Agriculture, Ecosystems and Environment 245 (2017) 11–21

Contents lists available at ScienceDirect

Agriculture, Ecosystems and Environment

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

Soil carbon changes in paddy fields amended with fly ash

Sang-Sun Lim[a,b], Woo-Jung Choi[a,*], Scott X. Chang[b], Muhammad A. Arshad[b], Kwang-Sik Yoon[a], Han-Yong Kim[c,*]

[a] Department of Rural and Biosystems Engineering, Chonnam National University, Gwangju, 61186, Republic of Korea
[b] Department of Renewable Resources, University of Alberta, Edmonton, Alberta, T6G 2E3, Canada
[c] Department of Applied Plant Science, Chonnam National University, Gwangju, 61186, Republic of Korea

ARTICLE INFO

Keywords:
Compost
Green manure
Mineral amendment
Rice grain yield
Soil carbon sequestration
Synthetic fertilizer

ABSTRACT

Increasing soil carbon (C) sequestration in the agricultural sector is an important strategy for mitigating climate change; however, conventional best management practices such as crop residue retention and organic fertilizer application do not always increase soil C content due to C loss by cultivation. In this context, application of fine-textured minerals such as coal fly ash (FA) may be effective in increasing soil C sequestration by enhancing plant biomass production and protecting soil C from being lost. We conducted a three-year field experiment in a paddy field with three levels of FA application (0, 5, and 10% by soil weight) in combination with the following four nitrogen (N) treatments: no input, and applications of urea, pig manure compost (compost) and hairy vetch (*Vicia Villosa* Roth.) green manure (vetch). Across the three seasons, rice grain yield was in the order of vetch = urea > compost > no input, reflecting the effect of N availability in each treatment. Application of FA (particularly at 10%) reduced the total rice plant biomass by hampering tillering. However, FA application did not reduce grain yield due to increased individual grain weight. In spite of decreased rice residue incorporation into the soil, FA application increased the soil C content at the end of the third season regardless of the N source, driven by reduced soil C loss. We conclude that the application of mineral soil amendments such as FA is effective in enhancing soil C sequestration without decreasing rice yield in paddy fields.

1. Introduction

Agricultural activities including land-use change and intensive cultivation have substantially contributed to the increase of greenhouse gas concentrations in the atmosphere (Lal, 2004). However, if best management practices (BMPs) are adopted, agricultural soils may become an effective carbon (C) sink as the C content of the soils is below the C saturation point, an equilibrium C content at which no further C can be sequestered with time under a steady C input (Lal, 2004; West and Six, 2007). Particularly, fine-textured paddy soils are considered to be more effective for C sequestration, as compared with upland soils, due to the slow decomposition of organic C under submerged or anaerobic conditions during the growing season (Sahrawat, 2004; Rui and Zhang, 2010).

Commonly used BMPs to increase C sequestration in soils include minimum or no tillage, cover cropping, addition of organic amendments, balanced fertilization, and rotational cropping (Lal, 2004; Yan et al., 2007; Tian et al., 2015). However, soil C sequestration relying on the traditional BMPs is not always efficient due to loss of applied organic C as well as native soil C loss as a result of soil disturbance by cultivation (Yan et al., 2007; Tian et al., 2015). For example, balanced fertilization with synthetic fertilizer may produce more rice plant residues but residue incorporation may not necessarily enhance soil C sequestration as rice residues are readily decomposed during cultivation (Viswanath et al., 2010). Among organic nutrient sources such as green manure and livestock manure compost, green manure application may not directly contribute to soil C sequestration due to its faster rate of decomposition (Lim and Choi, 2014; Park et al., 2015). Application of livestock manure compost which has recalcitrant C can enhance soil C sequestration; however, compost application may reduce rice yield due to its low nutrient availability (Yun et al., 2011). In this context, the application of mineral amendments such as coal fly ash (FA) that have a high specific area with organic fertilizers as a source of nutrients can be effective to enhance soil C sequestration via soil C stabilization (Six et al., 2004; Jastrow et al., 2007).

