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Maize production and field CO_2 emission under different straw return rates in Northeast China

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Abstract: In order to understand and clarify the impacts of straw return on maize production and field CO_2 emission in Northeast China, the most important agricultural base of the nation, a field experiment was conducted in 2012–2015, including no straw return (CK), straw amendment at 4000 kg/ha (S_4), and at 8000 kg/ha (S_8). The average grain yield was found significantly promoted by the two straw treatments, with comparably increased magnitudes of 11.0% and 12.8% for S_4 and S_8, respectively, and the benefits were gradually enlarged with increasing experimental duration. Although straw return tends to reduce slightly the harvest index, it was detected that it exerted significantly positive impacts on nitrogen harvest index. These results implied that added straw could lead to raising grain yield and enhancing nitrogen use efficiency simultaneously. In 2015, our monitoring showed that CO_2 emission was elevated with intensified use of straw, and S_4 and S_8 decreased carbon emission efficiency by 7.3% and 13.6%, respectively. However, there was no statistical difference between S_4 and CK. Overall, straw addition at the rate of 4000 kg/ha accompanied with inorganic fertilizer was recommended to be adopted in Northeast China, which was considered as a sustainable and relatively environment-friendly agricultural technique during maize production.

Keywords: straw incorporation; CO_2 efflux; field management; greenhouse gas; terrestrial ecosystem

Crop straw is an important biotic resource as it contains a lot of organic carbon (C) and mineral elements (Lehtinen et al. 2014, Liu et al. 2014). In China, the annual production of crop straw was about 700 million tons (Xia et al. 2014). At present, more than 80% of these straws are burned in the field or for cooking, which causes a serious air pollution problem and resource waste (Iqbal et al. 2009). Putting the straw back to the field is strongly recommended to be applied instead of burning because it cannot only replenish soil fertility and increase soil C sequestration but also enhances crop productivity resulting from providing more essential nutrients and altering soil physical properties (such as soil bulk density, soil temperature and moisture) (Liu et al. 2014, Hu et al. 2018). Although a few studies reported straw return could lower the crop yield at the beginning of the experiment due to nitrogen (N) immobilization by added straw (Huang et al. 2013, Lehtinen et al. 2014, Chen et al. 2018), the meta-analysis synthesizing global data demonstrated that straw return increased crop yield by average of 12.3% and the effect was site-specific (Liu et al. 2014). Crop harvest index (HI) and nitrogen harvest index (NHI) were the two important indicators reflecting the allocation strategies of the plant for utilizing photosynthetic assimilates and absorbed N, respectively (Chardon et al. 2012). To date, using a continuous and multiple-year experiment to detect the gradual impact of the straw amendment on crop yield and simultaneously explore the response of HI and NHI remains scared.

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CO_2 emission from the agricultural field is an important pathway of CO_2 efflux from terrestrial ecosystems to the atmosphere. A small fluctuation of field CO_2 emission can exert a large influence on CO_2 concentration in the atmosphere (Davidson et al. 2010), thus the control of CO_2 emission from the fields is crucial for regulating the global C cycle and reducing its global warming effects. Straw addition can undoubtedly affect field CO_2 emission because straw applied to the soil could accelerate the decomposition of soil organic matter by soil microorganisms and meanwhile stimulate the activity of crop roots (Badía et al. 2013, Hu et al. 2013), both of which raise soil CO_2 emission. Taken together, the greater soil CO_2 emission induced by straw addition would probably be accompanied with more grain productivity. To coordinate the environmental cost and its positive effect, the term, soil carbon emissions efficiency (CEE) was adopted as the evaluation standard, which was defined as grain yield per unit of carbon emission through CO_2 efflux (Hu et al. 2015, Lamptey et al. 2018).

