Priming effect of maize residue and urea N on soil organic matter changes with time

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ABSTRACT

To investigate the effects of urea nitrogen (N) and crop residues on soil organic carbon (SOC) decomposition, a batch of incubation experiments was carried out for 250 days by incorporating ¹⁵N-labeled urea and ¹³C-labeled maize residue into soil. Adding maize residue alone or adding maize residue together with urea N had a significant priming effect on SOC. Furthermore, the direction of the priming effect changed over the incubation. This effect could be characterized by three stages. The first stage occurred just after maize residue addition when the substrate for microorganisms switched from native SOC to easily available maize C (lasting ~7 days). The second stage showed a positive effect on the decomposition of native SOC (lasting ~28–58 days). The third stage showed a negative effect on the decomposition of native SOC. In contrast, adding N alone caused a positive effect over the first 65 days of incubation, followed by a slight negative priming effect. The overall effect of maize residue C and urea N addition on the decomposition of native SOC was dependent on the balance between the inhibitory and stimulatory effects. At the end of the incubation, adding maize residue alone had little effect on the decomposition of native SOC; urea N addition alone increased SOC decomposition by 9.1%, while adding N to soil amended with maize residue decreased SOC decomposition by 9.5%. The amount of residue-inhibited SOC decomposition per unit maize C mineralized was 0.21 ± 0.06 in the Maize + N treatment. Application of urea N significantly increased the mineralization rate of maize residue after 20 days of incubation. The increased N availability, microbial biomass and dissolved organic carbon (DOC) induced by the addition of N were responsible for the higher mineralization rate of maize residue. This indicates that the priming effect induced by maize residues could persist for a long time and involved not only one mechanism but a succession of processes. The response of the priming effect to the addition of maize residue and urea N differed depending on the microbial biomass, substrate C and N availability and the stage of decomposition. Adding N to soil amended with maize residue led to a more efficient use of maize residue at the slow mineralization stage.

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1. Introduction

Incorporation of crop residues into soil has long been used to improve soil quality and fertility (Moreno-Cornejo et al., 2014). Crop residues represent a major source of soil organic carbon (SOC) input, while adding this kind of “fresh” organic matter to the soil may change the turnover of native SOC through priming effects (Kuzyakov, 2002; Fontaine et al., 2004; Conde et al., 2005; Guenet

et al., 2010; Kochsiek et al., 2013; Li et al., 2013). Priming effects are generally considered strong short-term changes in the turnover of soil organic matter (SOM) caused by the substrate added to the soil (Kuzyakov, 2002). Negative and/or neutral priming effects induced by crop residue addition (Dalenberg and Jager, 1989; Blagodatskaya and Kuzyakov, 2008) have not been reported as often as positive effects (Kuzyakov, 2002; Fontaine et al., 2004; Conde et al., 2005; Nottingham et al., 2009; Guenet et al., 2010; Kochsiek et al., 2013; Li et al., 2013; Chen et al., 2014). It is generally believed that the quality and quantity of organic substances affect the intensity of the priming effect (Dalenberg and Jager, 1989; Fontaine et al., 2004; Kuzyakov and Bol, 2006; Blagodatskaya and Kuzyakov,

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2008; Blagodatskaya et al., 2009; Nottingham et al., 2009; Guenet et al., 2010; Li et al., 2013; Chen et al., 2014; Derrien et al., 2014; Mazzilli et al., 2014). Some complex organic substances (e.g., plant residues) can induce a more pronounced priming effect than easily available substances (e.g., glucose and sucrose) (Fontaine et al., 2004; Chen et al., 2014; Mazzilli et al., 2014). Many studies on the priming effect induced by crop residues were carried out over a relatively short time (i.e., from a few hours to several days) with the decomposition of crop residues in their early stage (Conde et al., 2005; Blagodatskaya et al., 2009; Nottingham et al., 2009; Li et al., 2013; Chen et al., 2014). As the primed soil respiration is not just a short-term response, it can also persist for many weeks or several months after the complete decomposition of organic substrates (Fontaine et al., 2004, 2011). The decomposition of crop residues is usually characterized by three distinct stages (rapid, intermediate and slow decomposition) according to their chemical components (soluble, cellulose and hemicellulose, and lignin-like compounds) (Hadas et al., 2004). The response of the priming effect to the decomposition of crop residues in their medium and later stages may be different from that in their early stage, since the quality and availability of crop residues decrease as the decomposition proceeds (Henriksen and Breland, 1999; Hadas et al., 2004; Chen et al., 2009). Therefore, it is necessary to investigate the long-term priming effect dynamics induced by the decomposition of crop residues, and to precisely estimate the net effect of the addition of crop residues on the decomposition of native SOC.

The nutrient availability in the soil is an important factor controlling the intensity and direction of the priming effect (Kuzakov et al., 2000; Conde et al., 2005; Guenet et al., 2010; Fontaine et al., 2011; Chen et al., 2014; Dimassi et al., 2014; Wang et al., 2014). Nitrogen is the most important nutrient that often limits crop growth and regulates soil C turnover by altering microbial biomass and microbial activity (Nohrstedt et al., 1989; Recous et al., 1995; Henriksen and Breland, 1999; Neff et al., 2002). However, in different studies adding mineral N to soil amended with organic substances has led to a positive effect on the decomposition of native SOC (Conde et al., 2005; Kochsiek et al., 2013; Li et al., 2013; Dimassi et al., 2014), as well as to a negative effect (Khan et al., 2007; Blagodatskaya et al., 2009; Guenet et al., 2010; Fontaine et al., 2011; Chen et al., 2014), or a neutral effect on native SOC decomposition (Sall et al., 2007; Kochsiek et al., 2013; Chen et al., 2014). In order to explain the different effects of N addition on the decomposition of SOM, two controversial hypotheses were proposed: either N deficiency increases SOC decomposition or sufficient N supply stimulates microbial growth and SOC decomposition (Conde et al., 2005; Khan et al., 2007; Blagodatskaya et al., 2009; Guenet et al., 2010; Fontaine et al., 2011; Kochsiek et al., 2013; Li et al., 2013; Chen et al., 2014; Dimassi et al., 2014). Addition of crop residues, especially those having a higher C:N ratio, can induce N immobilization, with the absence of inorganic N inhibiting SOC decomposition. The addition of inorganic N fertilizer can supplement microbial demand for available N, thereby increasing the microbial biomass and activity, and as a result accelerating the SOC decomposition (Conde et al., 2005; Kochsiek et al., 2013; Li et al., 2013; Dimassi et al., 2014). In contrast, some studies found that the microbes could use labile carbon released from crop residues to access recalcitrant SOC to

acquire needed N when the available N was in shortage, which resulted in higher decomposition of SOC (Khan et al., 2007; Blagodatskaya et al., 2009; Guenet et al., 2010; Fontaine et al., 2011; Chen et al., 2014). Although the mechanisms are opposite, both of the above-mentioned mechanisms are associated with the availability of organic C (Chen et al., 2014). An increase in microbial activity is not to be expected by improving N availability under C-limited conditions, due to a lack of essential energy sources, while improving N availability under N-limited conditions (C rich) allows increased microbial activity and growth (Kuzakov et al., 2000). Until now, few studies have reported the interactive effects of substrate availability and N supply on the dynamics of priming effect. Therefore, a greater understanding of how the N supply and its interaction with residue addition on the decomposition of native SOC is needed to help us manage the soil C cycle and maintain a higher soil C sequestration in agricultural soil. Also, a comparison of the dynamics of N release or immobilization with the dynamics of microbial biomass can help interpret the mechanisms of the priming effect.

