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Soil Respiration, Nitrification, and Denitrification in a Wheat Farmland Soil under Different Managements

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A field experiment was conducted during the 2010 to 2011 winter wheat–growing season to understand the soil respiration (R_s)*, nitrification, and denitrification rates in winter wheat farmland soil under no-tillage (NT) treatment with rice straw incorporation. The experimental treatments include NT, NT with rice straw covers on the surface (NTS), conventional tillage (CT), and CT with straw incorporation (CTS). No-tillage and straw incorporation treatments did not change the seasonal patterns of* R_s*, gross nitrification* (Gn)*, and denitrification* (D) *rates compared with CT. Compared with the CT treatment, the NT, NTS, and CTS treatments significantly reduced* R_s ($P < 0.01$)*, and the NT and NTS treatments significantly increased* Gn *and* D ($P < 0.01$)*. CTS also significantly increased* Gn ($P < 0.01$) *but had no significant effect on* D ($P > 0.05$)*. Further analysis showed that the temperature sensitivity of soil respiration* (Q_{10}) *of CT, NT, NTS, and CTS were 4.26, 1.86, 3.25, and 2.36, respectively. Our findings suggest that, compared with CT, the NT and straw incorporation treatments reduced* R_s *and* Q_{10} *and increased* Gn *and* D.

Keywords Denitrification, nitrification, no-tillage, rice straw incorporation, soil respiration, winter wheat

Introduction

The carbon (C) content in the soil pool is more than 1,750 Gt or approximately three times the vegetation C pool and twice the atmospheric pool (Granier et al. 2000). Therefore, any small changes in the soil C pool can adversely affect global C cycling. The soil C pool in croplands is an important part of the overall terrestrial ecosystem C pool. Carbon sequestration from croplands plays an important role in global change (Smith 2004). Meanwhile, croplands are one of the most active ecosystems affected by human activities.

Soil respiration, including the autotrophic respiration of plant roots and heterotrophic respiration of soil microorganisms, plays a key role in global C cycling (Buchmann 2000; Schlesinger and Andrews 2000). In addition, soil respiration and global warming closely

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influence each other (Sánchez et al. 2003; Schlesinger and Andrews 2000). Nitrification and denitrification are important processes involving nitrogen (N) turnovers and removals from agricultural ecosystems (Currie 1996; Müller, Stevens, and Laughlin 2004; Cookson et al. 2006). Moreover, these processes are the main sources of nitrous oxide (N_2O) and nitric oxide (NO) from soils (Russow, Spott, and Stange 2008; Skiba, Smith, and Fowler 1993).

Agricultural management affects the soil respiration rate (R_s) (Ding et al. 2007). Straw incorporation is an important strategy in organic-matter management in farmlands (Nie et al. 2007) as it can increase the soil organic C content (Freibauer et al. 2004) and influence R_s (Duong, Baumann, and Marschner 2009; Iqbal et al. 2009). Compared with conventional tillage (CT), the no-tillage (NT) approach can protect the structure of soil aggregates (Pikul et al. 2009; Olchin et al. 2008), strengthen soil mineralization, and increase soil C storage capacity (Jacobs et al. 2010). Previous studies have suggested that different tillage approaches could affect the soil N mineralization potential and N transformation (Kheyrodin and Antoun 2009; Muruganandam, Israel, and Robarge 2010). These approaches could also alter the quantity and microbial activity of soil microorganisms, thereby affecting the soil N cycle (Muruganandam, Israel, and Robarge 2010; Mahía et al. 2007). To our knowledge, only Gesch et al. (2007) and Dexter et al. (2000) have documented the effects of tillage and plant residue management on the soil respiration of agricultural soil. Thus, the possible impacts of tillage and straw incorporation on soil respiration, nitrification, and denitrification in typical croplands need further investigation.

In this study, we hypothesized that NT and straw incorporation approaches might reduce the R_s and increase the gross nitrification (Gn) and denitrification (D) rates in farmland soil. To test this hypothesis, we performed a field experiment on a winter wheat farmland. The objective was to investigate the effects of NT and straw incorporation treatments on the R_s, Gn, and D in cropland soil.

