Ecological Engineering 81 (2015) 289–297

Contents lists available at ScienceDirect

Ecological Engineering

journal homepage: www.elsevier.com/locate/ecoleng

Mitigating net global warming potential and greenhouse gas intensities by substituting chemical nitrogen fertilizers with organic fertilization strategies in rice–wheat annual rotation systems in China: A 3-year field experiment

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ARTICLE INFO

Article history:
Received 30 October 2014
Received in revised form 18 March 2015
Accepted 9 April 2015
Available online 16 April 2015

Keywords:
Soil carbon sequestration
Net ecosystem carbon budget (NECB)
Net global warming potential
Greenhouse gas intensity (GHGI)
Organic amendment
Rice agriculture

ABSTRACT

A 3-year field experiment was conducted to investigate the effects of different organic fertilization strategies for rice–wheat annual rotation systems on net global warming potential (net GWP) and greenhouse gas intensity (GHGI) by incorporating methane, nitrous oxide emissions, the changes in soil organic carbon (SOC) derived from the net ecosystem carbon budget (NECB), and the CO_2 equivalent emissions from manure and chemical nitrogen (N) fertilizer manufacturing. Six fertilization strategies were studied, including control (CK), N fertilizer (CF), pig manure compost + N fertilizer (MC), straw + N fertilizer (SC), straw + pig manure compost + N fertilizer (SM), and straw + straw-decomposing inoculant + N fertilizer (SI). The results indicated that the application of organic amendments did not change the seasonal pattern of GHG emissions but significantly affected their seasonal quantities. Averaged over the 3 cycles, the annual SOC sequestration rates contributed significantly to the net GWPs and were estimated to be 1.01 t C ha^{-1} yr^{-1} for the control and 1.13–1.27 t C ha^{-1} yr^{-1} for the fertilized plots. Compared to CF, the MC strategy significantly increased SOC while had similar size of net GWP and GHGI, thus deserving recommendation regarding sustainable soil productivity and GHGs mitigations. However, the other proposed organic strategies of SC, SM, and SI significantly increased net GWP and GHGI as well as SOC thus requiring further researches for GHGs mitigations. Therefore, we recommend that the application of manure substituting half chemical fertilizer be an effective strategy while straw returning in any currently studied strategies should be re-examined in the rice–wheat annual rotation system.

1. Introduction

Producing sufficient food to sustain the huge global population is a priority for both governments and scientists. Rice (*Oryza sativa* L.) and wheat (*Triticum aestivum* L.) are the world's two most important cereal crops and together contribute 45% of the digestible energy and 30% of the total protein in the human diet (Timsina and Connor, 2001). There are 13 million hectares of rice–wheat crop rotation systems in China, which are predominantly located in the provinces of Jiangsu, Anhui, Hubei and Sichuan along the Yangtze River Valley (Ma et al., 2009). The high level of crop production in China has been obtained by increasing the use of fertilizers (Ju et al., 2009), and the input of chemical nitrogen (N) fertilizer in the rice–wheat rotation system is as high as 550–600 kg N ha^{-1} yr^{-1} (Zhang et al., 2012). Chemical fertilizers have many advantages over organic manure due to the solubility of the nutrients and their immediate availability to plants as well as lower price and lower labor requirements for their application. However, the excessive use of N fertilizers may actually result in decreased N utilization efficiency in the crops (Vanlauwe et al., 2011) and also contribute to on-site land degradation (Guo et al., 2010), nutrient pollution and eutrophication (Howarth et al., 2011; Liu et al., 2014) and the greenhouse gas (GHG) emissions such as N_2O (Hoben et al., 2011).

Organic fertilizers, such as farmyard manure and crop residues, have long been proposed worldwide in agriculture to help to

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http://dx.doi.org/10.1016/j.ecoleng.2015.04.071
0925-8574/

reduce dependence on synthetic chemical fertilizers as well as to counteract soil degradation (Odhiambo and Magandini, 2008). However, long-term or heavy application of organic fertilizers may adversely affect plant growth (Jannoura et al., 2014), soil organisms (Amin et al., 2013), water quality (Wang et al., 2008) and GHG emissions such as CH_4 (Datta et al., 2013). Traditional organic inputs such as crop residues and animal manures cannot meet crop nutrient demands for high yielding due to their low nutrient contents. These will inevitably lead to adaptive strategies of optimizing organic and inorganic fertilization to realize maximum yield with minimal environmental costs, particularly GHG emissions (Hillier et al., 2012).

The three GHGs associated with agriculture are CH_4, N_2O and CO_2. It is estimated that ca. 10–12% of total global anthropogenic emissions, or between 5120 and 6116 Mt CO_2-equivalents, can be attributed to direct agricultural GHG emissions in 2005. The technical potential of the agricultural sector for mitigation is considered to be substantial as high as 5.5–6.0 Pg CO_2 equivalents yr^{-1} by 2030 (Smith et al., 2008). While the net emission of CO_2 equivalents can potentially be decreased by increasing the soil organic carbon (SOC) and/or decreasing GHG emissions. However, there are complex trade-offs between SOC sequestration and GHG emissions. For example, soil carbon sequestration from balanced fertilizer inputs may be offset by increased GHG emissions (Shang et al., 2011). Recently, greenhouse gas intensity (GHGI) has become widely adopted as a means to relate the net global warming potentials (GWP) with crop yields (Mosier et al., 2006; Zhang et al., 2012). Thus, the trade-offs among improved soil health, yield, carbon sequestration and GHG mitigation should be taken into account when considering the substitution of organic amendments for mineral fertilizers.

