized fraction of DOM contributes to the accumulation of slowly mineralized C in the soil (Neff and Asner, 2001; Qualls and Bridgman, 2005). Therefore, both the DOM-C input from crop residues and the CO₂-C output from organic matter mineralization should be taken into account to determine the net effect of residue-derived DOM on soil C balance.

Many studies on the biodegradation of DOM were conducted in forest ecosystems (Cleveland et al., 2004; Kalbitz and Kaiser, 2008; Kalbitz et al., 2003; Qualls and Haines, 1992), yet very few studies have been performed in agricultural ecosystems, and moreover, these studies were only conducted in laboratory environments. For example, Kalbitz et al. (2003) extracted DOM from 13 different samples (maize straw, forest floors, peats, agricultural soils) to investigate the biodegradation in a 90-day solution culture. They found that 89% and 17–32% of the DOM derived from maize straw and agricultural soils were mineralized at the end of the experiment, respectively. Cleveland et al. (2004) used both live foliage and senesced litter from temperate and tropical ecosystems to investigate the decomposition of plant-derived DOM in a 100-day solution culture. They observed that more than 70% of the initial litter-derived DOM was decomposed in the first 10 days. Chen et al. (2014) also reported that 28.7–35.7% of the initial rice plant-derived DOM was mineralized in 100 days incubation. However, these studies on the biodegradability of plant-derived DOM were conducted in solution cultures without the soils. These results may not reflect the biodegradability of plant-derived DOM in the presence of soils, since soil microorganisms as well as soil physical sorption and desorption can affect the fate of DOM in the soil (Kalbitz and Kaiser, 2008; Kalbitz et al., 2000). Moreover, the environmental conditions varies in the field, and the responses of the biodegradation of DOM to the external environmental changes remain unknown in the agricultural ecosystems. Therefore, the laboratory findings await verification under field conditions especially with growing crop.

It is estimated that about $7 \times 10^8 \text{ Mg yr}^{-1}$ of crop residues (equivalent to $5.3 \text{ t ha}^{-1} \text{ yr}^{-1}$) is produced in China (Bi et al., 2009; Gong et al., 2012). Incorporation of crop residues directly to soil will be the major way of crop residues management by using the combine harvest in future farming practices. A flush of DOM into soil may occur following the input of crop residues (Cleveland et al., 2004; Kalbitz et al., 2003), especially when the environmental conditions are favorable for the decay (Thangarajan et al., 2013). Such a high rate of plant-derived DOM incorporated in soils may activate microorganisms and accelerate SOC decomposition through priming effect. It remains unclear whether the amount of CO₂-C loss because of priming effect exceeds the amount of added C retaining in the soil. Therefore, an experiment with winter wheat grown in pots under field conditions was set up to investigate the effects of plant-derived DOM on soil CO₂ and N₂O emissions, as well as soil carbon and nitrogen sequestration by adding water extracts of maize stalk (i.e., plant-derived DOM) to soils.

2. Materials and methods

2.1. Site description

This study was conducted at Yucheng Agricultural Experiment Station, Chinese Academy of Sciences (36°50'N, 116°34'E), located in the North China Plain at 26 m above mean sea level and part of the Yellow River alluvial plain. The weather is warm-temperate and sub-humid monsoon climate with the long-term average annual precipitation of 593 mm and mean annual temperature of 13.1 °C, the average frost-free period is 220 days. Nearly 70% of the annual precipitation falls between June and September.