In China, to meet the food demands of an increasing population, more and more inorganic N fertilizer is being applied to the soil for enhancement of crop yields (Meng et al., 2005; Ding et al., 2010). The amount of annual mineral N fertilizer input accounts for more than one quarter of the total N fertilizer used around the world (FAO and FOODS, 2004). Maize is one of the most important cultivated crops in the North China Plain (Cui et al., 2012). Maize agricultural ecosystems are characterized by high inputs of inorganic N fertilizer and large inputs of maize residue with high C/N ratios (Hadas et al., 2004; Cui et al., 2012; Kochsiek et al., 2013). Addition of maize residue to soil can provide a large amount of labile C, which may increase microbial activity and accelerate the decomposition of SOC. However, maize residue has very little N (Thangarajan et al., 2013), and so its addition to soil may result in a N-limited environment for soil decomposers, since microbes require both C and N sources (Thangarajan et al., 2013). We hypothesize that addition of inorganic N fertilizer will supplement microbial N demand to decompose the maize residue, thereby reducing the need for decomposition of native SOM to access available N. Therefore, exogenous N addition may increase the decomposition of maize residue while decreasing the decomposition of SOC. Incorporation of urea N and ^{13}C -labeled maize residues into soils allows for differentiation between maize-derived C and native soil derived-C and provides precise estimates of the impact of N availability on the decomposition of maize residues and native SOC. The objectives of this study were to investigate (1) the changes in the priming effect during the decomposition of maize residue; (2) whether the N input modifies the priming effect; and (3) the net effect of maize residue and N additions on the decomposition of native SOC.

2. Materials and methods

2.1. Soil sampling

The soil used in this experiment was taken from the topsoil (0–20 cm) of an agricultural ecosystem at Yucheng Agricultural Experiment Station, Chinese Academy of Science (36°50'N,

Table 1
Basic properties of the soil at 0–20 cm.

pH	SOC (g kg^{-1})	TN (g kg^{-1})	TP (g kg^{-1})	TK (g kg^{-1})	Available N (mg kg^{-1})	Available P (mg kg^{-1})	Available K (mg kg^{-1})	Bulk density (g cm^{-3})	DOC (mg kg^{-1})
7.81 ± 0.07	9.09 ± 0.38	0.87 ± 0.12	2.45 ± 0.13	20.31 ± 0.19	66.87 ± 2.41	17.60 ± 2.84	157.87 ± 10.34	1.32 ± 0.04	124.11 ± 1.27

TN, TP and TK represent total nitrogen, total phosphorus and total potassium, respectively.

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 soil samples were air dried and passed through a 2 mm sieve to remove rocks, coarse crop residues and roots. The basic properties of the soil are shown in Table 1.

2.2. ^{13}C -labeled maize

A pulse labeling method was used to label maize leaves with $^{13}\text{CO}_2$ (>99.9% atom; Shanghai Engineering Research Center of Stable Isotope) in July 2013, as follows. Before labeling, maize leaf was enveloped with an airtight transparent plastic tent 90 cm in length and 30 cm in width. The air in the plastic tent was evacuated just prior to addition of $^{13}\text{CO}_2$. Pulse labeling was carried out for 5 days (from 26 July 2013 to 30 July 2013). Maize leaves were exposed once a day to $^{13}\text{CO}_2$ for 3 h (from 9:00 to 12:00 am) with a flow rate of $^{13}\text{CO}_2$ approximately 1 L h^{-1} . After labeling, the plastic tent was removed to allow rapid dilution of the remaining $^{13}\text{CO}_2$ in the atmosphere. At the end of labeling, the maize seedlings were harvested, rinsed with deionized water, dried for 24 h at 65°C , then ground to <2 mm. The $\delta^{13}\text{C}$ value of the finely ground maize residue was 80.56‰. The maize residue had an average C content of 468 g kg^{-1} and a mean total N content of 12.1 g kg^{-1} .

2.3. Experiment design and soil incubation

This experiment consisted of four treatments with three replications in a completely randomized design. The treatments were as follows: soil treated with ^{13}C -labeled maize residue (Maize), ^{15}N -labeled urea (N), a combination of ^{13}C -labeled maize residue and ^{15}N -labeled urea (Maize + N), as well as a control with no additions to soil (CK). The soil moisture was maintained at 65% of water holding capacity and pre-incubated at 25°C in the dark for one week. Exactly 100 g of pre-incubation soil (equivalent to 86.21 g dry soil) was placed in a 500 mL glass jar. The ^{13}C -labeled maize residue ($\delta^{13}\text{C}=80.56\text{‰}$) was applied at a rate of 6088 kg Cha^{-1} in the Maize treatment. ^{15}N -labeled urea (enrichment 5.22 atom%) was applied at a rate of 200 kg N ha^{-1} in the N treatment. In the Maize + N treatment, the application rate of maize residue and urea N was 3868 kg Cha^{-1} and 100 kg N ha^{-1} , respectively. These application rates of maize residue and urea N follow the typical application by farmers in the North China Plain. Namely, the amount of C and N inputs for each treatment was as follows: ^{13}C -labeled maize straw (2.71 g C kg^{-1} dry soil), ^{15}N -labelled urea ($89.32 \text{ mg N kg}^{-1}$ dry soil), and a combination of ^{13}C -labeled maize straw and ^{15}N -labeled urea (1.73 g C kg^{-1} dry soil + $44.66 \text{ mg N kg}^{-1}$ dry soil). ^{13}C -labeled maize residue was thoroughly mixed with the soil. ^{15}N -labeled urea was dissolved in deionized water and added in the form of solution (1 mL for each glass jar). To separate the urea solution effect on the soil moisture, other treatments received an equivalent amount of deionized water (1 mL for each glass jar). During the incubation, the mouth of the glass jar was capped with a Parafilm with a small hole in the center to allow the exchange of air in the jar with the outside atmosphere. Ports in the top of each jar were sealed with rubber stoppers. The jar was weighed weekly and deionized water was added as required to maintain constant soil moisture. The glass jars were incubated in the dark at 25°C for 250 days.