Materials and Methods

Experimental Site

The field experiment was conducted in a farmland at the Ecological and Agricultural Meteorology Experimental Station (32.16° N, 118.86° E), Nanjing University of Information Science and Technology, Southeast China. Annual rotations, such as paddy rice (*Oryza sativa*)–winter wheat (*Triticum aestivum*) and soybean (*Glycine max*)–winter wheat, are the main agricultural cropping systems in this area. The annual average temperature and rainfall in this site are 15.6 °C and 1,100 mm, respectively. The soil (0 cm to 20 cm) is classified as hydromorphic, containing 26.1% clay with an initial pH (H_2O) level of 6.20, total organic C of 14.98 g kg^{-1}, and total N of 0.77 g kg^{-1}.

Field Experiments

The field experiments were conducted during the 2010–2011 winter wheat–growing season. A local prevailing winter wheat cultivar, Yangmai 12, was sown on 3 November 2010 and harvested on 1 June 2011. Table 1 shows the different growth stages and fertilization of wheat. The experiment followed a completely randomized plot design, with three replicate plots (1 m × 2 m area each) for every treatment. The treatments include NT, NT with rice straw covers on the surface (NTS), conventional tillage (CT, with depth of approximately 15 cm), and CT with rice straw incorporation (CTS, where the straws were

Table 1
Main growth stages and fertilization schedules of winter wheat

Date	Growth stages	Date	Fertilization
3 November 2010	Sow	3 November 2010	100 kg N ha^{-1} (urea), 78 kg P ha^{-1}, 100 kg K ha^{-1}
28 December 2010	Tillering	16 January 2011	50 kg N ha^{-1}, 21 kg P ha^{-1}, 27 kg K ha^{-1}
4 February 2011	Turning green	21 February 2011	50 kg N ha^{-1}
17 March 2011	Elongation		
9 April 2011	Booting		
17 April 2011	Heading		
23 April 2011	Flowering		
28 April 2011	Grain filling		
1 June 2011	Harvest		

buried after plowing). The rice straws were cut into short sections (2 cm to 3 cm in length), and the dry weight of the rice straws employed was 225 g m^{-2}.

Determination of Soil Respiration

R_s was measured using the LI-8100 automated soil CO_2 flux system (LI-8100, LI-COR, Lincoln, Neb., USA). An integrated pump circulates the headspace air from the chamber to the nondispersive infrared gas analyzer during the closed state of the chamber, and the CO_2 concentration data and calculated flux rates in the system are recorded. Before the measurement, the PVC soil collars (outer and inner diameters of 21.3 and 20.3 cm, respectively) were inserted 1 to 2 cm deep into the soil, with the top edges kept at approximately 7 to 8 cm above the soil surface. The collars were left on the field throughout the experiment. However, all plants inside the collars were removed during the study period. Each treatment had three soil collars as replicates, and 12 soil collars were randomly placed in the experimental field. R_s was measured once a week during the no-rain period. The R_s measurements started at 8:00 in the morning to minimize errors due to temperature.

The soil temperature and moisture (5 cm depth) were simultaneously measured using probes equipped with LI-8100.

Determination of Gn *and* D

The *Gn* and *D* rates during three crucial growth stages of wheat (turning green–elongation, booting–flowering, and grain filling–ripening stages) were determined using the BaPS technique. The BaPS system was equipped with a container holding a maximum of seven soil cores (Ingwersen et al. 1999). Circular stainless covers (7 cm in diameter) were used to collect soil samples. Twelve intact soil samples were taken from each treatment, and four cores were simultaneously measured in the BaPS container. In other words, three parallel replicates were set for each treatment.

BaPS is based on the determination of the CO_2, O_2, and total gas balances of the soil samples. Nitrification and denitrification are the main biological processes responsible for gas pressure changes inside such an isothermal and gas-tight system (Breuer, Kiese, and Butterbach-Bahl 2002). The *Gn* and *D* can be calculated based on gas and inverse balance approaches. The unit of *Gn* and *D* is μg N kg^{-1} h^{-1}, which represents the amount of N production per dry weight of soil (kg) per hour. A detailed description on BaPS and relevant measuring processes can be found in the papers of Ingwerson et al. (1999) and Breuer et al. (2002).