Northeast China is the largest base of maize production across the country, which occupies 31% of national maize area and contributes to about 35% of the total maize yield (Yang et al. 2014). Northeast China has been suffering from intensive agricultural production and a large surplus of crop straw. To maintain high maize productivity for the nation's grain security and simultaneously to minimize the negative environmental cost, finding a proper straw return rate is urgently needed. Consequently, a 4-year continuous straw return experiment was conducted from 2012 to 2015 and the field CO_2 efflux was monitored in one growing season of 2015. The specific objectives of the present study were to: (1) characterize the effects of different rates of straw return on crop production, HI and NHI over 4 years; (2) quantify CO_2 emissions and identify the appropriate straw return rate based on CEE.

MATERIAL AND METHODS

Study site. The research was carried out in the Shenyang Experimental Station (41°32'N, 123°23'E, at the altitude of 31 m a.s.l.), which is located in the Liaoning province, Northeast China. The mean annual temperature is 7.5°C (maximum 39.3°C; minimum –33.1°C), with the frost-free period of 147–164 days. The mean annual precipitation is about 500 mm, mainly concentrated in the growing season (May to September). The soil in this experimental site is an Alfisol, typical soil species for agricultural production in the region.

Experiment design and sampling. The field experiment was initiated in 2010. This experiment included three treatments: no straw incorporation (CK); incorporation of maize straw at 4000 kg/ha (S_4) and 8000 kg/ha (S_8). A randomized block design using three replications for each treatment was employed, with a plot size of 1.8 m × 4 m. The cultivar of the maize was Dongdan 72. In each plot, rows of the plant were spaced at an interval of 60 cm, and maize was seeded by hand at 25 cm intervals following the regional recommendation (about 66 000 plants/ha). Protective zones between plots (1 m width) also existed to facilitate agricultural management and make the study more accurate. Every October after harvest, the chopped straw of the previous crop was manually incorporated into the top 20 cm of soil. The same inorganic fertilizers were applied, with the amount of 150 kg N/ha/year and 90 kg P/ha/year. P was mixed into the soil before sowing, and N was applied three times during the growing season, with the ratio of 3:4:3. There was no artificial irrigation during the experiment period.

From 2012 to 2015, the crops at each entire plot were manually harvested after reaching maturity and were divided into grain and straw. The crop samples were oven-dried at 70°C to a constant weight to determine the crop yield and stover biomass. Soil samples (0–20 cm depth) were collected in October of 2015 after harvesting. One soil sample consisted of five soils from different sites randomly collected from each plot. The samples were all passed through 2-mm sieve after removing visible organic debris and soil fauna. All plant and soil parameters (such as available N, P, and K) were determined according to the description of Lu (2000).

Field measurements. In the growing season of 2015, the closed static chamber method combined with gas chromatography was used to determine weekly the CO_2 efflux. This method was described in detail in our previous publication (Jiang et al. 2010). The CO_2 emission measured was a mixture of autotrophic and heterotrophic respiration. The results of the experiment had be preliminarily analyzed from another perspective (Jiang et al. 2017, 2019). Cumulative values of CO_2 emission and CEE were calculated according to the method of Hu et al. (2015). CEE was a ratio of grain yield against the corresponding field carbon emission.

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Soil temperatures (5 cm) and soil moisture (0–5 cm soil layer) were monitored in each plot during the air sampling date using portable digital thermometers (JM624, Tianjin, China) and a time domain reflectometry (Witu, Shenyang, China), respectively. Precipitation data were collected from an automatic weather station in the experimental station.

Statistical analysis. All analyses were performed using the SPSS V13.0 (SPSS, Chicago, USA). One-way ANOVA with the Duncan's *HSD* (honestly significant difference) test was firstly used to identify the difference between the tested parameters among straw incorporation treatments. Then repeated-measures ANOVA were employed to detect the effect of sample year, straw treatment and their interaction on crop production, HI and NHI, with the sample year as the repeat factor.