2.4. CO_2 sampling and analysis

Before sampling, the Parafilm was removed to allow for the exchange of air in the glass jar with the outside atmosphere for about 1 h. Then each glass jar was tightly sealed with a lid. A hole drilled in the lid of the jar was fitted with a rubber septum to make glass jar a closed system and allow gas samples to be taken from

the headspace of the jar. The gas samples were taken 24 times using a syringe to extract 5 mL of gas from the headspace after closing the jars for 1 h. During that time the glass jars were incubated at 25°C in darkness. The CO_2 samples for $\delta^{13}\text{C}$ - CO_2 analysis were taken at 0 d, 7 d, 20 d, 35 d, 65 d, 130 d and 250 d of incubation by sampling 300 mL of headspace gas and injecting it into a pre-evacuated exetainer (Shanghai, Shenyuan Corporation, China). The isotopic signature of the gas was measured with an isotope ratio mass spectrometer (Delta V Advantage, Thermo Fisher Scientific, Inc., USA).

The syringes with gas were allowed to equilibrate to ambient temperature for 2 h before being manually injected into a gas chromatograph (Agilent GC 4890, Kyoto, Japan). The GC 4890 was equipped with FID and ECD detectors. The CO_2 gas was separated by one stainless steel column that was packed with 50/80 mesh porapak Q and was detected by FID. The oven was operated at 55°C , the ECD at 330°C and the FID at 200°C (Huang et al., 2004).

The cumulative gas emissions were calculated as follows:

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

where F_i is the mean gas flux (mg kg^{-1} dry soil h^{-1}) 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.

2.5. Partitioning CO_2 sources and quantifying the priming effect

The respired CO_2 -C derived from maize residue and native SOC was calculated as follows:

$$C_{\text{maize}} = C_t \times \frac{(\delta_t - \delta_s)}{(\delta_{\text{maize}} - \delta_s)} \quad (2)$$

$$C_s = C_t \times \frac{(\delta_{\text{maize}} - \delta_t)}{(\delta_{\text{maize}} - \delta_s)} \quad (3)$$

where C_t ($C_t = C_{\text{maize}} + C_s$) is the total CO_2 -C emissions during the considered time interval and δ_t is the corresponding $\delta^{13}\text{C}$ value of the respired CO_2 evolved from the soil amended with maize residue. C_{maize} is the amount of C derived from the added maize residue and δ_{maize} is the $\delta^{13}\text{C}$ value of maize residue ($\delta^{13}\text{C}=80.56\text{‰}$). C_s is the amount of C derived from native SOC and δ_s is the $\delta^{13}\text{C}$ value of the respired CO_2 evolved from SOC.

Mineralization of maize residues in soil was calculated as follows:

$$\text{CM}(\%) = \frac{C_{\text{maize}}}{\text{Total maize residue C added}} \times 100 \quad (4)$$

where CM represents C mineralization from maize residues (%). C_{maize} is the amount of C derived from the added maize residue.

The priming effect during the whole incubation period was calculated using the following equation:

$$\text{PE} = (\text{CO}_2 - C_{\text{treatment}} - \text{CO}_2 - C_{\text{control}}) \quad (5)$$

where CO_2 - $C_{\text{treatment}}$ is the amount of CO_2 derived from SOC in the treatments with maize residue and/or urea N addition and CO_2 - C_{control} is the amount of CO_2 derived from SOC without maize residue and/or urea N addition. The cumulative priming effect in a certain time was calculated as the sum of the previous cumulative priming effect and the current priming effect.

2.6. Soil analysis

The soil was destructively sampled for the analysis of microbial biomass carbon (MBC), dissolved organic carbon (DOC) and mineral N (NH_4^+ -N and NO_3^- -N). MBC was analyzed by the

chloroform fumigation-extraction method (Vance et al., 1987): about 10 g of fresh soil was fumigated with chloroform for 24 h. The fumigated and non-fumigated soils were extracted with 0.5 M K_2SO_4 and filtered. Thereafter, the soluble organic carbon in the 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). The DOC in the soil was extracted according to the method described by Gregorich et al. (2003): 10 g of fresh soil sample was shaken with deionized water at a 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 dissolved organic matter (DOM) was measured using a high temperature combustion total carbon analyzer (Shimadzu TOC, Kyoto, Japan). Soil NH_4^+-N and NO_3^--N were extracted with 2 M KCl for 1 h and then analyzed on the continuous flow analyzer (FIA) (SEAL Analytical, AA3, Germany). Total extractable N was calculated as the sum of NH_4^+-N and NO_3^--N concentrations. SOC concentration was determined with the wet-oxidation-redox titration method (Lu, 2000).

2.7. Statistical analysis

Repeated measures ANOVA with least significant difference (LSD) post hoc tests were performed to examine CO_2 emissions, MBC, DOC and mineral N contents under different treatments. Correlation analysis was used to describe the relationships between maize-derived CO_2 and MBC and DOC. All analyses were conducted using SPSS 16.0 (SPSS, Chicago, IL, USA) for Windows. Results were considered statistically significantly different when the significant level was greater than 5% ($P < 0.05$). Graphics were carried out using the SigmaPlot 12.5 graphics program (Systat Software Inc., California, USA).

3. Results

3.1. Soil CO_2 emissions

A flush of CO_2 -C emissions was observed just after incorporation of maize residue into the soil (Fig. 1a). The initial CO_2 -C efflux reached about $2702 \mu g \text{ kg}^{-1} \text{ h}^{-1}$ in the Maize treatment and $1852 \mu g \text{ kg}^{-1} \text{ h}^{-1}$ in the Maize + N treatment. During the following 15 days, the CO_2 -C emission rate in the maize-amended soils decreased rapidly and dropped to 9–12% of the initial values. Soil amended with maize residue alone had a higher emission rate than that amended with maize residue together with urea N during that period ($P < 0.05$). The patterns of CO_2 -C emissions in the CK and N treatments were similar and were relatively steady compared with the soil amended with maize residue alone or with N. Application of N also increased CO_2 -C emissions, but this positive effect was not as great as residue additions. After 15 days of incubation the magnitude of the differences in CO_2 -C emissions between treatments had decreased, but the CO_2 -C emission rates in the soil amended with residue were relatively steady and still higher than the N and CK treatments. After 190 days of incubation, the CO_2 -C emission rates under different treatments reached background levels. There was significant interaction between maize residue and urea N on total soil CO_2 -C emissions (Table 2). Throughout the whole experiment, the order of average CO_2 -C emission rate was as follows: Maize residue ($844 \pm 4 \mu g \text{ kg}^{-1} \text{ h}^{-1}$) > Maize + N ($545 \pm 17 \mu g \text{ kg}^{-1} \text{ h}^{-1}$) > N ($199 \pm 8 \mu g \text{ kg}^{-1} \text{ h}^{-1}$) > CK ($133 \pm 2 \mu g \text{ kg}^{-1} \text{ h}^{-1}$).