2.2. Experimental design and operation

A pot experiment with winter wheat was set up on October 10, 2013 using the soils collected from the top 20 cm of a field with a long-term wheat/corn double cropping annually for about 30 years. Soils were air-dried and passed through a 2-mm sieve, any visible roots and organic residues were removed, and after that it was mixed thoroughly prior to the experiment. This soil is calcareous fluvisols according to the FAO-UNESCO system, a silt-loam texture with 12% sand, 66% silt and 22% clay, and an average pH_{H2O} of 7.90. It contained 14.57 g kg⁻¹ of SOC, 0.87 g kg⁻¹ of total nitrogen (N), 2.06 g kg⁻¹ of total phosphorus (P), 22.90 g kg⁻¹ of total potassium (K), 118.54 mg kg⁻¹ available N, 18.47 mg kg⁻¹ available P, 165.66 mg kg⁻¹ available K and 144.65 mg kg⁻¹ DOC.

The experiment consisted of four treatments with six replications in a completely randomized design. The treatments were as follows: a control with no DOM additions to soil (CK), plant-derived DOM added to soil (PDOM), urea nitrogen added to soil (N), and a combination of plant-derived DOM and urea N added to soil (PDOM + N). The size of pots used in the experiment was 30 cm in height and 40 cm in diameter. A total of 40 kg of soil was packed into each pot at a density of 1.3 g cm⁻³ and at a depth of 24.5 cm. Pots were equilibrate under field conditions for two weeks before seeds were sowed. The initial soil moisture was adjusted to 70% of field capacity. Winter wheat grown in each pot was evenly sown in two rows with row spacing of 15 cm on October 10, 2013, and harvested on June 4, 2014. Each pot grew 60 wheat plants. To determine the root biomass at harvest, a soil core of 4.9-cm diameter was taken randomly between the wheat rows in each pot to a depth of 20 cm. All root samples were washed in 0.5 mm mesh size nylon bags, and then separated the roots from soil through 0.5 mm sieve (Bernard and Fiala, 1986). The root samples were dried at 70 °C to constant weight.

2.3. Plant-derived DOM preparation and application rate

Corn stalk (including leaves, 1014 g dry-weight equivalent; 70 °C) was machine-ground, then placed into a 80 L barrel and 50 L of deionized water was added. After one month of extraction at 25 °C, the supernatant solution was filtered through 0.45 μm membrane and stored at -20 °C, and thawed overnight prior to use (Kalbitz et al., 2003). In wheat growing phase, all treatments (PDOM, N, and PDOM + N), excluding the control (CK), received the same total amount of N addition at a rate of 24.52 g N m⁻², which is equivalent to 77 mg N kg⁻¹ dry soil, and it is the typical application rate of farmers in the North China Plain. The PDOM treatment received 24.52 g DOM-N m⁻², and the N treatment received 24.52 g urea-N m⁻², while the PDOM + N treatment received 12.26 g DOM-N m⁻² and 12.26 g urea-N m⁻². The amount of DOM-C applied to soil associated with the addition of DOM was 331.53 g DOM-C m⁻² in PDOM and 165.76 g DOM-C m⁻² in PDOM + N, resulting in a C:N ratio of 13.52 and 6.76 in PDOM and PDOM + N treatments, respectively. The DOM and urea-N were surface-dressed in two

stages: the first half was applied on October 20, 2013 when wheat was seedling appearing, and the second half was applied on March 28, 2014 in the boot stage. The DOM and urea-N were added in the form of solution to achieve the same soil moisture, and the control was added the same volume of deionized water.

2.4. Gas sampling and analysis

The CO₂ and N₂O fluxes were measured 14 times during the wheat growing season in 2013–2014 by using static chamber–GC method. The gas was sampled with closed flux chambers made of Polyvinyl (PVC) pipe. The gas chamber consisted of two parts: a bottom base (25 cm in height, 10 cm in diameter) and a lid fitted with a gas sampling port equipped with rubber septum. The chamber lid top was equipped with 3-way luer lock. The chambers were inserted directly into the soil to a depth of 5 cm in October after wheat was germinated. Gas samples were taken between 9:00 am and 11:00 am at each sampling time.