Statistical Analysis

The average *Rs, Gn, D*, and standard errors (SEs) were calculated based on triplicate measurements. One-way analysis of variance (ANOVA) was used to test the data variability among different treatments. To examine the temperature sensitivity of soil respiration, we performed regression analysis using $y = ae^{bx}$, where y is the R_s, x is the soil temperature, coefficient a is the intercept of respiration at 0 °C, and coefficient b represents the temperature sensitivity of soil respiration. The exponential regression was used to analyze the relationship between the data (*Rs, Gn*, and *D*) and the environmental factors (soil temperature and moisture). In this study, significance implies $P = 0.05$ unless stated otherwise. All statistical analyses were conducted using SPSS 13.0 (SPSS Inc., Chicago, Ill., USA).

Results and Discussion

Effects of NT and Straw Incorporation on Soil Respiration

The R_s values of the different treatments are shown in Figure 1. Compared with CT, the NT and straw incorporation treatments did not change the seasonal pattern of R_s. In the turning green–elongation stage, the R_s values of the four treatments were relatively lower. During the booting–flowering and grain filling–ripening stages, the R_s values increased. Figure 2 shows the average R_s of the four treatments in different growth stages. The average R_s values of NT and CT were significantly different ($P < 0.05$). Compared with CT, NT significantly decreased the average R_s. The NT and NTS results during the turning green–elongation and booting–flowering stages were significantly different. The CT and CTS results during the turning green–elongation and grain filling–ripening stages were also

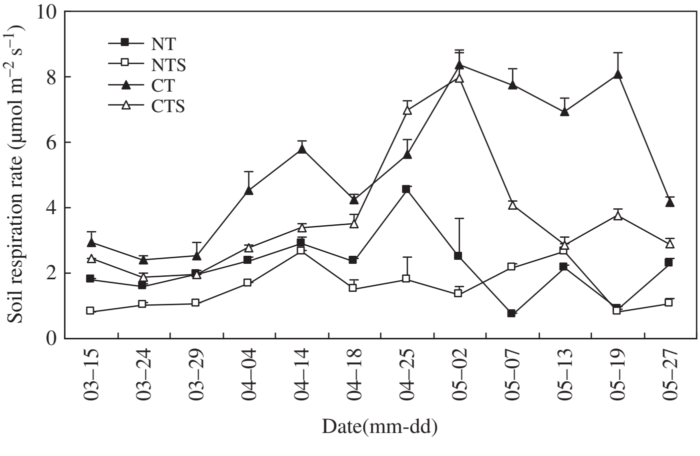

Figure 1. Temporal variation of soil respiration rate (R_s) in different soils treatments. Values are expressed as means (± SE), with the error bars showing SE.

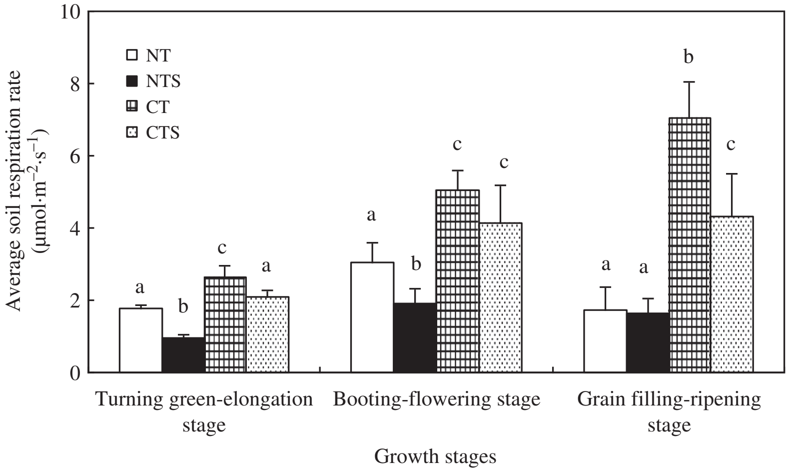

Figure 2. Average soil respiration rate (R_s) values in different growth stages. Different letters represent significant differences between treatments. Values are expressed as means (±SE), with the error bars showing SE.

different, indicating that straw incorporation reduced R_s. Meanwhile, straw incorporation in CT significantly increased R_s compared with that in NTS. In all growth stages, the average R_s of CT was the greatest.