Cumulative CO_2 -C emissions were in the same order as the average CO_2 -C emission rates under different treatments (Fig. 1b). Compared with the CK ($693 \pm 17 \text{ mg C kg}^{-1} \text{ soil}$), the cumulative CO_2 -C emissions increased by $63 \pm 4\%$, $37 \pm 4\%$, and $9 \pm 1\%$ in the

Fig. 1. Effects of maize residue and urea N additions on (a) CO_2 -C emission rates and (b) cumulative CO_2 -C emissions. CK represents soil with no additions ($\bullet$), Maize represents soil amended with maize residue ($\circ$), N represents soil amended with urea nitrogen ($\blacktriangle$), Maize + N represents soil amended with maize residue together with urea N ($\triangle$). Values represent means $\pm$ SE ($n = 3$).

Table 2

Effects of maize residue, urea N and their interaction on soil CO_2 emissions during 250 days of incubation.

	Maize residue	N	Maize residue $\times$ N
Total soil CO_2 emissions			
df	1	1	1
F value	9034.83	436.10	1076.17
P value	<0.001	<0.001	<0.001
Native SOC derived CO_2 emissions			
df	1	1	1
F value	29.79	55.55	22.73
P value	<0.001	<0.001	<0.001

Maize, Maize + N, and N treatments, respectively. Although $\text{CO}_2\text{-C}$ emission rates were significantly higher in the first 15 days of incubation in the maize-amended soil, it only accounted for 22–26% of the cumulative $\text{CO}_2\text{-C}$ emissions. Approximately 94–96% of the cumulative $\text{CO}_2\text{-C}$ was emitted over the first 190 days of incubation.

3.2. Priming effect

According to the $\delta^{13}\text{C}\text{-CO}_2$, we calculated the priming effect induced by the addition of maize residue and urea N (Fig. 2). A negative priming effect was observed in the Maize and Maize + N treatments within the first 7 days of incubation. The priming then switched from negative to positive between day 7 to day 65 in the Maize treatment, and from day 7 to day 35 in the Maize + N treatment; after that it returned to negative priming effect in both the Maize and Maize + N treatments. In contrast, adding N alone caused a positive effect over the first 65 days of incubation, after that there was a slight negative priming effect. At the end of the experiment, the overall effects of application of maize residue and urea N on the decomposition of native SOC were as follows: application of maize residue alone had little effect on the decomposition of native SOC, since the positive priming effect was offset by the negative priming effect; adding urea N alone stimulated the decomposition of SOC by $9.1 \pm 0.6\%$, while adding N to soil amended with maize residue retarded the decomposition of SOC by $9.5 \pm 2.7\%$ (Fig. 3). There was significant interaction between maize residue and urea N on the decomposition of native SOC (Table 2). At the end of the incubation, about 39.5% and 33.7% of the cumulative $\text{CO}_2\text{-C}$ emissions originated from the decomposition of maize residue in the Maize and Maize + N treatments, respectively. The amount of residue-inhibited SOC decomposition per unit maize mineralized was greater in the Maize + N treatment (0.21 ± 0.06) than in the Maize treatment (0.03 ± 0.05).

3.3. Mineralization of maize residue

Adding urea N had little effect on the mineralization of maize residue in the first 20 days of incubation (Table 3). However, it had a stimulatory effect on the mineralization of maize residue thereafter ($P < 0.05$; Table 3). At the end of the experiment, about 16.4% and 18.5% of the added maize C was decomposed in the Maize and Maize + N treatments, respectively.

3.4. Mineral N content in the soil

The concentration of mineral N in the Maize treatment decreased from an initial $67.6 \text{ mg N kg}^{-1}$ soil to $15.9 \text{ mg N kg}^{-1}$ soil within 25 days (Fig. 4). Although the mineral N content increased at the later stage of incubation, it was still lower than that in the CK. This indicates that adding maize residue alone caused N immobilization. In the Maize + N treatment, the concentration of mineral N increased gradually during the first day, followed by a decrease over the next 10 days, and an increase in the following 5 days; thereafter it was relatively constant. The increased mineral N during the first day might be the result of the release of N from the maize residue and the soil N pool. Throughout the whole experiment, a combination of maize residue and urea N significantly increased the N availability in the soil as compared to the CK. The amounts of mineral N content in the N and CK treatments were relatively constant over the whole experiment. The average mineral N content was in the order of: N ($91 \pm 0.4 \text{ mg N kg}^{-1}$) > Maize + N ($78 \pm 1 \text{ mg N kg}^{-1}$) > CK ($66 \pm 1 \text{ mg N kg}^{-1}$) > Maize ($40 \pm 0.3 \text{ mg N kg}^{-1}$). The average mineral N content in the soil was 0.8% and 2.1% of the added straw dry matter in the Maize and Maize + N treatments, respectively.

3.5. MBC and DOC in the soil

Adding maize residue alone or with N significantly increased the MBC content in the soil (Fig. 5a). Two peaks of MBC were observed in the maize-amended soils: the first one was observed after 1 h of maize residue addition, with a maximum of 666 mg

Fig. 2. Effects of maize residue and urea N additions on the priming effect. Results are expressed in cumulative values (means $\pm$ SE, $n = 3$). Maize represents soil amended with maize residue (○), N represents soil amended with urea nitrogen (▼), Maize + N represents soil amended with maize residue together with urea N (△). Values represent means $\pm$ SE ($n = 3$).

Fig. 3. Maize-derived C and native soil derived-C in the cumulative CO₂ emissions under different treatments. Different letters (lower case for maize-derived C, upper case for native soil derived C) indicate significant differences at $P < 0.05$. Values represent means $\pm$ SE ($n = 3$).

Table 3

Cumulative mineralization rate of maize residue (%) at different sampling times ($n = 3$).

	0 d	7 d	20 d	35 d	65 d	130 d	250 d
Maize	1.63 $\pm$ 0.03a	6.42 $\pm$ 0.10a	9.17 $\pm$ 0.06a	10.38 $\pm$ 0.07b	12.81 $\pm$ 0.12b	15.00 $\pm$ 0.07b	16.41 $\pm$ 0.19b
Maize + N	1.41 $\pm$ 0.20a	5.98 $\pm$ 0.25a	9.31 $\pm$ 0.16a	10.87 $\pm$ 0.20a	13.68 $\pm$ 0.27a	16.55 $\pm$ 0.32a	18.48 $\pm$ 0.36a

Different letters in the same column indicate significant differences at $P < 0.05$.

C kg⁻¹ in the Maize treatment and 592 mg C kg⁻¹ in the Maize + N treatment; another peak was observed after 5 days of incubation. Throughout the experiment, the mean MBC content in the Maize

and Maize + N and N treatments was 84%, 59% and 6%, respectively, greater than that in the CK (237 ± 6 mg C kg⁻¹, $P < 0.05$). A significant positive relationship between MBC and maize-derived

Fig. 4. Effects of maize residue and urea N additions on mineral N content. CK represents soil with no additions (●), Maize represents soil amended with maize residue (○), N represents soil amended with urea nitrogen (▼), Maize + N represents soil amended with maize residue together with urea N (△). Values represent means $\pm$ SE ($n = 3$).