During gas sampling, the chamber headspace was sampled 4 times using a 25 ml syringe with 3-way luer lock at 5 min interval, i.e., gas sampled at 0, 5, 10 and 15 min after closing the chamber. Meanwhile, the air temperature inside the chamber was measured with a digital thermometer, and soil temperature and moisture at 5 cm depth were also measured with a digital thermometer and a time domain reflectometry (TDR) probes (Dynamax Inc., USA).

The syringes, filled with gas samples, were allowed to equilibrate to ambient temperature for 2 h before manually injected to a gas chromatograph equipped with FID and ECD detectors (Agilent GC 4890, Kyoto, Japan). The CO₂ gas was separated by one stainless steel column that was packed with 50/80 mesh porapak Q and was detected by FID. The N₂O was separated by two stainless steel columns that were packed with an 80/100 mesh porapak Q, and detected by ECD. The oven was operated at 55 °C, the ECD at 330 °C and the FID at 200 °C, respectively (Huang et al., 2004). The cumulative gas emission was calculated as follows:

$$\text{Cumulative gas emission} = \sum_{i=1}^n (F_i \times 24 \times D_i) \quad (1)$$

Where F_i is the mean gas flux ($\text{mg m}^{-2} \text{h}^{-1}$ for CO₂, and $\mu\text{g m}^{-2} \text{h}^{-1}$ for N₂O, respectively) of the two successive sampling dates, D_i is the number of days in the sampling interval and n is the number of sampling times.

The N₂O emission factor is the amount of N₂O–N emitted expressed as a percentage of the total N applied, which was calculated as follows:

$$\text{N}_2\text{O emission factor}(\%) = \frac{\sum(\text{N}_2\text{O} - \text{amendment}) - \sum(\text{N}_2\text{O} - \text{CK})}{\text{total N added}} \times 100 \quad (2)$$

Where F_i represents the cumulative N₂O emission from organic or inorganic amendments treatments (PDOM, N and PDOM + N), and $\sum\text{N}_2\text{O} - \text{CK}$ represents the cumulative N₂O emissions from CK.

2.5. Soil sampling and analysis

Soil samples in the 0–20 cm depth were collected after gas sampling (except for the first 3 sampling time). The DOC in the soil was extracted with deionized water (soil:solution ratio of 1:5) for 30 min. After centrifugation for 5 min at 4500 rpm, the supernatant was filtered through 0.45 μm membrane filters before measurement (Gregorich et al., 2003). The DOC content of the extracted DOM was measured using a high temperature combustion total carbon analyzer (Shimadzu TOC, Kyoto, Japan). The mineral N ($\text{NH}_4^+ - \text{N}$ and $\text{NO}_3^- - \text{N}$) was extracted with 1 M NaCl (soil: solution ratio of 1:5) by shaking for 30 min (Lu, 2000). The extracts were then filtered through 0.45 μm membrane filters. The concentrations of $\text{NH}_4^+ - \text{N}$ and $\text{NO}_3^- - \text{N}$ were determined by flow injection autoanalyser (FIA) (SEAL Analytical, AA3, Germany). Microbial biomass carbon (MBC) was analyzed by the chloroform fumigation-extraction method (Vance et al., 1987). Briefly, 10 g of field-moist soil was fumigated with chloroform for 24 h. The fumigated and nonfumigated soils were extracted with 0.5 M K₂SO₄ (soil: solution ratio 1:5) and filtered. The soluble organic carbon in extracts was measured using a high temperature combustion total carbon analyzer (Shimadzu TOC, Kyoto, Japan). A K_{EC} factor of 0.38 was used to estimate MBC from extractable C (Vance et al., 1987). At the end of the experiment, soil samples were collected from the top 20 cm soil layer with a 4.9-cm diameter soil core sampler to determine the soil bulk density on dry weight basis. A soil core was collected from each pot, and was separated into two depths: 0–10 and 10–20 cm. A portion of the soil samples was air-dried and passed through a 0.25-mm sieve for measuring SOC and TN contents. The content of SOC was determined by dichromate oxidation method (Lu, 2000), and total soil N (TN) was analyzed by Kjeldahl method (Bremner, 1965). We calculated the soil C and N