No-tillage soils had greater soil organic C than CT soils (Jacobs et al. 2010), which improved the utilization efficiency of the microbial C source (Cookson, Murphy, and Roper 2008; Wang et al. 2008). This improvement leads to more reduced soil CO_2 emissions under NT and NTS, compared with CT and CTS. Further analysis showed that the average R_s of CTS was greater than that of NT. This difference may be attributed to the fact that the disruption of soil aggregates has stronger influence on the efficiency of C stabilization than the application of straw into the soil profile (Olchin et al. 2008).

Effects of NT and Straw Incorporation on the Temperature Sensitivity of Soil Respiration

Regression analysis indicates that R_s increased exponentially with increasing soil temperature (Figure 3), thereby showing that soil respiration is positively correlated with soil temperature. This result is consistent with the findings of previous studies that soil temperature is the main factor affecting soil respiration, along with soil organic matter (Ussiri and Lal 2009; Chen et al. 2010).

The re-estimated b values were used to calculate the soil respiration quotient ($Q_{10} = e^{10b}$). The Q_{10} values of different treatments were 4.26 (CT), 3.25 (NTS), 2.36 (CTS), and 1.86 (NT). In contrast to CT, the NT and straw incorporation (NTS and CTS) treatments reduced Q_{10}, indicating that the NT and straw incorporation treatments reduced the temperature sensitivity of soil respiration. Our results suggest that the Q_{10} value of soil respiration was significantly affected by NT and straw incorporation ($P < 0.01$). Further studies on plant chemistry and the decomposition processes in soil are needed to understand the mechanisms of the effects of NT and straw incorporation on the temperature sensitivity of soil respiration. Further studies on the different responses of autotrophic and heterotrophic respiration to NT and straw incorporation should also be conducted.

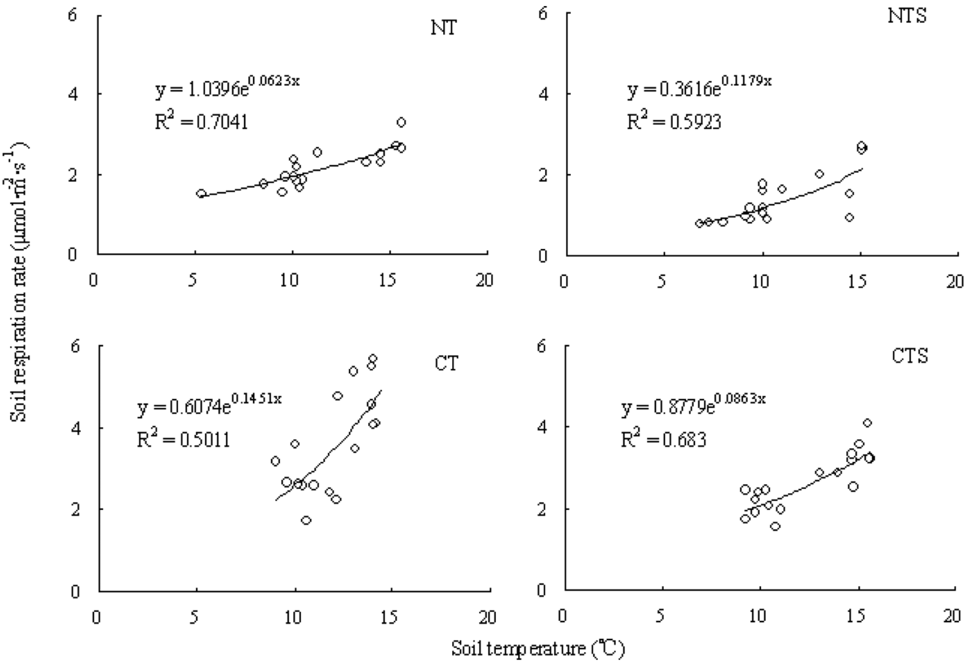

Figure 3. Soil respiration rate (R_s) in relation to soil temperature.