Fig. 5. Effects of maize residue and urea N additions on MBC and DOC. CK represents soil with no additions (●), Maize represents soil amended with maize residue (○), N represents soil amended with urea nitrogen (▼), Maize + N represents soil amended with maize residue together with urea N (△). Values represent means $\pm$ SE ($n=3$).

CO₂ emissions was observed in the maize-amended soils ($R=0.784$, 0.714 for the Maize and Maize+N treatments, $P<0.05$, $n=18$). A similar relationship was found between total soil CO₂ emissions and MBC in the maize-amended soils, but it had a lower correlation coefficient ($R=0.514$, 0.682 for the Maize and Maize+N treatments, $P<0.05$, $n=18$). This indicates that maize residue addition increased microbial activity and the microorganisms were more inclined to mineralize maize residues than the relatively recalcitrant SOC.

The DOC concentration ranged from 64 to 227 mg C kg⁻¹, and two peaks of DOC concentration in the soil were observed at 2 days and 45 days following the application of maize residue and urea N (Fig. 5b). DOC concentrations were highly variable between different treatments in the first day, while displaying a similar pattern thereafter. Throughout the experiment, the DOC concentration increased by 19%, 10% and 5% in the Maize, Maize+N and urea N treatments, respectively, as compared to the CK (135 ± 0.3 mg C kg⁻¹). There was a positive relationship between DOC concentration and maize-derived CO₂ emissions in the maize-amended soils ($R=0.476$, 0.745 for the Maize and Maize+N treatments, $P<0.05$, $n=18$). A similar relationship was found between total soil CO₂ emissions and DOC in the maize-amended soils, but it had a lower correlation coefficient ($R=0.457$, 0.258 for the Maize and Maize+N treatments, $P<0.05$, $n=18$). This suggests that the addition of maize residue stimulated DOC release, and exogenous N supply met the demand of decomposer populations for available N. Abundant available substrate (C and N sources) supply further enhanced the decomposition of maize residue.

4. Discussion

4.1. Effect of N and crop residue additions on the decomposition of native SOC

Application of maize residue and urea N significantly increased total soil CO₂ emissions. This was in the order of Maize > Maize+N > N > CK. Adding urea N alone increased the decomposition of SOC by 9.1%. Similar results have previously been observed both in the field and in the laboratory. Lu et al. (2011) and Ding et al. (2010) found that N addition increased SOC decomposition by 6.5–16.1%

in the field, and Lu et al. (2014) reported that N addition significantly increased soil CO₂ emissions by 35.6% in a laboratory incubation. The positive effect observed during the current experiment was likely related to the increased microbial biomass, DOC and N availability in N-amended soil as compared to the CK (Figs. 4 and 5), since those factors have a positive effect on the decomposition of SOC (Kuzakov et al., 2000; Chen et al., 2014; Lu et al., 2014). Moreover, N addition could increase the activity of cellulose-decomposing enzymes in the soil (Henriksen and Breland, 1999; Carreiro et al., 2000; Keeler et al., 2009) and accelerate the decomposition of soil labile C (Neff et al., 2002; Keeler et al., 2009; Ding et al., 2010; Lu et al., 2014), but decrease the activity of lignin-degrading enzymes and retard the decomposition of recalcitrant SOC (Green et al., 1995; Carreiro et al., 2000). This could explain why a positive effect of N addition on the decomposition of native SOC was observed over the first 65 day, followed by a slight negative effect.

The maize residue addition alone retarded the decomposition of native SOC in the first 7 days of incubation and accelerated the decomposition of native SOC in the medium stage of incubation (from day 7 to day 65); thereafter it strongly reduced the decomposition of native SOC (Fig. 2). Changes in the priming effect over time led to the final CO₂ emissions derived from the native SOC in the Maize treatment being comparable to that in the CK (Fig. 3). The reasons for the changes in the priming effect from negative to positive might be as follows: the decomposition of maize residue at the early stage was dominated by mineralization of the easily decomposable soluble fractions (e.g., carbohydrates and amino acids) released from the maize residue, and the microorganisms could preferentially utilize the soluble fractions derived from maize residue rather than the recalcitrant fractions of native SOC (Green et al., 1995; Kuzakov and Bol, 2006; Khan et al., 2007; Guenet et al., 2010). However, during the subsequent stage (from day 7 to day 65), although the DOC was relatively constant (Fig. 5b), the mineral N content in the soil decreased rapidly (Fig. 4). Thus the available N in the soil was probably not sufficient to meet the demand of microbes, which led to the microbes decomposing recalcitrant SOC to acquire available N (Blagodatskaya et al., 2009; Chen et al., 2014). Therefore, a positive priming effect occurred. Moreover, N limitation might lead to a shift of

microbes from r- to K-strategists, and the K-strategists are considered to be able to decompose recalcitrant SOC for mineral N acquisition (Fontaine et al., 2003; Blagodatskaya et al., 2009; Chen et al., 2014). The causes of the negative priming effect in the later stage of incubation might be the result of the re-release of the added maize residue which was adsorbed or physico-chemical protected by the soil as the maize residue was incorporated into the soil (Kuzyakov et al., 2000). Another possible reason is remineralization of residue-¹³C immobilized by the microbes due to microbial death and cell lysis (Dalenberg and Jager, 1989; Kuzyakov et al., 2000; Fontaine et al., 2011). It has been reported that the microbes have a lower C/N ratio than crop residue and SOC (Pulleman and Tietema, 1999; Kuzyakov et al., 2000; Cleveland and Liptzin, 2007; Fontaine et al., 2011), thus the former may be preferentially utilized by the remaining microbes in the soil. At first sight, such priming effect dynamics (switch from negative to positive effect) seems to be unusual because in most previous experiments a one directional change occurred: decrease (Dalenberg and Jager, 1989; Kuzyakov et al., 2000; Blagodatskaya and Kuzyakov, 2008; Lu et al., 2014) or increase (Conde et al., 2005; Chen et al., 2007; Kochsiek et al., 2013; Li et al., 2013; Chen et al., 2014; Mazzilli et al., 2014). Previous studies suggested that the observation of only one direction of the priming effect might result from a long sampling interval, thereby missing the change from decreased to increased decomposition of SOC at the initial stage of organic substances addition (Kuzyakov and Bol, 2006). Also, a short-term incubation might miss changes in the priming effect at the medium and later stages of decomposition. It is important to note that the priming effect may not be a short-term phenomenon but that it can persist for many weeks or several months after the complete decomposition of organic substrates (Fontaine et al., 2004, 2011). The decomposition of maize residue is usually characterized by three stages: a rapid decomposition at the beginning when the easily decomposable soluble fractions are available, followed by an intermediate rate when cellulose and hemicellulose are decomposing, and thereafter a slow rate when lignin is decomposing (Recous et al., 1995; Hadas et al., 2004). The response of the priming effect to the decomposition of maize residue in its early stage differed from that in the medium and later stages. At the end of the experiment, adding maize residue alone had little effect on the decomposition of native SOC, suggesting that the overall effect was dependent on the balance between positive and negative effects.

