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Effects of long-term straw incorporation on the net global warming potential and the net economic benefit in a rice–wheat cropping system in China

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ABSTRACT

Straw incorporation has multiple effects on greenhouse gas emissions and soil productivity. However, few studies have comprehensively evaluated the effects of long-term straw incorporation. An ongoing long-term straw incorporation experiment in a rice–wheat cropping system in China was established in 1990 and was used in the present study to evaluate the net global warming potential (NGWP) and the net economic benefit (NEB) of the straw return. The following four field treatments were included: a control (CK); N, P and K fertilization (NPK); fertilization plus a moderate rate of straw application (NPKS1); and fertilization plus a high rate of straw application (NPKS2). We calculated the increase in the soil organic carbon (SOC) and the straw-induced emissions of CH_4 and N_2O, which were expressed as the global warming potential (GWP) in units of CO_2-equivalent (CO_2-eq) at the 100-year scale. The straw-induced NEB was defined as the difference between the economic income, which was calculated by multiplying the increase in straw-induced crop grain yield by the grain price, and the economic loss was computed by multiplying the increase in straw-induced CO_2-eq emissions by the carbon price. The results showed that long-term straw incorporation significantly increased the CH_4 emissions and the topsoil SOC density. The GWP of the straw-induced CH_4 emissions was 3.21–3.92 times that of the straw-induced SOC sequestration rate, suggesting that long-term direct straw incorporation in the rice–wheat systems worsens rather than mitigates the climate change. Additionally, continuous straw incorporation slightly enhanced the rice and wheat grain yields, contributing to the production of the NEB. We determined that under the current carbon price, ranging from 2.55 to 31.71 EUR per ton CO_2-eq, the direct straw incorporation will produce a positive NEB, ranging from 156 to 658 RMB ha^{-1} $year^{-1}$, if the grain yield prices do not fluctuate, which does not provide a significant incentive for farmers to change from their traditional direct straw incorporation pattern. Considering the other benefits that the straw application produced, such as improving soil fertility and the water retention capacity, we recommend that the government should establish an incentive for ecological compensation to encourage farmers to implement proper straw incorporation, such as composting straw under aerobic conditions before application.

1. Introduction

Atmospheric methane (CH_4) and nitrous oxide (N_2O) are important greenhouse gases (GHGs). The global warming potentials (GWP) of these gases over a time span of 100 years are approximately 25 and 298 times greater, respectively, than that of carbon dioxide (CO_2) (IPCC, 2007). Rice-based ecosystems are significant contributors to atmospheric CH_4 (Cai et al., 1997; Li et al., 2004; Yan et al., 2005). Paddy fields are also recognized as an important source of N_2O emissions in China, accounting for 22% of the total emissions from the cropland (Xing, 1998). China is the largest rice-producing country in the world, accounting for

Abbreviations: EUR, euro (currency); GWP, global warming potential; NGWP, net global warming potential; NEB, net economic benefit; LNEB, lowest net economic benefit; HNEB, highest net economic benefit; RMB, renminbi (Chinese yuan); SOC, soil organic carbon; SOCD, soil organic carbon density; SOCSR, soil organic carbon sequestration rate; SOM, soil organic matter; GHGs, greenhouse gases; RGYC, rice grain yield change; WGYC, wheat grain yield change.

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approximately 26% of the global rice production (Xing et al., 2009). The total annual emissions of CH_4 and N_2O from Chinese rice paddy fields range from 7.7 to 8.0 Tg year^{-1} and from 88.0 to 98.1 Gg year^{-1}, respectively (Yan et al., 2003; Zheng et al., 2004; Yao et al., 2012). The summer rice–winter wheat rotation is an important cropping system, occupying 60% of the paddy fields in southeast China (Zheng et al., 2000).

In China, as much as 7.945×10^8 t year^{-1} of crop straw is produced. The production steadily increases at an annual rate of 1.251×10^7 t (Zhong et al., 2003). Approximately 19% of the entire crop residue is burned in Chinese fields (Yan et al., 2006), which results in a loss of nutrients, organic matter and emissions of toxic gases and GHGs, such as CO, CO_2, CH_4, NO_x and N_2O, threatening the health of humans and ecosystems (Yoshinori and Kanno, 1997). In addition to replenishing the soil organic carbon (SOC) and the nutrients, crop straw incorporation can improve the physical and biochemical conditions of the soil (Yan and Gong, 2010). Therefore, in China, to improve the soil fertility and to protect the deteriorating environment, returning crop straw to the fields rather than burning is strongly encouraged (Ma et al., 2007).

Crop residue incorporation affects the emissions of CH_4 and N_2O and the SOC sequestration in rice-based cropping systems. It is generally believed that the incorporation of crop straw provides a source of readily available C and N, which affects the CH_4 and N_2O production and emission (Zou et al., 2005; Ma et al., 2009; Yao et al., 2010). Several studies have noted that the incorporation of exogenous crop residues provides substrates for microbial methanogenesis, therefore significantly stimulating the CH_4 emissions from the rice fields (Zou et al., 2005; Yang et al., 2010). Meanwhile, the effects of straw incorporation on the N_2O emissions are influenced by the soil properties, the synthetic nitrogen fertilizer application, the C:N ratio of the residue, and the method of incorporation (Huang et al., 2004; Yao et al., 2009; Liu et al., 2011; Chen et al., 2013). A meta-analysis that integrated 112 scientific assessments of the crop residue return on the N_2O emissions has found that the practice exerted no statistically significant effect on the N_2O release (Shan and Yan, 2013).