Fig. 1. Dynamics of the CO₂-C flux and N₂O-N flux in each treatment. Treatments: CK represents blank (●), PDOM means the addition of plant-derived DOM (○), N means the addition of urea nitrogen (▼), PDOM + N represents the addition of plant-derived DOM combined with urea nitrogen (△). Values are means $\pm$ SE ($n=6$).

storage according to the contents of SOC and TN in the 0–10, 10–20 cm soil layer, and multiplied by the corresponding bulk density and soil depth (Yang and Wander, 1999). The soil C (N) storage at the top 20 cm depth was used as the basis for C (N) sequestration comparison. Treatment effects on soil C (N) sequestration was calculated by the difference between the final and initial SOC (TN) storage.

2.6. Data analysis

Repeated measures ANOVA with Least Significant Difference (LSD) post hoc test was performed to examine CO₂ emission, N₂O emission, soil temperature, soil moisture, MBC, DOC, DON, and mineral nitrogen (NH₄⁺-N and NO₃⁻-N) in different treatments. Correlation and stepwise linear regression analysis were used to describe the relationships between soil CO₂ and N₂O fluxes and soil parameters. A one-way analysis of variance (ANOVA) with LSD was used to test the differences in root biomass, cumulative CO₂ and N₂O emission, as well as soil C and N sequestration among treatments. All analyses were conducted using SPSS 16.0 (SPSS, Chicago, IL, USA) for Windows. The difference in results was considered statistically significant when the confidence interval was greater than 5% ($P < 0.05$). Graphs were plotted using the SigmaPlot 12.5 graphics program (Systat Software Inc., California, USA).

3. Results

3.1. Soil CO₂ and N₂O emission

Addition of DOM increased soil CO₂ emissions and this effect varied over time ($P < 0.05$, Fig. 1a). The CO₂ emission was low in the early period of the wheat growing phase, but it increased very fast after March, with the highest emission observed in mid April (Fig. 1a). The rank of cumulative CO₂-C emission among treatments was the same as the order of average CO₂ flux under treatments (PDOM > PDOM + N > N > CK). The cumulative CO₂-C emission from PDOM and PDOM + N was about $46 \pm 3\%$ and $39 \pm 2\%$ higher than that from CK ($107 \pm 1 \text{ g C m}^{-2}$; Fig. 2); and was about $15 \pm 2\%$ and $10 \pm 1\%$ higher than that from urea-N treatment (Fig. 2).

Nitrous oxide emissions decreased gradually as the experiment proceeded (Fig. 1b). Application of DOM increased soil N₂O emissions and this effect varied significantly over time ($P < 0.05$, Fig. 1b). The addition of DOM contributed to a $37 \pm 1\%$ and $37 \pm 2\%$ increase in cumulative N₂O-N emission in PDOM and PDOM + N

treatments, as compared with CK; and a $7 \pm 1\%$ and $8 \pm 1\%$ increase in PDOM and PDOM + N treatments, as compared with N treatment (Fig. 2). The N₂O emission factor was 0.3%, 0.2%, and 0.3% in PDOM, N, and PDOM + N treatments, respectively, indicating more of the applied N lost as N₂O in DOM-amended soils.

3.2. Soil temperature and moisture

Soil temperature at 5 cm depth varied from 2.2 °C to 28.7 °C during the wheat growth period, with a mean of 12.9 °C (Fig. 3a). Soil temperature exhibited an increasing trend during the whole experiment. Soil moisture at 5 cm depth ranged from 4.9% to 23%, with a mean of 16% (Fig. 3b). There were no significant differences between treatments for soil temperature and moisture.