RESULTS AND DISCUSSIONS

Grain yield, stover biomass and soil properties. Across the 4-year observation, the grain yield of maize was markedly increased by straw additions ($P < 0.05$), and S_4 and S_8 comparably raised the average grain yield by 11.0% and 12.8%, relative to CK (**Figure 1a**). This was by the global meta-analysis (Liu et al. 2014). Added straw might negatively affect crop yields due to microbial N immobilization, which reduced plant N uptake (Huang et al. 2013, Chen et al. 2014). This phenomenon was not observed in our experiment, probably because N fertilizers were applied three times during the maize growth period, which eliminated the negative impacts. Thus, using straw in combination with inorganic nitrogen fertilizer is an attractive way to achieve high crop yields. Through repeated-measures ANOVA, the significant interaction was found between observation years and added straw treatments effect on grain yield (Table 1). Moreover, the magnitude increased by straw addition became more dramatic with increasing experimental duration (Figure 1a). This result suggested the benefits of straw were cumulative, which could not be captured by a short-term experiment. Some longer studies (Bi et al. 2009) and a meta-research (Huang et al. 2013) supported this inference, and they further argued that straw return

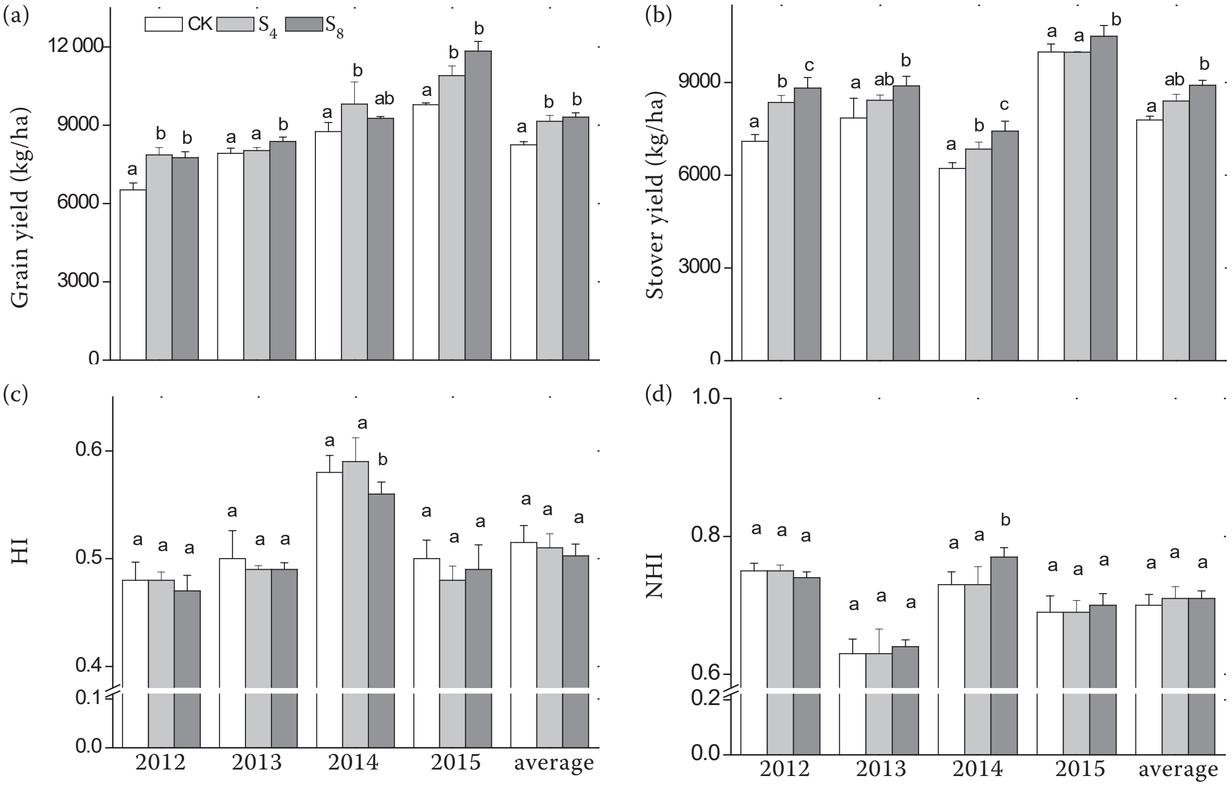

Figure 1. Impacts of the straw amendment on the grain yields, stover yield, harvest index (HI) and nitrogen harvest index (NHI) in a maize field of Northeast China from 2012–2015. Values are means ± standard error. CK – no straw addition; S_4 – straw amendment at a level of 4000 kg/ha; S_8 – straw amendment at 8000 kg/ha. Different lower-case letters indicate significant differences ($P < 0.05$) in the same year