Fly ash is a byproduct from coal power plants, and it is estimated that 750 million tons of FA is generated per annum on a global basis (Blissett and Rowson, 2012). Due to the large specific area of the silt-sized particles, FA provides sites for the formation of organo-mineral complexes (Jala and Goyal, 2006). In addition, FA can fix CO_2 produced

* Corresponding authors at: Chonnam National University, Gwangju, 61186, Republic of Korea.
E-mail addresses: wjchoi@jnu.ac.kr (W.-J. Choi), hyk1020@jnu.ac.kr (H.-Y. Kim).

http://dx.doi.org/10.1016/j.agee.2017.03.027
Received 8 June 2016; Received in revised form 28 March 2017; Accepted 30 March 2017
0167-8809/

from soil respiration via carbonation of calcium (Ca) and magnesium (Mg), (Ca^{2+} or Mg^{2+}) + $CO_3{}^{2-}$ → $CaCO_3$ or $MgCO_3$, that are present in FA, thereby decreasing CO_2 emission while increasing soil C content (Lim et al., 2012a; Lim and Choi, 2014). However, it has not been verified yet if FA application can increase soil C sequestration in the field with growing plants. Lack of such information limits the practical use of FA for enhancing soil C sequestration. Originally, FA has been considered as a soil amendment for acidic infertile soils due to its high pH and the macro- and micro-elements it contains (Basu et al., 2009; Jala and Goyal, 2006). Many studies reported that FA application at a low rate (e.g., < 12% w/w) improved rice growth (Basu et al., 2009; Jala and Goyal, 2006 and references cited therein) without increasing heavy metal concentrations in the rice plant (Nayak et al., 2015). Therefore, FA-induced reduction in soil C loss together with increased rice growth may enhance soil C sequestration in paddy soils, particularly when the traditional BMPs such as plant residue retention and application of organic input (e.g., compost or green manure) are combined.

In this study, we addressed the questions 1) if FA as a mineral amendment increases soil C sequestration in rice paddy?; 2) if so, what is the mechanisms (via increased rice growth vs. reduced soil C loss) of the increased soil C sequestration?; and 3) how does the effect of FA on soil C vary with nitrogen (N) sources such as synthetic fertilizer, livestock manure compost, and green manure that are co-applied with FA? To answer the questions, the effect of FA application on rice growth (total biomass production, grain yield, and parameters of growth and yield components) and soil C content was investigated over three rice growing seasons. We hypothesized that FA can enhance C sequestration in the soil via reducing gaseous C loss and/or increasing rice plant biomass and such effect of FA on soil C sequestration would be different among the typical N sources including synthetic fertilizer, green manure, and livestock manure compost due to different N availability of the N sources and contrasting decomposability of the organic matter that is added with livestock manure compost and green manure.

2. Materials and methods

2.1. Study site and soil

This study was conducted in an experimental rice paddy field (126°53′E, 35°10′N, 33 m above sea level) at Chonnam National University, Gwangju, Korea from 2010 to 2012. This area belongs to a typical East Asian temperate monsoon climate system with an annual mean temperature of 13.8 °C and precipitation of 1391 mm over the past 30 years. Weather data were collected from the Gwangju meteorological station in the vicinity (200 m away) of the studied paddy field. The cumulative precipitation and solar radiation, and daily mean temperature during the rice growing seasons from June to October differed with years; e.g., higher temperature in 2010 than in 2011 and 2012 (Fig. 1). In 2012, two typhoons (Tembin and Bolaven) struck this area at the heading and grain-filling stages of rice plant growth (Fig. 1).

The soil was classified as an Inceptisol (coarse loamy, mixed, mesic family of Fluvaquetic Endoaquepts) in the USDA Soil Taxonomy (RDA, 2000). Surface (0–20 cm) soil samples were collected from ten randomly located points within the field. The soils were air-dried, passed through a 2-mm sieve, and analyzed for particle-size distribution and chemical properties including pH, electrical conductivity (EC), total C, total N, total P, and available P (Table 1). The detailed analytical procedures are described in the Supplementary data.

2.2. N sources and fly ash

Chemical grade urea, fused phosphate and KCl were used as synthetic fertilizers. Pig manure compost (compost) that was produced by composting pig manure with sawdust as a bulking agent for approximately 2 months was purchased from a compost manufacturing company. For green manure application, hairy vetch (*Vicia Villosa* Roth.) (vetch) was provided by a research station of Rural Development Administration (RDA) of Korea. The compost and vetch were freeze-dried, stored in a refrigerator, and used for the three-year field experiment.