3.3. Soil MBC, DOC, DON, NH₄⁺ and NO₃⁻

The MBC was affected by DOM, urea-N, and their interaction with time ($P < 0.05$; Fig. 4a). The seasonal patterns of MBC during the wheat growing season were similar to the dynamics of CO₂ flux in each treatment. Adding DOM increased MBC content in soil ($P < 0.05$; Fig. 4a). The MBC in PDOM and PDOM + N treatments was $35 \pm 1\%$ and $37 \pm 1\%$ greater than that in CK, respectively.

The DOC content was affected by the treatments and their interaction with time ($P < 0.05$, Fig. 3b). Addition of DOM and urea-N increased the DOC content as compared with CK ($P < 0.05$).

An immediate increase in DON (from March 26 to April 21) was observed after the application of supplementary fertilizer (March 28) (Fig. 4c). Adding DOM alone decreased the DON content in the soil ($P < 0.05$; Fig. 4c).

The seasonal patterns of NH₄⁺-N and NO₃⁻-N contents in the soil were similar (except for the first two samplings, Figs. 4d and e). Adding DOM and urea-N increased the mineral N content (NH₄⁺-N and NO₃⁻-N) ($P < 0.05$). The stimulatory effect of urea-N addition on NO₃⁻-N was more pronounced than DOM addition.

3.4. Factors that control CO₂ and N₂O emissions

Significant correlations were found between CO₂ flux as well as N₂O flux and soil parameters (soil temperature, soil moisture, DOC, MBC, DON, NH₄⁺-N, NO₃⁻-N and DOC/DON) (Tables S1 and S2). A positive correlation between CO₂ flux and soil moisture, and microbial biomass carbon was observed in each treatment (Table S1). The variation of MBC accounted for 28%, 71%, 47%, and 21% the variation in soil CO₂ flux in CK, PDOM, N and PDOM + N treatments, respectively. The N₂O flux was positively correlated

Fig. 2. Cumulative CO₂-C and N₂O-N emissions in each treatment. Values are means ± SE (n = 6). Different letters indicate significant difference at $P < 0.05$.

Fig. 3. Dynamics of soil temperature and soil moisture at 5 cm depth. Treatments: CK represents blank (●), PDOM means the addition of plant-derived DOM (○), N means the addition of urea nitrogen (▼), PDOM + N represents the addition of plant-derived DOM combined with urea nitrogen (△). Values are means $\pm$ SE ($n = 6$).

with DON concentration and negatively correlated with soil temperature, DOC content and DOC/DON ratio (Table S2). Stepwise regression analysis was used to identify key factors regulating CO_2 and N_2O fluxes from soils. The results showed that soil MBC and soil moisture were the key factors regulating the CO_2 fluxes in the stepwise regression equation in each treatment, and both could explain 64–81% of the variation in soil CO_2 flux (Table S3). The key factors regulated N_2O fluxes were DOC and soil temperature, explaining 57–78% of the variation in N_2O flux (Table S3). These results suggest that the temporal variations in soil CO_2 and N_2O emissions are dependent on soil moisture, microbial biomass and soil temperature as well as soluble organic substrates.

3.5. Soil Carbon and Nitrogen sequestration

The root biomass at harvest was 164 ± 10 , 258 ± 29 , 215 ± 22 and $222 \pm 17 \text{ g m}^{-2}$ in CK, PDOM, N and PDOM+N treatments, respectively. Adding DOM alone increased the root biomass in comparison with CK ($P < 0.05$). The root biomass accounted for 28% of the variation in cumulative CO_2 emission in this study.

Adding DOM to soil decreased soil C sequestration by 151 and 51 g C m^{-2} in PDOM and PDOM+N treatments, respectively (Table 1). However, the soil C sequestration increased by 155 and 60 g C m^{-2} in CK and N treatment, suggesting DOM addition accelerated the mineralization of native soil organic carbon (i.e., a positive priming effect).