Table 1. Repeated-measures ANOVAs for the effects of year (Y), the rate of straw addition (S), and their interactions on grain yield (GY), stover yield (SY), harvest index (HI) and nitrogen harvest index (NHI)

	df	GY		SY		HI		NHI	
		F	*P*	*F*	*P*	*F*	*P*	*F*	*P*
Between subjects									
S	2	6.65	< **0.05**	18.60	< **0.001**	1.29	> 0.05	0.391	> 0.05
Within-subjects									
Y	3	19.69	< **0.001**	8.192	< **0.001**	23.52	< **0.001**	29.64	**0.001**
Y × S	6	2.75	< **0.05**	0.19	> 0.05	0.878	> 0.05	0.31	> 0.05

P values in bold are statistically significant ($P < 0.05$)

could enhance the long-term sustainability of crop production. The stover yields were also significantly increased by added straw ($P < 0.05$) (Figure 1b). The grain yield of each treatment had been elevated year by year along with the experiment, while the stover yields did not displayed similar trends. The underlying mechanism remained to be elucidated in the next step study.

After the multiple-year experiment, the soil fertility and soil properties were all improved by the straw input as indicated by a significant increase of the total N, available N, available P and available K ($P < 0.05$) (Table 2). These were the primary bases for the positive influence on the maize yield and stover biomass as the use of straw was intensified (Huang et al. 2013, Liu et al. 2014). Moreover, maize root growth was observed to be dramatically stimulated by straw amendment (Table 2). In addition, to provide essential nutrition, Xu et al. (2018) argued that added straw could favor the root to utilize the N and water in deep soil layer, which enhances N and water use efficiency. This was one of the possible reasons for higher NHI after input of straw (see the next section).

HI and NHI. Table 1 shows that HI and NHI were relatively less regulated by year and the treatments as compared to grain and stover yields (Chardon et al. 2012), but it was detected that straw addition tended to reduce HI while raising NHI and this trend was statistically significant between S_8 and CK in 2014 ($P < 0.05$) (Figure 1c,d). Based on a comprehensive study, Hu et al. (2018) pointed out that early growth of plant might be favoured by straw addition but at the expense of development at critical reproductive stages, hence reducing HI. This explanation could be reflected by the dynamics of soil moisture in our study (see the next section). These results also suggested that an opportunity still existed to further increase grain yield by improving HI in added straw practice. The NHI is a ratio of N content in crop grain to whole plant N, which is an indicator of crop N use efficiency (Cheng et al. 2007, Chardon et al. 2012). The increased NHI by straw addition was consistent with the other studies (Cheng et al. 2007, Zhao and Cheng 2008). A possible explanation of the higher NHI could be that added straw improved synchronism between the soil inorganic N supply and the crop N uptake throughout the immobilisation-mineralisation process and meanwhile reduced the environmental risk of N losses (Chen et al. 2014, Cheng et al. 2015, Xu et al. 2018).

Table 2. Comparison of maize root biomass and soil properties among straw incorporation treatments in 2015

Treatment	Root (kg/ha)	MBC (mg/kg)	SOC (g/kg)	DOC (mg/kg)	Total N (g/kg)	Available N	Available P	Available K
						(mg/kg)		
CK	1200(61)^{a}	147.5 (6.3)^{a}	10.02(0.16)^{a}	44.24(1.89)^{a}	0.99(0.02)^{a}	87.36(1.22)^{a}	5.99(0.22)^{a}	87.76(2.20)^{a}
S_4	1401(81)^{a}	206.2 (13.8)^{b}	11.23(0.42)^{b}	60.56(4.11)^{b}	1.10(0.03)^{b}	99.57(2.47)^{b}	6.47(0.18)^{b}	93.46(1.90)^{b}
S_8	1840(88)^{b}	267.4 (9.3)^{c}	12.37(0.27)^{c}	82.71(3.26)^{c}	1.23(0.03)^{c}	105.43(0.48)^{c}	8.41(0.65)^{c}	110.57(2.18)^{c}