The dynamics of the priming effect in the Maize + N treatment was similar to the Maize treatment. We attributed the initial negative priming effect to preferential substrate utilization by microorganisms (Kuzyakov and Bol, 2006; Guenet et al., 2010), as discussed above. However, the following positive priming effect had a smaller intensity and shorter duration in the Maize+N treatment than that in the Maize treatment. This may be partially attributed to the higher N availability and relatively steady DOC contents in the Maize+N treatment (Figs. 4 and 5a). An increased availability of microbial substrate induced extracellular enzyme production or increased enzyme activity leading to co-mineralize fresh C and recalcitrant SOC (Kuzyakov et al., 2000; Blagodatskaya and Kuzyakov, 2008). This mechanism of the priming effect may also have occurred in the Maize treatment, but N deficiency accelerating SOC decomposition may dominate in the Maize treatment. A more pronounced negative priming effect occurred in the Maize + N treatment as the experiment proceeded. Apart from the reasons mentioned for the Maize treatment that could explain this phenomenon, additional reasons might be as follows: First, adding N to the soil resulted in a more efficient utilization of maize residues by microbes at the slow mineralization stage (Table 3); N addition could increase the C availability to microbial mineralization at the slow mineralization stage (Blagodatskaya et al., 2009).

As a result, microbes may preferentially decompose the more available substrate released from residue rather than the recalcitrant SOC (Kuzyakov and Bol, 2006; Guenet et al., 2010). The positive relationship between MBC and maize-derived CO₂ further confirmed that the microbes were more inclined to use maize residue rather than native SOC; Second, N addition had a positive effect on the decomposition of maize residue at the later stage of degradation, while added mineral N had opposite effects on the decomposition of maize residue and the recalcitrant SOC, since a high concentration of N inhibits the degradation of humic substances (Green et al., 1995; Sall et al., 2007). At the end of the experiment, the net effect of N added to the maize-amended soil was negative. The significant interaction between maize residue and urea N was the result of a reduction in the decomposition of native SOC (Table 2). This led to the decomposition of native SOC decreasing by 9.5% as compared to the CK. A decrease in SOC decomposition in response to N and organic substance additions have also been observed in other studies (Khan et al., 2007; Blagodatskaya et al., 2009; Guenet et al., 2010; Fontaine et al., 2011; Chen et al., 2014). The negative effect of combining maize residue with N on the decomposition of native SOC demonstrates that there is a beneficial response by stabilization of organic C in our test soil. In addition, the priming effect may persist much longer than previously believed. In order to precisely estimate the contribution of complex organic substances and/or mineral N addition on the decomposition of native SOC, we should consider the priming effect on a long time scale. The mechanisms of the priming effect may be modified by the N input. If the soil is rich in available C, but the available N is lacking, then the microbes may increase SOC mineralization to meet the N requirement. However, if the available N is rich, microbial activity may increase, which in turn increases native SOC mineralization. Therefore, the controversial hypotheses of N availability on the priming effect are not paradoxical. Soil microorganisms may simply adjust their activities or composition according to soil N availability.

4.2. Effect of N addition on the mineralization of maize residue

Soil amended with maize residue (the Maize and Maize + N treatments) showed an initial CO₂-C release flush (Fig. 1a). This phenomenon was also observed by Chen et al. (2009) and Moreno-Cornejo et al. (2014). The initial CO₂-C flush was mainly derived from the decomposition of maize residue, since the contribution of maize-derived C to the emitted CO₂-C was about 99% and 90% in the Maize and Maize+N treatments, respectively in the first day. The contribution, however, decreased as the experiment proceeded. The decomposition of maize residue exhibited two distinct phases: an initially fast decay stage (lasting for about 15 days), followed by a relatively slow decay phase (from day 15 to day 190 of the incubation). Similarly, Chen et al. (2009) reported that maize residue was rapidly mineralized in the soil over the first 14 days of incubation and the subsequent decomposition was slow. Higher rates of soil respiration in the first stages of incubation were likely a consequence of higher microbial biomass and DOC content in the soil amended with maize residue (Fig. 5). Previous studies found that maize residue addition provided sufficient readily available substrates and nutrients (such as non-cellulosic polysaccharides and amino acids) to microorganisms and activated microbial activities in the first stage of incubation (John et al., 2003; Marschner and Kalbitz, 2003; Hadas et al., 2004; Chen et al., 2009). The decrease in the respiration in the following days might be due to a decline in the quality of substrate and microbial biomass in the soil (Fig. 5). In the slow decomposition stage, a slight increase in CO₂ emissions on day 45 might be attributed to an increased DOC content in the soil, since there was a close positive relationship between DOC and maize-derived CO₂ flux throughout the experiment.

After 250 days of incubation, 16.4% of the input ^{13}C in the Maize treatment had been released as $^{13}\text{CO}_2$ and this value increased to 18.5% in the Maize + N treatment (Table 3). This indicates that N addition had a positive effect on the mineralization of maize residue. However, this positive effect was not observed until after 20 days of incubation, and became increasingly pronounced thereafter (Table 3). This is consistent with the results of Blagodatskaya et al. (2009), who observed that adding N to the soil led to microbes utilizing maize residue more efficiently during the slow mineralization stage. The reason for the increase of decomposer efficiency with increasing N availability may be related to a shift in the decomposer community composition, toward microorganisms that are more efficient but have a greater N requirement (Ågren et al., 2001). Although rapid N immobilization occurred after the maize residue addition (Fig. 4), there was no significant difference in the mineralization rate of the maize residue in the Maize and Maize + N treatments in the first 20 days of incubation (Table 3). Similarly, Hadas et al. (2004) and Recous et al. (1995) also observed that N deficiency did not reduce the decomposition of maize residue in the first two weeks, suggesting that the initial N availability (soil mineral N and easily decomposable residue N) was not a limiting factor for the decomposition of maize residue at the early stage of degradation (Henriksen and Breland, 1999; Trinsoutrot et al., 2000). However, as the experiment proceeded (from day 20 to day 65), the decline in the quality of substrate and soil N availability in the Maize treatment coincided with the reduction in the mineralization rate of maize residue (Fig. 1a; Table 3), whereas the MBC content in the Maize treatment was significantly higher than in the Maize + N treatment (Fig. 5). This might be attributed to an acceleration of biomass N recycling, changes in C and N metabolism (Recous et al., 1995; Fontaine et al., 2011), and changes in microbial succession since the microbial succession was considered as a function of the nature of the substrate being decomposed (Swift et al., 1979; Henriksen and Breland, 1999). Although the mineral N content in the Maize treatment increased at the later stage of incubation (from day 65 to day 250; Fig. 4), the concentration of available N was about 1% of the added straw dry matter in the Maize treatment (2.10% for the Maize + N treatment). Concentrations of available N below 1.2% of straw dry matter significantly reduced the rate of C mineralization from straw residues (Pinck et al., 1950; Recous et al., 1995). This suggests that N deficiency could be responsible for the relatively low amount of straw mineralization in the Maize treatment. In contrast, the mineral N content in the Maize + N treatment was about two times higher than in the Maize treatment, and the N availability can have significant long-term effects on the decomposition of maize residue in the soil (Green et al., 1995; Blagodatskaya et al., 2009). Therefore, N addition resulted in a relatively higher mineralization rate of maize residue. As the maize residue has a large amount of the intermediately available C (e.g., cellulose and hemicellulose, accounting for 40–50% of the total C) (Hadas et al., 2004), which will be degraded followed by the exhaustion of readily available C (Henriksen and Breland, 1999; Hadas et al., 2004; Chen et al., 2009), adding N fertilizer could increase the activity of β -glucosidase and cellobiohydrolase, which in turn will promote the mineralization of the maize residue (Chen et al., 2014; Lu et al., 2014).