Soil amended with urea-N had higher soil N sequestration than that amended with DOM (PDOM + N, $P < 0.05$), while adding DOM alone had little effect on soil N sequestration compared with CK (Table 2).

4. Discussion

4.1. Effects of plant-derived DOM on soil CO_2 emission and soil carbon sequestration

Addition of DOM increased CO_2 emission (Fig. 2) and microbial biomass (Fig. 4a), but decreased soil C sequestration (Table 1). The increased MBC in DOM-amended soils and the positive relationship between MBC and CO_2 flux (Table S1) indicated that application of DOM stimulated microbial activity and accelerated the decomposition of the applied DOM and soil organic matter.

Several studies reported that the addition of labile substrates could trigger dormant and potential active microorganisms, alter microbial community composition and potential metabolic activities, accelerate the turnover of SOC (Derrien et al., 2014; Fontaine et al., 2003; Fontaine et al., 2004a; 2004b; Kuzyakov, 2010; Liang et al., 1996; Paterson and Sim, 2013) and induce a negative C balance (Liang et al., 1996; Fontaine et al., 2004a, 2004b). Application of DOM led to 198% and 133% SOC priming effects in PDOM and PDOM + N treatments, relative to the control soil. The intensity of priming effect induced by DOM addition was comparable with that induced by glucose in a short-term incubation (Paterson and Sim, 2013; Rousk et al., 2014). Greater decline of soil C sequestration occurred in PDOM than in PDOM + N may be caused by the following reasons. Firstly, the application rate of DOM in PDOM was higher than that in PDOM+N. The intensity of the priming effect increased with increasing the addition rates of soluble organic substrate (Paterson and Sim, 2013; Rousk et al., 2014). Secondly, apart from the direct effect of DOM addition on the priming effect, the depletion of SOC storage might be partially attributed to the indirect effect induced by DOM through increasing root growth in PDOM. Higher soil CO_2 emission was observed in mid April, which was most likely related to rhizosphere and root respiration, since crop was thriving during that period (Franzluebbers et al., 1995). Rhizodeposition could stimulate microbial activity and substantially increase SOC decomposition rate (Kuzyakov, 2002; Kuzyakov and Cheng, 2004; Kuzyakov and Bol, 2006). The significant positive correlation between the cumulative CO_2 emission and root biomass ($R^2 = 0.28$, $P < 0.05$) could further supported this view. Fu and Cheng (2002) also found positive correlation between root biomass and rhizosphere-primed soil C.

Soil amended with urea-N or with no addition had a lower CO_2 emission compared with DOM-amended soils. This may be ascribed to lack of exogenous C supply and the relatively lower microbial biomass (Fig. 4a). Positive soil C sequestrations were observed in CK and N treatments, suggesting that the C input exceeded the C output in the soil. The additional C input may be from the root biomass incorporated into the soil organic matter. Kuzyakov and Schneckenberger (2004) reported that during one vegetation period the wheat allocated about 1.50 t C ha^{-1} to below ground, and about 20% of root derived-C was incorporated into soil organic matter. However, Johnson et al. (2006) reported that

Fig. 4. Soil concentrations of MBC, DOC, DON, NH₄⁺, and NO₃⁻ in each treatment. Treatments: CK represents blank (●), PDOM means the addition of plant-derived DOM (○), N means the addition of urea nitrogen (▼), PDOM+N represents the addition of plant-derived DOM combined with urea nitrogen (△). Values are means ± SE (n = 6).

previous studies have underestimated the contribution of root-derived C to SOC in the field studies, and the contribution of C through rhizodeposition from wheat ranged from 0.8 to 3.6 t C ha⁻¹ yr⁻¹. Soil C sequestrations in CK and N treatments in our study were within this range. The soil amended with DOM might also incorporated part of root-derived C into the soil, but the additional C input might be decomposed quickly by the microorganisms due to the higher microbial biomass in DOM-amended soils.