CK – no straw incorporation; S_4 – incorporation of maize straw at a rate of 4000 kg/ha; S_8 – incorporation of maize straw at a rate of 8000 kg/ha; MBC – microbial biomass carbon; SOC – soil organic carbon; DOC – dissolved organic carbon. The values are the means with standard error. The different letters denote significant differences ($P < 0.05$) among treatments in the same column

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Dynamics of meteorological factors and CO_2 flux. The seasonal variations of rainfall, soil moisture and temperature in 2015 are illustrated in Figure 2a,b. Soil moisture exhibited three peaks caused by precipitation, and the maximum occurred at the beginning of August. The dynamics of CO_2 flux followed a similar pattern (Figure 2c); demonstrating soil water condition was an overriding regulator for CO_2 flux in a rain-fed crop field (Rong et al. 2015). Although no statistically significant differences of soil temperature and soil moisture were observed among the three treatments (data not shown), the soil moisture was relatively lower for added straw in the early growing period (June) (Figure 2a). The accelerated water loss through crop leaf transpiration due to crop growth stimulation by straw addition might be the reason of soil moisture reduction in June (Wang et al. 2011, Lamptey et al. 2018). However, the water shortage might negatively affect later critical crop development and yield formation (Frederick and Camberato 1994, Chen et al. 2010). This explanation coincided with the speculation for smaller HI in added straw treatments (S_4 and S_8) as discussed above. During the 4-year experiment, the decreased magnitude of HI by S_8 was more dramatic and significantly lower than CK ($P < 0.05$) (Figure 1c). According to the meteorology record, the precipitation in 2014 was smaller than the other three years. These results corroborated our inference about low HI-induced by water shortage from another perspective.

Cumulative CO_2 emission and CEE. In 2015, the cumulative CO_2 emission (CE) was profoundly enhanced by straw addition, with an increased percentage of 20.2% and 40.1% for S_4 and S_8, respectively (Table 3). The first reason was that the increase of labile organic carbon provided by added straw, such as DOC (dissolved organic carbon) in our case (Table 2), promoted the soil