Effects of NT and Straw Incorporation on Gn *and* D

The *Gn* rates of the different treatments are shown in Figure 4. In the turning green–elongation stage, compared with CT, the NT and NTS treatments significantly increased *Gn* by 124% ($P < 0.01$) and 252% ($P < 0.01$), respectively. Meanwhile, CTS increased *Gn* by 58% ($P > 0.05$). In the booting–flowering stage, the *Gn* rates in NT, NTS, and CTS soils were 6.62, 8.66, and 3.47 times greater than that in CT soil ($P < 0.01$), respectively. In the grain filling–ripening stage, the *Gn* rates in NT, NTS, and CTS soils were 3.07, 4.97, and 1.62 times greater than that in CT soil ($P < 0.01$), respectively.

Figure 5 shows the *D* rates of the different treatments. In the turning green–elongation stage, the *D* rates in NT and NTS soils were 4.30 and 6.21 times greater than that in CT soil ($P < 0.01$). In the booting–flowering stage, compared with CT, the NT and NTS treatments significantly increased *D* by 393% and 476% ($P < 0.01$), respectively, whereas the CTS treatment did not increase *D* ($P > 0.05$). In the grain filling–ripening stage, the NT and NTS treatments increased *D* by 66% and 189% ($P < 0.01$), respectively, whereas the CTS treatment decreased *D* by 62% ($P < 0.01$).

The *Gn* rates of the different treatments were NTS > NT > CTS > CT. The *D* rates were NTS > NT > CT $\geq$ CTS. Two processes of N cycle exhibited similar characteristics. This similarity may be attributed to the close association among the different transformation processes involved in the N cycle (Nannipieri and Paul 2009). The NTS and NT treatments had higher *Gn* and *D* rates, whereas CT treatment had lower *Gn* and *D* rates. This discrepancy may be due to the varying N content in the different treated soils. Groffman (1985) also found that nitrification and denitrification activities were greater at the upper 5 cm of NT soils than in CT soils. In contrast to CT, NT and straw incorporation treatments had greater N transformation and mineralization rates (Kheyrodin and Antoun 2009; Muruganandam, Israel, and Robarge 2010). Moreover, NT and straw incorporation

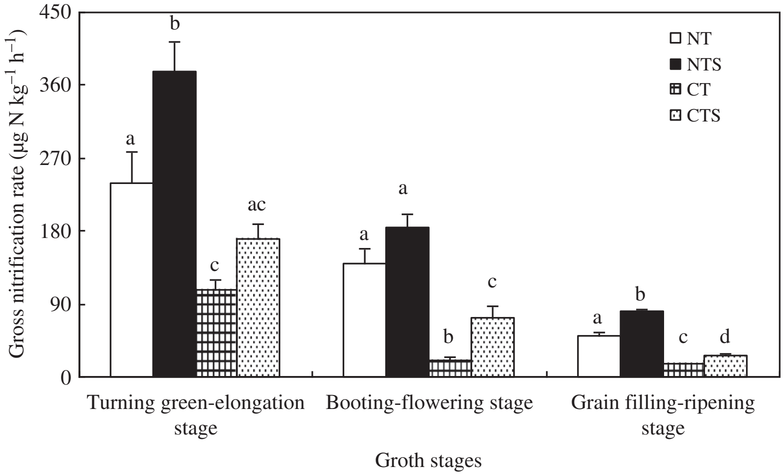

Figure 4. Gross nitrification rates (*Gn*) of different treatments soils during different growth stages. Values are expressed as means (±SE), with the error bars showing SE.

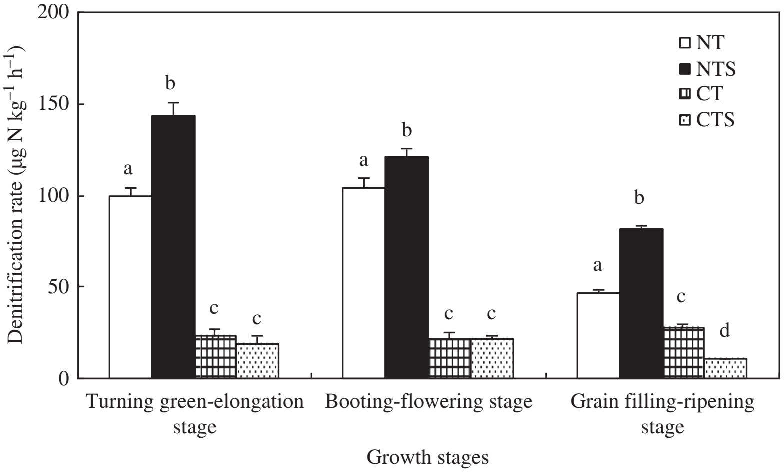

Figure 5. Denitrification rates (*D*) of different treatments soils during different growth stages. Values are expressed as means (±SE), with the error bars showing SE.