5. Conclusions

The priming effect may persist for a long time because of incorporation of complex organic substances into the soil and the intensity of the priming effect depends on the microbial biomass, substrate C and N availability and the stage of decomposition. The mechanisms of the priming effect involved in this study may include: preferential substrate utilization, activation of microbial

activity, co-metabolism, and microbial succession. Adding N alone had a positive effect on the mineralization of native SOC. The overall effect of N added to the maize-amended soil caused a negative priming effect on the decomposition of native SOC, which is favorable for soil C sequestration. Also, the addition of urea N increased the decomposition of maize residue at the slow mineralization stage; the higher available mineral N and microbial biomass, as well as the DOC content were responsible for this stimulatory effect. The response of the priming effect to the addition of maize residue and urea N has important practical implications for the farmer. Application of N fertilizer to the maize-amended soil or incorporation of maize residue alone was favorable for soil C sequestration. But incorporation of large quantities of maize residues in soil would probably lead to N immobilization, which would restrict N availability for growing crops in the field. Moreover, the amount of residue-inhibited SOC mineralization per unit maize mineralized was greater when N fertilizer was incorporated into maize-amended soil. Therefore, adding N fertilizer to maize-amended soil would be a better option for crop growth and soil C sequestration in the field.

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References

- Ågren, G.I., Bosatta, E., Magill, A.H., 2001. Combining theory and experiment to understand effects of inorganic nitrogen on litter decomposition. *Oecologia* 128, 94–98.
- Blagodatskaya, E., Blagodatsky, S., Anderson, T.H., Kuzyakov, Y., 2009. Contrasting effects of glucose, living roots and maize straw on microbial growth kinetics and substrate availability in soil. *Eur. J. Soil Sci.* 60, 186–197.
- Blagodatskaya, E., Kuzyakov, Y., 2008. Mechanisms of real and apparent priming effects and their dependence on soil microbial biomass and community structure: critical review. *Biol. Fertil. Soils* 45, 115–131.
- Carreiro, M., Sinsabaugh, R., Repert, D., Parkhurst, D., 2000. Microbial enzyme shifts explain litter decay responses to simulated nitrogen deposition. *Ecology* 81, 2359–2365.
- Chen, H., Billen, N., Stahr, K., Kuzyakov, Y., 2007. Effects of nitrogen and intensive mixing on decomposition of ^{14}C -labelled maize (*Zea mays* L.) residue in soils of different land use types. *Soil Till. Res.* 96, 114–123.
- Chen, H., Fan, M., Billen, N., Stahr, K., Kuzyakov, Y., 2009. Effect of land use types on decomposition of ^{14}C -labelled maize residue (*Zea mays* L.). *Eur. J. Soil Biol.* 45, 123–130.
- Chen, R., Senbayram, M., Blagodatsky, S., Myachina, O., Dittert, K., Lin, X., Blagodatskaya, E., Kuzyakov, Y., 2014. Soil C and N availability determine the priming effect: microbial N mining and stoichiometric decomposition theories. *Global Change Biol.* 20, 2356–2367.
- Cleveland, C.C., Liptzin, D., 2007. C: N: P stoichiometry in soil: is there a Redfield ratio for the microbial biomass? *Biogeochemistry* 85, 235–252.
- Conde, E., Cardenas, M., Ponce-Mendoza, A., Luna-Guido, M.L., Cruz-Mondragón, C., Dendooven, L., 2005. The impacts of inorganic nitrogen application on mineralization of ^{14}C -labelled maize and glucose, and on priming effect in saline alkaline soil. *Soil Biol. Biochem.* 37, 681–691.
- Cui, F., Yan, G., Zhou, Z., Zheng, X., Deng, J., 2012. Annual emissions of nitrous oxide and nitric oxide from a wheat–maize cropping system on a silt loam calcareous soil in the North China Plain. *Soil Biol. Biochem.* 48, 10–19.
- Dalenberg, J.W., Jager, G., 1989. Priming effect of some organic additions to ^{14}C -labelled soil. *Soil Biol. Biochem.* 21, 443–448.
- Derrien, D., Plain, C., Courty, P.-E., Gelhaye, L., Moerdijk-Poortvliet, T.C., Thomas, F., Versini, A., Zeller, B., Koutika, L.-S., Boschker, H.T., 2014. Does the addition of labile substrate destabilise old soil organic matter? *Soil Biol. Biochem.* 76, 149–160.
- Dimassi, B., Mary, B., Fontaine, S., Perveen, N., Revalliot, S., Cohan, J.-P., 2014. Effect of nutrients availability and long-term tillage on priming effect and soil C mineralization. *Soil Biol. Biochem.* 78, 332–339.
- Ding, W., Yu, H., Cai, Z., Han, F., Xu, Z., 2010. Responses of soil respiration to N fertilization in a loamy soil under maize cultivation. *Geoderma* 155, 381–389.
- FAO, J., FOODS, M.H.I., (2004). Food and Agriculture organization of the United Nations. Rome, URL: <http://faostat.fao.org>.