According to the DOM-C input from crop residues and the C output from the organic matter mineralization, a net C gain was observed in DOM-amended soils (175 g C m⁻² for PDOM and 17 g C m⁻² for PDOM+N). However, when we calculated the soil C sequestration based on the difference between the final and initial soil C storage, a negative soil C sequestration was observed in DOM-amended soils (Table 1). We attributed the contrary results to underestimating the CO₂-C output in calculation of the C

Table 1

Soil C sequestration at 0–20 cm depth in each treatment (g C m^{-2} , means $\pm$ SD, $n = 6$).

Treatment	Initial soil C storage	Final soil C storage	Soil C sequestration
CK	3788.2	3943 $\pm$ 85a	155 $\pm$ 85a
PDOM	3788.2	3637 $\pm$ 67c	–151 $\pm$ 67c
N	3788.2	3484 $\pm$ 194ab	60 $\pm$ 56ab
PDOM + N	3788.2	3737 $\pm$ 45bc	–51 $\pm$ 45bc

Soil C sequestration is the difference between the final and initial soil organic C storage. CK represents blank, PDOM means the addition of plant-derived DOM, N means the addition of urea nitrogen, PDOM + N represents the addition of plant-derived DOM combined with urea nitrogen. Different letters within columns indicated significant difference at $P < 0.05$.

Table 2

Soil N sequestration at 0–20 cm depth in each treatment (g N m^{-2} , means $\pm$ SD, $n = 6$).

Treatment	Initial soil N	Final soil N	soil N sequestration
CK	266.2	235 $\pm$ 1b	8 $\pm$ 1b
PDOM	266.2	236 $\pm$ 2ab	9 $\pm$ 2ab
N	266.2	248 $\pm$ 13a	22 $\pm$ 13a
PDOM + N	266.2	235 $\pm$ 5b	9 $\pm$ 5b

Soil N sequestration is the difference between the final and initial soil total N storage; CK represents blank, PDOM means the addition of plant-derived DOM, N means the addition of urea nitrogen, PDOM + N represents the addition of plant-

balance. We first measured the CO_2 flux on November 17, 2013 (Fig. 1a), but part of DOM was added to the soil as topdressing on October 20, 2013. This extended sampling interval might lead to substantial decomposition of the added DOM in the early period of wheat growing season, and resulted in underestimation of the CO_2 –C emission in the present study. Kalbitz et al. (2003) reported that 80% of DOC derived from maize straw was mineralized in the first 30 days of incubation. Another reason might be that the added DOM was lost through leaching under field conditions. Therefore, in order to precisely quantify the contribution of DOM supply to soil CO_2 emission, a higher sampling frequency is required at the initial stage of DOM addition.

4.2. Effects of plant-derived DOM on soil N_2O emission and soil nitrogen sequestration

Application of DOM enhanced N_2O emission, and this effect was more pronounced than the addition of urea-N (Fig. 2). This result might be related to the following reasons. Firstly, DOM addition provided not only available N but also available C source for the nitrifier and denitrifier, which in turn enhanced N_2O production (Cui et al., 2012; Hayakawa et al., 2009; Huang et al., 2004; Miller et al., 2009; Muhammad et al., 2011). Secondly, as the experimental soil has a relatively high pH, application of N fertilizer in the form of urea can be easily dissolved in water and transform to NH_4^+ , which is easily volatilized in high soil pH. Approximately 44–48% of the applied N was lost by NH_3 volatilization when the urea was applied to the soil surface in the North China Plain (White et al., 2002).