However, the method for measuring SOC is not sensitive enough to detect seasonal or annual changes (Zheng et al., 2008). Recently, Zhang et al. (2014) reported that net ecosystem carbon budget (NECB) is an alternative method for estimating SOC changes after comparing to SOC changes over a 5-year field experiment. The NECB approach, which provides a simplified, chamber-based technique for calculating changes in SOC on the crop seasonal time scale, is particularly important for newly established field trials (Jia et al., 2012; Ma et al., 2013). The extent to which the NECB, net GWP, and GHGI can be reduced by the different organic fertilization strategies in comparison with conventional chemical fertilizers in paddy field remains unclear.

We hypothesize that: (1) different combinations of organic fertilizer with chemical fertilizer may achieve comparably high grain yields by providing the same amount of nutrients; (2) different combinations of organic fertilizer with chemical fertilizer may increase SOC sequestrations and offset the probable effects on extra emissions of CH_4 and N_2O. The desired outcome is that the results can be used to assess options of using agricultural wastes as resources for maintaining soil fertility, improving crop yields and mitigating greenhouse effects. Therefore, a field experiment was established in 2011 to gain insight into the effects of combining pig manure compost and/or crop residues with chemical fertilizer on soil C sequestration rates, GHG emissions and net GWP and GHGI over three cycles of rice–wheat annual rotations and to find feasible mitigation strategies utilizing agricultural wastes for sustainable agriculture.

2. Materials and methods

2.1. Experimental sites

A field experiment was performed in a typical rice–wheat rotation system from June 27, 2011 to May 18, 2014. The station was located in Baimao Village (31°32′N, 120°55′E), Suzhou City, Jiangsu Province, China, which lies in the center of the Yangtze River Delta in eastern China in the northern subtropical humid climatic zone. The main cropping system is flooded rice and drained wheat on an annual rotation. Soil samples from a depth of 0–20 cm were collected in 2011 after the wheat was harvested for the analysis of physical–chemical characteristics. The soil is classified as a fluvisol with a bulk density of 1.20 g cm^{-3}, a pH (1:2.5, H_2O) of 7.60, a SOC of 11.6 g C kg^{-1}, a total N of 2.30 g kg^{-1}, an available P of 39.0 mg kg^{-1} and an exchangeable K of 74.3 mg kg^{-1}. The monthly average air temperature and precipitation during the three rice–wheat rotation cycles from 2011 and 2014 are shown in Fig. 1.

2.2. Field experimental treatments and crop management

The field experiment was conducted in a randomized complete block design of six treatments (see Table 1) with four replicates. Each plot was 6.4 m × 7.2 m, and adjacent plots were separated by concrete ridges (30 cm width) with plastic covering. The blocks were separated by irrigation furrows (50 cm width) and two ridges. The treatments included control (CK), N fertilizer (CF), pig manure compost + N fertilizer (MC), straw + N fertilizer (SC), straw + pig manure compost + N fertilizer (SM), and straw + straw-decomposing inoculant + N fertilizer (SI) and are listed in detail in Table 1. For the SM and SI treatments, the chopped straw of the previous crop was incorporated into the top 20 cm of the soil at a rate of 3 t ha^{-1} by ploughing. A straw-decomposing inoculant containing actinomycetes, lactic acid bacteria, bacillus, photosynthetic bacteria and yeast (Xin Tiandi biological fertilizer Engineering Center Company, Yixing, Wuxi, China) was sprayed onto the soil surface for the SI treatment at a rate of 20.7 kg ha^{-1}.

Water management, fertilization and other managements in this experiment followed local practices. The fields were submerged before the rice seedlings (cultivar Changyou 5) were transplanted in late June. All of the remaining straw was removed from the surface except in SC, SI and SM, and hand plowing to a depth of 20 cm was carried out in late June. Subsequently, 2–3 rice seedlings aged 25 days were transplanted to 1 hill in a 15 cm × 20 cm space in the field. All plots were kept flooded for approximately, 40 days after rice transplanting. The one week of mid-season drainage was conducted before reflooding followed by a dry–wet alteration without waterlogging till rice harvest. Approximately a month after the rice was harvested, winter wheat (cultivar Yangmai 14) was seeded directly onto the soil surface without mixing the seeds with the topsoil. There was no irrigation during the period of wheat growth, so rainwater was the only source of soil moisture. The wheat was harvested in late May.

The amounts of 240 kg N ha^{-1} $crop^{-1}$ as the total of chemical and organic fertilizers were applied to each crop of wheat and rice. N fertilizer as urea was applied in four splits within each crop; 40% was applied as basal fertilizer and 60% as supplementary fertilizer during crop growth at 3, 6 and 9 weeks after rice transplantation and 7, 13 and 16 weeks after wheat sowing. Also, calcium superphosphate and potassium chloride were applied at 120 kg P_2O_5 ha^{-1} and 90 kg K_2O ha^{-1}, respectively, as basal fertilizers to all plots except the CK. All of the organic amendments (pig manure compost and straw) were incorporated into the soil two weeks before the transplanting of rice or the sowing of wheat for the organic fertilizer application treatments. Only the basal fertilizers were incorporated into the surface soil (0–15 cm), and the topdressings were surface-broadcasted.

2.3. Chamber measurement of methane and nitrous oxide fluxes and ecosystem respiration (R_e)

CH_4 and N_2O emissions and R_e were determined simultaneously and using the static-opaque chamber method described by