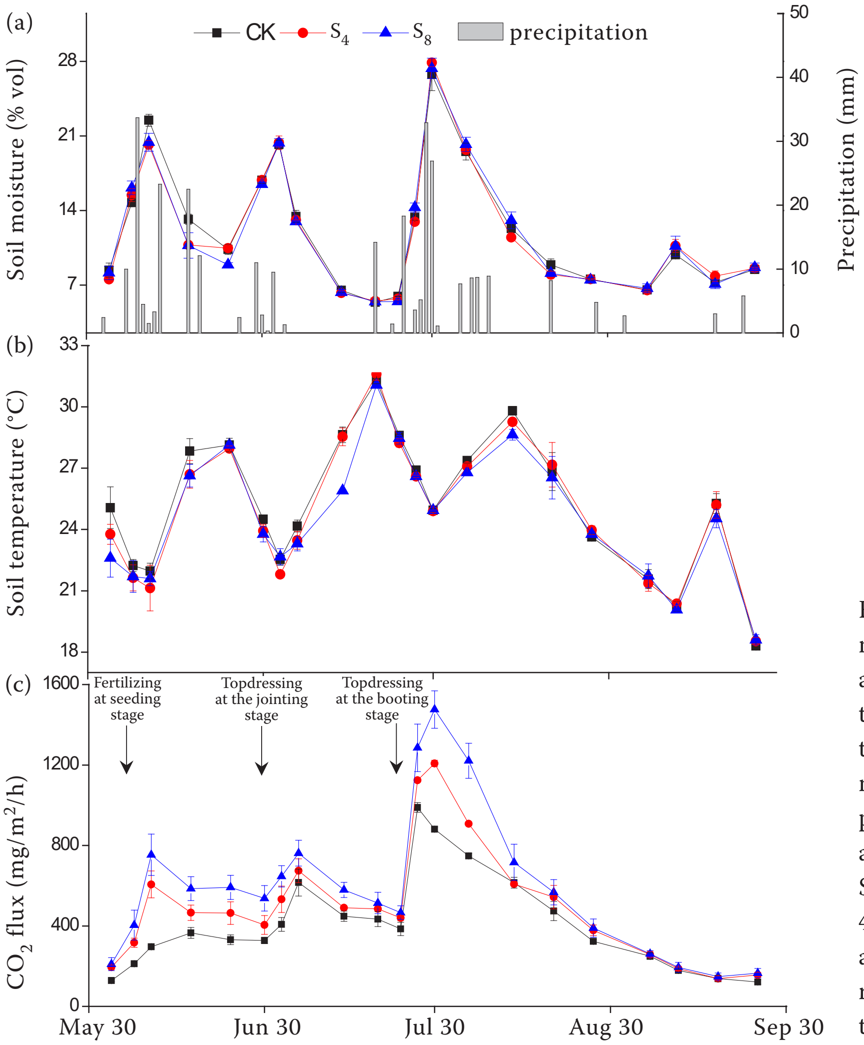

Figure 2. Seasonal changes of soil moisture in the 0–5 cm soil layer and (a) precipitation; (b) 5 cm soil temperature and (c) CO_2 flux for three straw return treatments in a maize field of Northeast China. Data points represent the mean ± standard error. CK – no straw addition; S_4 – straw amendment at a level of 4000 kg/ha; S_8 – straw amendment at 8000 kg/ha. The vertical arrows represent nitrogen fertilizer application at different maize growth stages

Table 3. The difference of grain yield (GY); cumulative carbon emissions (CE) through CO_2 flux and carbon emission efficiency (CEE) of three straw return rates in 2015

Treatment	GY		CE		CEE	
	(kg/ha)	PC (%)	(kg/ha)	PC (%)	(kg/kg)	PC (%)
CK	9790^a	–	3088^a	–	3.17^b	–
S_4	$10\,905^b$	11.4	3711^{ab}	20.2	2.93^{ab}	–7.3
S_8	$11\,841^b$	20.9	4325^b	40.1	2.73^a	–13.6

CK – no straw incorporation; S_4 – incorporation of maize straw at a rate of 4000 kg/ha; S_8 – incorporation of maize straw at a rate of 8000 kg/ha. The different letters denote significant differences ($P < 0.05$) among treatments in the same column. PC (percentage change) stands for a percentage change relative to CK

microbe activities (as indicated by MBC (microbial biomass carbon)) as the labile organic carbon can be easily utilized by soil microbes (Cheng et al. 1996). Secondly, straw incorporation stimulated the growth of crop root due to improved soil fertility (Table 2), subsequently increasing CO_2 emission from roots (Hu et al. 2013). Another possible mechanism was that the inputted materials in straw possessed the ability to degrade additional SOM from the original soil, which was called as positive priming effects (Kuzyakov et al. 2000, Badía et al. 2013).

CEE, defined as grain yield associated with per unit carbon emission, was used to evaluate the environmental friendliness of agricultural techniques. Because the enhanced magnitude of straw addition for CO_2 emission was larger than grain yield, CEE was reduced by 7.3% and 13.6% for S_4 and S_8, respectively. However, there was no statistical difference between S_4 and CK, while S_8 was significantly lower than CK ($P < 0.05$) (Table 3). Meanwhile, S_4 could dramatically and significantly enhance grain yield by 11.4% compared to CK in 2015 ($P < 0.05$). On the other hand, the enhanced magnitudes of a 4-year mean grain yield for S_4 and S_8 were comparable across the multiple-year experiment (Figure 1a).

Consequently, straw addition at the rate of 4000 kg/ha in combination with inorganic fertilizer was considered as a sustainable agricultural technique, which was recommended to be widely adopted in Northeast China. This agricultural technique could obviously improve the soil qualities and properties, and simultaneously maintain high crop production, only accompanied by the slight environmental burden as assessed by CEE. Further research for more sites in Northeast China was needed to verify our conclusion.

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