In general, N_2O emission is negatively correlated with the C/N ratio in organic amendments (Huang et al., 2004). However, there were no significant differences in the cumulative N_2O emissions in PDOM and PDOM + N treatments (Fig. 2), even though the latter with a lower C/N ratio of the added organic solution. This was likely that the insufficient available carbon limited microbial activities and thus N_2O emission (Cui et al., 2012), since the amount of DOM-C addition in PDOM + N treatment accounted for only half of DOM-C addition in PDOM treatment. Martín-Olmedo and Rees (1999) reported that the DOC supply played a more important role in N_2O

emissions than differences in C/N ratio. The stepwise regression analysis showed that the DOC content in soil was negatively correlated with N_2O emission (Table S2). This result was consistent with Huang et al. (2004), who reported that the increment of N_2O was accompanied with a reduction of DOC when maize residue and urea were amended together. It is commonly accepted that soil mineral N content (NH_4^+ -N and NO_3^- -N) is the key factor affecting N_2O emissions (Dobbie et al., 1999; Dobbie and Smith, 2003). However, it had little effect on N_2O emissions in the present study (Tables S2 and S3). This suggests that the release of N_2O to some extent was dependent on the supply of soluble organic carbon rather than soil N availability.

4.3. Crop residue management under field conditions

In this study, adding plant-derived DOM increased soil CO_2 and N_2O emissions and decreased soil C sequestration. Returning crop residues back to soil is a common farming practice and the crop residue is a major source of soil DOM (Chantigny, 2003). Therefore, management practices that increase the stability of highly soluble C inputs and/or retard the decomposition of crop residues should be adopted to increase soil C sequestration. For a given crop residue type, the placement of crop residues affects the distribution of C and N in soil, which in turn influences microbial activity and the decomposition rate of plant residues (Angers and Eriksen-Hamel, 2008; Nicolardot et al., 2007). Incorporation of crop residues to soil may be favorable for DOM retention, since deeper soil layers absorb DOM more efficiently than surface soils, and the physical adsorption can convert DOM to more refractory compounds (Boyer and Groffman 1996; Kalbitz and Kaiser, 2008). Moreover, the amount and activity of soil microorganisms was found to be minimal in subsoil horizons, and the decomposition rate of organic amendments decreased with soil depth (Gill and Burke 2002). A slower decomposition of incorporated residues resulted in residue-derived C accumulated at the bottom of the plow layer (Angers and Eriksen-Hamel, 2008; Nicolardot et al., 2007). In addition to the placement of crop residues, we should also take the timing of residue-C return to the soil into consideration. Several authors have concluded that the production of DOC is a function of the microbial community in the soil (Guggenberger and Zech, 1993; McDowell and Likens, 1988), and thus environmental variables that impact microbial activity such as soil temperature and moisture will impact the release of DOM (Kalbitz et al., 2000). The study area is characterized by warm-temperate and sub-humid climates. Rapid decomposition of crop residues may occur during the rainy season (June to September) where the temperature and moisture are favorable for the decay of crop residues. Our previous study have observed that the DOC contents in the plow layer (0–20 cm) increase from spring to summer and decrease from summer to autumn in the soil amended with crop residues (Qin et al., 2014). We should avoid incorporation of crop residues to soils in rainy season, since the warm and wet conditions during that period are favorable for the production of DOM. Therefore, incorporation of crop residues to soil during dry season may be a better option for increasing soil C sequestration and minimizing adverse effects on the environment.

5. Conclusions

Adding plant-derived DOM to soils accelerated the decomposition of SOC and decreased soil C sequestration. The increased microbial biomass and root biomass were responsible for the stimulation of SOC mineralization in DOM-amended soils. Addition of DOM to soil increased N_2O emissions, and the production of N_2O was dependent on the supply of soluble organic carbon rather than soil N availability. The response of SOC decomposition to the

addition of DOM has important practical implications for the farmers. Agricultural management practices that increase the stability of highly soluble C inputs and/or reduce the decomposition of crop residues should be adopted to decrease soil greenhouse gases emission and increase soil C sequestration. Incorporation of crop residues to soils during dry season may be a good option for increasing soil C sequestration and decreasing greenhouse gas emission.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at <http://dx.doi.org/10.1016/j.apsoil.2015.07.016>.

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