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Winter tillage with the incorporation of stubble reduces the net global warming potential and greenhouse gas intensity of double-cropping rice fields

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ABSTRACT

Tillage with the incorporation of stubble is a common practice in rice cultivation, but its effect on the net global warming potential (GWP) and greenhouse gas intensity (GHGI) is poorly documented. A three-year field experiment in a double-cropping rice system was conducted to investigate the rate of sequestration of soil organic carbon, CH_4 and N_2O emissions, the net GWP and the GHGI. Two timings of tillage with three amounts of stubble incorporation were prepared: winter tillage (tillage after the harvest of late rice) and spring tillage (tillage before the transplantation of early rice) with no (0 t ha^{-1}), low (3.5 t ha^{-1}) and high (5.2 t ha^{-1}) amounts of stubble incorporation. The results showed that the rates of sequestration of soil organic carbon with the incorporation of stubble were 0.85–1.06 t C ha^{-1} yr^{-1} for winter tillage, 67–429% higher than for spring tillage. Winter tillage significantly increased CH_4 and N_2O emissions in the winter fallow season relative to spring tillage, whereas it tended to decrease both emissions in the early and late rice seasons, thus playing a small part in the annual emissions. The total CH_4 and N_2O emissions averaged 106.5–198.2 kg ha^{-1} yr^{-1} and 114.4–229.4 g N ha^{-1} yr^{-1}, respectively. Significant decreases in the net GWP (46–82%) and GHGI (49–84%) were observed when changing the tillage practices with the incorporation of stubble from spring to winter. Compared with high levels of stubble incorporation, winter tillage with low levels of stubble incorporation significantly decreased both the net GWP and the GHGI. The total grain yield was 13.0–13.3 t ha^{-1} yr^{-1} for winter tillage, 3–5% higher than for spring tillage. These findings suggest that tillage with the incorporation of stubble in the winter fallow season, particularly with 3.5 t ha^{-1} stubble, is an effective strategy to mitigate the net GWP and GHGI while maintaining a high grain yield in the double-cropping rice system.

1. Introduction

Methane (CH_4) and nitrous oxide (N_2O) are two of the most important greenhouse gases (GHGs). On a 100-year timescale, they have global warming potentials (GWPs) 34 and 298 times greater than carbon dioxide (CO_2), respectively, contributing about 17 and 6% to the overall global increase in radiative forcing (Myhre et al., 2013). The concentrations of atmospheric CH_4 and N_2O have increased from 722 and 270 ppb in the pre-industrial period to 1853 and 328.9 ppb in 2016, respectively (WMO, 2017). Agriculture is regarded as one of the major sources of anthropogenic CH_4 and N_2O, responsible for 5–19 and 17–20% of global CH_4 and N_2O emissions (Denman et al., 2007). China, the largest rice-producing country, accounts for about 28% of global rice production (FAOSTAT, 2014) and the total CH_4 and N_2O emissions from paddy fields are estimated to be 6.4 Tg yr^{-1} and 180 Gg yr^{-1}, respectively (Zhang et al., 2014). There is much interest from agricultural scientists in how to mitigate GHG emissions while still achieving high crop yields (Burney et al., 2010; Chen et al., 2014; Liu et al., 2015; Pittelkow et al., 2014; van Der Gon et al., 2002).

No-tillage cultivation methods during the rice growing season have been found to be a promising strategy for mitigating GHG emissions from paddy fields. Many studies have shown that no-tillage methods substantially decrease CH_4 and N_2O emissions during the rice growing season relative to tillage methods (Ahmad et al., 2009; Ali et al., 2009; Li et al., 2013, 2011), although an investigation from Zimbabwe in southern Africa showed that total CH_4 and N_2O emissions were much greater from areas using no-tillage methods than from those using tillage methods (Nyamadzawo et al., 2013). By contrast, Liang et al.

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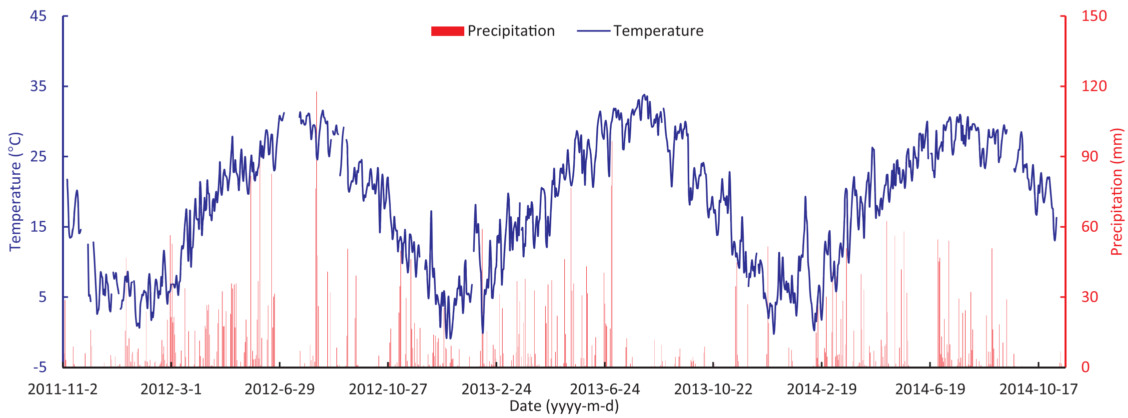

Fig. 1. Temporal variation in air temperature and precipitation over three annual cycles from November 2011 to November 2014.