Many studies have demonstrated that straw return is beneficial to soil carbon sequestration (e.g., Lu et al., 2009; Shang et al., 2011; Ma et al., 2013). After reviewing the field experiment results in China, Lu et al. (2009) have estimated that the annual carbon sequestration potential induced by the straw return could increase from the current level of 9.76 Tg to 34.4 Tg, if the practice of straw return grows in terms of its popularity. Yan and Gong (2010) have reported that organic fertilizer incorporation benefits SOC sequestration for three reasons. First, organic fertilizer incorporation directly integrates the organic material into the soil. Second, organic fertilizer incorporation increases the input of the root exudate by stimulating the crop growth. Finally, organic fertilizer incorporation improves the physical conditions of the soil and subsequently enhances the root development. In addition to increasing the soil carbon and sequestering of the atmospheric carbon, straw incorporation can improve soil fertility through certain mechanisms, such as providing macronutrients and micronutrients and improving the chemical and physical properties of the soil (Li et al., 2007; Yan et al., 2013). All of the benefits that straw incorporation delivers to the soil ecosystem will eventually result in a change in the crop's grain yield.

A comprehensive evaluation of straw incorporation in rice-based cropping systems should consider both the environmental and the economic effects of the practice. From an environmental perspective, the contribution of straw incorporation to the greenhouse effect constitutes the major focus, and the net GWP (NGWP) is a useful indicator to evaluate the effects of straw incorporation on the GHG emissions and the SOC changes in rice–wheat cropping systems. From an economic perspective, the net economic benefit (NEB) can provide a scientific basis for government agencies to formulate straw-related policies to guide farmers in taking eco-friendly approaches to the straw incorporation method.

The effects of straw return on the soil fertility and crop growth tend to gradually emerge after long-term incorporation. The decomposition process of incorporated straw occurs over a relatively long time; therefore, the effect of the straw application on the soil fertility may not be obvious during the first few years, but a positive response can emerge in the form of long-term cumulative effects. Currently, most research probing the effects of straw incorporation on soil fertility, crop growth and GHG emissions has been performed through short-term, often sporadic, field observations. Therefore, in the present study, we measured CH_4 and N_2O over a period of two years as part of an ongoing long-term straw incorporation experiment initiated in 1990. The objective of the study was to comprehensively appraise the effects of straw incorporation in a rice–wheat cropping system from the environmental and the economic perspectives. Furthermore, in the subsequent discussion presented in this paper, we also propose suggestions for government agencies to guide farmers to adopt eco-friendly methods of straw incorporation.

2. Materials and methods

2.1. Experimental sites

A long-term straw incorporation experiment, which includes the present study, is based at the Changshu Agroecological Experimental Station (31°32′93″ N, 120°41′88″ E) of the Chinese Academy of Sciences in the Jiangsu Province. The cropping regime is dominated by two crops every year (winter wheat and summer rice (*Oryza sativa* L.)). The soil is classified as an Anthrosol developed from lacustrine sediments. The experimental soil has pH of 8.09, organic matter content of 34 g kg^{-1}, total N content of 1.98 g kg^{-1}, available P content of 5.67 mg kg^{-1}, and available K content of 92 mg kg^{-1}. The daily mean temperature and precipitation during two annual rotations from 2009 to 2011 are shown in Fig. 1.

2.2. Field treatment and management

The long-term experiment, ongoing since 1990, has the following four treatments: (1) the control (CK), to which no fertilizer is applied; (2) the chemicals N, P and K (NPK); (3) incorporation of harvested rice/wheat straw at a moderate rate of 2.25 t dry-weight ha^{-1} season^{-1} plus balanced chemical fertilizers (NPKS1); and (4) incorporation of harvested rice/wheat straw at a high rate of 4.50 t dry-weight ha^{-1} season^{-1} plus balanced chemical fertilizers (NPKS2). All of the treatments are laid out in a randomized block design with three replicates, and each plot is 4 m × 5 m. The high and moderate rates are approximately equivalent to 100% and 50%, respectively, of the harvested rice and wheat straw yield.

Fertilizers in the form of urea (for N), calcium superphosphate (for P), and potassium chloride (for K) are used throughout the experiments. The application of urea, at a rate of 180 kg N ha^{-1}, is divided into three parts for the rice and the wheat growing seasons. In the rice growing season, the split is 40% as a basal fertilizer, 40% as a tillering fertilizer, and 20% as a panicle fertilizer, while in the wheat growing season, the split is 40% as a basal fertilzer, 40% as an elongation and booting fertilizer, and 20% as a panicle fertilizer. The P and K fertilizers are applied as basal fertilizer at rates of