- Fontaine, S., Bardoux, G., Benest, D., Verdier, B., Mariotti, A., Abbadie, L., 2004. Mechanisms of the priming effect in a savannah soil amended with cellulose. *Soil Sci. Soc. Am. J.* 68, 125–131.
- Fontaine, S., Henault, C., Aamor, A., Bdioui, N., Bloor, J., Maire, V., Mary, B., Revaillet, S., Maron, P., 2011. Fungi mediate long term sequestration of carbon and nitrogen in soil through their priming effect. *Soil Biol. Biochem.* 43, 86–96.
- Fontaine, S., Mariotti, A., Abbadie, L., 2003. The priming effect of organic matter: a question of microbial competition? *Soil Biol. Biochem.* 35, 837–843.
- Green, C., Blackmer, A., Horton, R., 1995. Nitrogen effects on conservation of carbon during corn residue decomposition in soil. *Soil Sci. Soc. Am. J.* 59, 453–459.
- Gregorich, E., Beare, M., Stoklas, U., St-Georges, P., 2003. Biodegradability of soluble organic matter in maize-cropped soils. *Geoderma* 113, 237–252.
- Guenet, B., Neill, C., Bardoux, G., Abbadie, L., 2010. Is there a linear relationship between priming effect intensity and the amount of organic matter input? *Appl. Soil Ecol.* 46, 436–442.
- Hadas, A., Kautsky, L., Goek, M., Erman Kara, E., 2004. Rates of decomposition of plant residues and available nitrogen in soil, related to residue composition through simulation of carbon and nitrogen turnover. *Soil Biol. Biochem.* 36, 255–266.
- Henriksen, T., Breland, T., 1999. Nitrogen availability effects on carbon mineralization, fungal and bacterial growth, and enzyme activities during decomposition of wheat straw in soil. *Soil Biol. Biochem.* 31, 1121–1134.
- Huang, Y., Zou, J., Zheng, X., Wang, Y., Xu, X., 2004. Nitrous oxide emissions as influenced by amendment of plant residues with different C:N ratios. *Soil Biol. Biochem.* 36, 973–981.
- John, B., Ludwig, B., Flessa, H., 2003. Carbon dynamics determined by natural ^{13}C abundance in microcosm experiments with soils from long-term maize and rye monocultures. *Soil Biol. Biochem.* 35, 1193–1202.
- Keeler, B.L., Hobbie, S.E., Kellogg, L.E., 2009. Effects of long-term nitrogen addition on microbial enzyme activity in eight forested and grassland sites: implications for litter and soil organic matter decomposition. *Ecosystems* 12, 1–15.
- Khan, S., Mulvaney, R., Ellsworth, T., Boast, C., 2007. The myth of nitrogen fertilization for soil carbon sequestration. *J. Environ. Qual.* 36, 1821–1832.
- Kochsiek, A., Knops, J., Zhang, W., 2013. Effects of nitrogen availability on the fate of litter-carbon and soil organic matter decomposition. *Br. J. Environ. Clim. Change* 3, 24–43.
- Kuzyakov, Y., 2002. Review: factors affecting rhizosphere priming effects. *J. Plant Nutr. Soil Sci.* 165, 382.
- Kuzyakov, Y., Bol, R., 2006. Sources and mechanisms of priming effect induced in two grassland soils amended with slurry and sugar. *Soil Biol. Biochem.* 38, 747–758.
- Kuzyakov, Y., Friedel, J.K., Stahr, K., 2000. Review of mechanisms and quantification of priming effects. *Soil Biol. Biochem.* 32, 1485–1498.
- Li, L., Han, X., You, M., Yuan, Y., Ding, W., Qiao, Y., 2013. Carbon and nitrogen mineralization patterns of two contrasting crop residues in a Mollisol: effects of residue type and placement in soils. *Eur. J. Soil Biol.* 54, 1–6.
- Lu, R.K., 2000. *Methods for Soil Agrochemistry Analysis*. China Agricultural Science and Technology Press, Beijing, pp. 106–310.
- Lu, M., Zhou, X., Luo, Y., Yang, Y., Fang, C., Chen, J., Li, B., 2011. Minor stimulation of soil carbon storage by nitrogen addition: a meta-analysis. *Agric. Ecosyst. Environ.* 140, 234–244.
- Lu, W., Ding, W., Zhang, J., Li, Y., Luo, J., Bolan, N., Xie, Z., 2014. Biochar suppressed the decomposition of organic carbon in a cultivated sandy loam soil: a negative priming effect. *Soil Biol. Biochem.* 76, 12–21.
- Marschner, B., Kalbitz, K., 2003. Controls of bioavailability and biodegradability of dissolved organic matter in soils. *Geoderma* 113, 211–235.
- Mazzilli, S.R., Kemanian, A.R., Ernst, O.R., Jackson, R.B., Piñeiro, G., 2014. Priming of soil organic carbon decomposition induced by corn compared to soybean crops. *Soil Biol. Biochem.* 75, 273–281.
- Meng, L., Ding, W., Cai, Z., 2005. Long-term application of organic manure and nitrogen fertilizer on N_2O emissions, soil quality and crop production in a sandy loam soil. *Soil Biol. Biochem.* 37, 2037–2045.
- Moreno-Cornejo, J., Zornoza, R., Faz, A., 2014. Carbon and nitrogen mineralization during decomposition of crop residues in a calcareous soil. *Geoderma* 230–231, 58–63.
- Neff, J.C., Townsend, A.R., Gleixner, G., Lehman, S.J., Turnbull, J., Bowman, W.D., 2002. Variable effects of nitrogen additions on the stability and turnover of soil carbon. *Nature* 419, 915–917.
- Nohrstedt, H.-Ö., Arnebrant, K., Bååth, E., Söderström, B., 1989. Changes in carbon content, respiration rate, ATP content, and microbial biomass in nitrogen-fertilized pine forest soils in Sweden. *Can. J. For. Res.* 19, 323–328.
- Nottingham, A.T., Griffiths, H., Chamberlain, P.M., Stott, A.W., Tanner, E.V., 2009. Soil priming by sugar and leaf-litter substrates: a link to microbial groups. *Appl. Soil Ecol.* 42, 183–190.
- Pinck, L.A., Allison, F.E., Sherman, M.S., 1950. Maintenance of soil organic matter: II. losses of carbon and nitrogen from young and mature plant materials during decomposition in soil. *Soil Sci.* 69, 391–402.
- Pulleman, M., Tietema, A., 1999. Microbial C and N transformations during drying and rewetting of coniferous forest floor material. *Soil Biol. Biochem.* 31, 275–285.
- Recous, S., Robin, D., Darwis, D., Mary, B., 1995. Soil inorganic N availability: effect on maize residue decomposition. *Soil Biol. Biochem.* 27, 1529–1538.
- Sall, S., Bertrand, I., Chotte, J.L., Recous, S., 2007. Separate effects of the biochemical quality and N content of crop residues on C and N dynamics in soil. *Biol. Fertil. Soils* 43, 797–804.
- Swift, M.J., Heal, O.W., Anderson, J.M., 1979. *Decomposition in Terrestrial Ecosystems*. Univ of California Press, pp. 66–112.
- Thangarajan, R., Bolan, N.S., Tian, G., Naidu, R., Kunhikrishnan, A., 2013. Role of organic amendment application on greenhouse gas emission from soil. *Sci. Total Environ.* 1–25.
- Trinsoutrot, I., Recous, S., Mary, B., Nicolardot, B., 2000. C and N fluxes of decomposing ^{13}C and ^{15}N *Brassica napus* L.: effects of residue composition and N content. *Soil Biol. Biochem.* 32, 1717–1730.
- Vance, E.D., Brookes, P.C., Jenkinson, D.S., 1987. An extraction method for measuring soil microbial biomass C. *Soil Biol. Biochem.* 19, 703–707.
- Wang, Q., Wang, S., He, T., Liu, L., Wu, J., 2014. Response of organic carbon mineralization and microbial community to leaf litter and nutrient additions in subtropical forest soils. *Soil Biol. Biochem.* 71, 13–20.