(2007) observed that tillage relative to no-tillage methods significantly increased CH_4 emissions by 67% while decreasing N_2O emissions by 19% in a single-cropping rice field in northern China in the winter fallow season. There are generally two timings of tillage in rice cultivation: the fields are either tilled as soon as the rice is harvested in the previous winter season (winter tillage) or plowed just prior to the transplanting of rice seedlings (spring tillage). Early studies considered the effects of either spring or winter tillage on GHG emissions during the rice growing season or the winter fallow season, but there have been few reports of the effects of winter tillage on GHG emissions from fields and the corresponding GWP over an annual cycle (Zhang et al., 2016a).

The incorporation of rice stubble into soils during tillage is an important method of using straw resources during the cultivation of rice. Decomposition of the straw supplies nutrients such as N, P and K and has a key role in increasing the soil organic carbon (SOC) content and maintaining crop yields (Bhattacharyya et al., 2012; Ji et al., 2012; Wang et al., 2005). Spring tillage with the incorporation of rice stubble has been reported to significantly increase the sequestration of SOC by 414% (Ji et al., 2012) and grain yields by 9–30% during the rice growing season (Zhang et al., 2016b). Winter tillage gives better contact of the crop stubble with the soil than spring tillage, accelerating the decomposition of organic matter in the winter fallow season (Watanabe and Kimura, 1998; Zhang et al., 2016a) and influencing the sequestration of SOC in the paddy fields. However, there have been few studies on the response of the sequestration of SOC to changing the timing of tillage with the incorporation of stubble from spring to winter.

Double-cropping rice fields account for > 40% of the total harvested area (Yearbook, 2014) and emit about 50% of the total CH_4 from paddy fields in China (Zhang et al., 2011). As a representative region of the double-cropping system for rice, Jiangxi Province has the largest (about 24%) area of double-cropping rice cultivation in China (Yearbook, 2014) and emits substantial amounts of CH_4 and N_2O. In the past few decades, field management after the rice harvest in China has usually been neglected in the winter season. In the double-rice cropping regions in particular, the fields are often left fallow and untilled with standing stubble residues throughout the whole winter season (Ji et al., 2012). The length of the retained rice stubble is different after the late rice harvest in various paddy fields, causing some differences in the amount of stubble incorporated. It is hypothesized that incorporating various lengths of stubble residue by tillage during the winter fallow season has different effects on CH_4 and N_2O emissions and the sequestration of SOC, although this has not yet been well documented in rice paddy fields.

The overall balance between the GWP and sequestration of SOC constitutes the net GWP. A new metric, the greenhouse gas intensity (GHGI), has been proposed to integrate GHG emissions with crop yields and can be estimated by the net GWP per ton of grain yield (Liu et al., 2015; Shang et al., 2011). To address the two goals of increasing food production and environmental sustainability, effective field management techniques should be developed with a low net GWP and GHGI, but high productivity. Little is currently known about the net GWP and GHGI response to the timing of tillage with the incorporation of different lengths of stubble. Therefore we studied the rice grain yield, SOC content, and CH_4 and N_2O emissions from a double-cropping rice field in Jiangxi Province, southeast China from November 2011 to November 2014 under two timings of tillage with the incorporation of three different lengths of stubble. The rate of sequestration of SOC and the net GWP and GHGI were also estimated. The objectives of this study were to clarify the effects of tillage timing and stubble length on the sequestration of SOC and the emissions of CH_4 and N_2O from the double-cropping rice system and to evaluate their effects on the net GWP and GHGI. We hypothesized that changing tillage practices with the incorporation of stubble from spring to winter promotes the sequestration of SOC and decreases both the net GWP and GHGI.

2. Materials and methods

2.1. Experimental site and treatments

The field experiment was carried out at Yingtan City, Jiangxi Province, China (28° 15′ N, 116° 55′ E) from November 2011 to November 2014. Detailed information about this site has been reported previously (Zhang et al., 2016a). The soil is classified as a typical Haplaquept (18.2% clay, 31.3% silt, 50.5% sand), and the 0–20 cm layer has a bulk density of 1.13 g cm^{-3}, a pH of 4.74, an organic C content of 16.9 g kg^{-1} and a total N content of 1.62 g kg^{-1}. Over the three annual rotation cycles in 2011–2012, 2012–2013 and 2013–2014, the total precipitation and mean air temperature were 2419, 1484 and 1668 mm and 18.6, 20.0 and 19.3 °C, respectively (Fig. 1). The mean air temperature in the 2011, 2012 and 2013 winter fallow seasons was 10.0, 9.7 and 9.4 °C, respectively, and 24.3–25.5, 21.6–23.7 and 24.8–24.9 °C, respectively, during the following early and late rice seasons (Fig. 1).

Six treatments were laid out in the winter fallow season in a randomized block design with three replicates: winter tillage (tillage as soon as the previous late rice had been harvested) with the incorporation of no (WT0), low (WTL) or high (WTH) stubble; and spring tillage (no-tillage throughout the whole winter fallow season, but tillage prior to the transplantation of early rice in the following season) with the incorporation of no (ST0), low (STL) and high (STH) stubble. Each experimental plot was 20 m^2 (5 m × 4 m) in area. The lengths of no, low and high stubble left standing in the fields after the late rice harvest averaged about 0, 30 and 55 cm, respectively, equivalent to the application of straw at rates of 0, 3.5 and 5.2 t ha^{-1}, respectively. The remaining rice residues were removed from the fields. Spring tillage is