In each year, the compost (10 kg in dry weight) was passed through a 4-mm sieve and vetch (10 kg) was chopped to < 4 mm. A portion (100 g) of the samples was further ground to < 2 mm and analyzed for chemical properties following the same methods as soil analysis (Table 1). Additionally, chemical stability degree, the ratio of acid hydrolysable organic matter to total organic matter, was determined by a modified Klason lignin method (López et al., 2010). The chemical properties of the compost and vetch did not differ among years, and thus the average values are reported. Although the C/N ratio of the compost (10.7) and vetch (11.5) was not significantly different, the chemical stability degree was much higher for the compost (27.3%) than for the vetch (2.2%), indicating that the compost was more recalcitrant to microbial decomposition than the vetch (Table 1).

Fly ash (ca. 500 kg) was obtained from a coal power plant at Hadong, Korea. A portion (20 g) of the FA sample was oven-dried at 105 °C and analyzed for pH, EC, total C and N concentration, and particle size distribution using the same methods for soil analysis. Elemental composition was determined using X-ray fluorescence spectrometry (S4 PIONEER, Bruker, Germany); water extractable metals concentration with ICP-AES (Optima-7000DV, PerkinElmer, Boston, USA) after extraction with distilled water; and NH_4OAc extractable metals concentration with ICP-AES (Optima-7000DV, PerkinElmer, Boston, USA) after extraction with 1 mol L^{-1} ammonium acetate. The FA used in this study had typical properties of those used in other studies including high pH, EC, and CaO content (e.g., Pandey and Singh, 2010), and some of the properties of the FA were reported in our previous studies (Lim et al., 2012b; Lee et al., 2014; Lim and Choi, 2014). Briefly, the pH and EC were 11.7 and 1.55 dS m^{-1}, respectively; CaO and MgO contents were 7.0 and 2.5%, respectively; and total C content was 24.2 g kg^{-1}. The FA was mainly composed of silt-sized (0.002–0.05 mm) particles (75.4%) followed by sand (> 0.05 mm, 22.7%), with only 1.9% clay (< 0.002 mm), and the concentrations of NH_4OAc-extractable arsenic (As) (6.8 mg kg^{-1}) and boron (B) (95.1 mg kg^{-1}) were higher than those of other elements such as copper and zinc (< 1.2 mg kg^{-1}) (Lim and Choi, 2014).

2.3. Field experiment

A total of thirty-six plots (plot size: 1 m × 1 m) were established for four N sources (no input (CK), urea, compost, and vetch) and three FA application rates (0, 5 and 10% w/w, coded as FA_0, FA_5, and FA_{10}, respectively) in a split-plot design arranged in 3 blocks (Table S1). The N source was the main-plot treatment and the FA application rate was the split-plot treatment. Twelve plots (four N sources × three FA rates) were laid out in each block, and plots were spaced 1 m apart and each plot was confined by inserting flexible plastic barriers (35 cm in height) into the plow pan layer of the soil (around 20 cm deep) to minimize cross-contamination among plots.

Ten days before the transplanting of rice (*Oryza sativa* L., cv. Ilmybyeo, subsp. japonica) in the first year (2010), FA was applied to the surface of each plot and manually mixed with the top (0–20 cm) soil. The FA application rate was determined as a percentage of FA to the dry weight of the top soil, and thus 5 and 10% are equivalent to approximately 10.7 and 21.4 kg m^{-2} (Table S1). The application of FA at 5 and 10% supplied 260 and 520 g C m^{-2}, respectively, in the form of black C and it was calculated that the addition of black C (mostly associated with silt-sized particles) at those two application rates increased C concentration of silt-sized particles of the bulk soils by 1.4 and 2.8 g C kg^{-1}, respectively. No FA was applied in 2011 and 2012. Nutrients were applied 3 days before transplanting each year. Fused phosphate (4.5 g P_2O_5 m^{-2}) and KCl (4 g K_2O m^{-2}) were mixed