could increase the quantity and microbial activities of soil microorganisms and thus accelerate the soil nitrogen cycle (Muruganandam, Israel, and Robarge 2010; Mahía et al. 2007; Phillips 2008). In general, the amount of available inorganic N is one of the factors regulating *D* rates in soils (Phillips 2008). Clark et al. (2009) also suggested that the nitrification process is consequently limited by nitrate (NO_3^-, and ammonium (NH_4^+) availability in soil.

Furthermore, the *Gn* and *D* rates in different treatments had similar seasonal patterns, showing greater values in the early growth period, which then decreased gradually. This phenomenon may be attributed to the freezing and thawing in the early spring season, which are beneficial to the mineralization, nitrification, and denitrification of N in soils and straw (Su, Kleineidam, and Schloter 2010). Moreover, the seasonal variation of

Table 2

Effects of no-tillage and straw incorporation on the relationships between gross nitrification rate (*Gn*) and soil temperature and moisture

Parameter	Treatment	*Gn*	R^2	*P* value
Soil temperature (*t*)	NT	$868.2e^{-0.128t}$	0.919	<0.01
	NTS	$1174.3e^{-0.124t}$	0.940	<0.01
	CT	$272.5e^{-0.138t}$	0.655	<0.05
	CTS	$700.7e^{-0.148t}$	0.937	<0.01
Soil moisture (θ_v)	NT	$37.7e^{0.160\theta v}$	0.892	<0.01
	NTS	$82.0e^{0.060\theta v}$	0.931	<0.01
	CT	$9.0e^{0.374\theta v}$	0.832	<0.01
	CTS	$11.9e^{0.273\theta v}$	0.912	<0.01

Table 3

Effects of no-tillage and straw incorporation on the relationship between denitrification rate (*D*) and soil temperature and moisture

Parameter	Treatment	*D*	R^2	*P* value
Soil temperature (*t*)	NT	$215.3e^{-0.065t}$	0.758	<0.01
	NTS	$233.2e^{-0.048t}$	0.950	<0.01
	CT	$16.8e^{0.022t}$	0.183	>0.05
	CTS	$30.4e^{-0.041t}$	0.295	>0.05
Soil moisture (θ_v)	NT	$45.2e^{0.077\theta v}$	0.670	<0.01
	NTS	$85.2e^{0.022\theta v}$	0.815	<0.01
	CT	$23.2e^{0.002\theta v}$	0.000	>0.05
	CTS	$8.8e^{0.096\theta v}$	0.438	>0.05

Gn rates in soils can be readily predicted by soil moisture and temperature (Stange and Neue 2009; Kiese, Hewett, and Butterbach-Bahl 2008). In the current study, all *Gn* and *D* rates, except the *D* rates of CT and CTS, are negatively correlated with soil temperature and positively correlated with soil moisture (Tables 2 and 3). These results are consistent with previous studies (Stange and Neue 2009; Kiese, Hewett, and Butterbach-Bahl 2008; Chen et al. 2011). Rice and Smith (1983) also found that nitrification rates are greater in NT soils than in CT soils because the former type has more favorable soil moisture conditions.

Conclusions

Compared with CT, NT and straw incorporation treatments did not change the seasonal pattern of soil respiration. However, they reduced the R_s values and Q_{10} values. The *Gn* and *D* rates of the different treatments had the same seasonal pattern, suggesting greater values in the turning green–elongation stage, which then decreased gradually in the booting–flowering and grain filling–ripening stages. The NT and straw incorporation significantly increased the *Gn* and *D* rates. Therefore, *Gn* and *D* rates are negatively correlated with soil temperature and positively correlated with soil moisture.

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