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Optimization of removal and recycling ratio of cover crop biomass using carbon balance to sustain soil organic carbon stocks in a mono-rice paddy system

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ABSTRACT

The cultivation of a winter cover crop as green manure is strongly recommended to improve soil quality in mono-rice paddy systems; however, the biomass is largely removed to feed cattle in many Asian regions. To determine the minimum recycling ratio of the biomass that can sustain soil organic carbon (SOC) levels and produce more fodder for cattle, the SOC balance, which is the difference between OC input and output during rice cultivation, was evaluated with the various levels of biomass addition. The sources of OC input included cover crop biomass and fertilizer, and the OC outputs were estimated by the losses from the mineralization of C (emissions of CH_4 and CO_2). A mixture of barley (75% of the recommended dose, RD) and hairy vetch (hereafter, vetch, 25% of the RD) seeds were broadcast after rice harvests in 2011 and 2012, and the aboveground biomass (11.5–12 Mg ha^{-1}, based on dry weight) harvested in the following years was incorporated at different ratios (0–100%) into soils one week before transplantation of rice with the same chemical fertilization. The incorporated OC was lost primarily through emissions of CO_2 (73–85% of the OC output). However, the proportion of CH_4 loss increased significantly with an increase in the rate of aboveground biomass application, which was caused by the development of anaerobic soils. A negative SOC balance, which implied soil fertility was at risk from a decreasing stock of SOC, was observed with total aboveground biomass removal. However, the balance of SOC increased significantly with an increase in level of biomass recycling and reached a sustainable level at approximately 28–30% recycling of aboveground biomass; thus, the current levels of SOC could be sustained. In conclusion, more than 30% of the aboveground biomass of the cover crop (3.4–3.6 Mg ha^{-1} dry weight) should be incorporated as a green manure to sustain levels of SOC in mono-rice cultivation systems with chemical fertilization.

1. Introduction

The intensified cultivation of rice may pose risks to long-term sustainability and productivity (Lal, 1997), primarily because of low levels of soil organic carbon (SOC), low soil fertility and an imbalance in the management of nutrients (Reddy and Krishnaia, 1999). The use of green manure is an important soil management practice with the potential to maintain SOC contents and to reduce dependence on mineral fertilizers (Elfstrand et al., 2007). In the mono-rice cultivation systems of temperate zone countries such as Korea, the cultivation of winter cover crops as a green manure is strongly recommended. These crops include N-fixing plant species such as hairy vetch and Chinese milk vetch and non-leguminous species such as rye, barley and wheat, which generally produce high-biomass yields (Yasue, 1991; Singh et al., 1999; Cho et al., 2003). The winter cover crops are seeded after rice harvest in the late fall and are then incorporated in situ as green manure before rice transplanting in the following year.

The addition of leguminous cover crop biomass sustains the vegetative growth of rice, but the rice grain quality deteriorates, and the addition of non-leguminous cover crops with high C/N ratios decreases rice productivity because of slow mineralization; therefore, the combined cultivation of the two different cover crops is broadly used in paddy soils in Korea (Jeon et al., 2008; Ryu

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et al., 2010; Haque et al., 2013; Jeon et al., 2013). For example, non-leguminous barley is seeded with leguminous hairy vetch, and this combination has additional high utility as cattle feed.

Historically, in this region, farmers have struggled with a lack of materials to feed their animals, and thus most of the rice straw is removed for cattle feed at harvest (Supplementary material 1). Most of the biomass of winter cover crops, which are cultivated as green manure, is also removed from the field, but the effect of total biomass removal on the sustainability and quality of rice paddy soils has not been well studied. Cover crops are cultivated in mono-rice systems to simultaneously improve SOC contents and produce more cattle fodder, and thus the minimum recycling ratio of cover crop biomass must be systematically determined.

In this study, a SOC balance technique was used to determine the minimum ratio for recycling of winter cover crop biomass as green manure to sustain SOC stocks and to produce more cattle fodder in mono-rice paddy systems.

2. Materials and methods

2.1. Cover crop and rice cultivation

The experiments were conducted at the same site for two years, with a one-year cover crop-rice rotation. The experimental plots were installed in a typical rice paddy soil at the Gyeongsang National University Experimental Farm (36°50′N, 128°26′E), Jinju, South Korea, in 2010 (Supplementary material 2). The soil texture was a silt loam, and the soil was classified as a typic haplaquent with somewhat impeded drainage. The soils were characterized with a pH of 6.2 (1:5 with H_2O), an organic C content of 11.9 g kg^{-1} and available P at 34 mg kg^{-1}.

In the arable soils of Korea, 140 or 90 kg ha^{-1} of barley or hairy vetch seeds is recommended for a winter cover crop, respectively (Jeon et al., 2013), but the mixture of barley (75% of the recommended dose, RD) and vetch seeds (25% of RD) is broadly used to improve biomass productivity. After the harvest of rice in 2010 and 2011, a seed mixture (75% and 25% of the RD for barley and vetch, respectively) was broadcast applied. In early June of the following years (2011 and 2012), the aboveground biomass of the cover crop was harvested manually at the mid-maturing stage of barley (Table 1). The biomass productivity was 11.5–12 Mg ha^{-1} dry weight, which was the combination of 5.0–5.5 Mg ha^{-1} of barley and 6.0–6.5 Mg ha^{-1} of hairy vetch. The biomass was 67–69% moisture (wt wt^{-1}), with 42.0–42.3 g kg^{-1} total C and C/N ratios of 20.0–21.2.

To determine the belowground biomass production of the cover crops, soil cores (8 cm diam.) were collected in each plot in two horizons (0–20 and 20–40 cm). Because cover crop seeds were evenly broadcast inside the plots, the soil samples were collected at three representative positions without distinguishing the in row and between row positions. The roots were separated with a hydropneumatic elutriation system. The roots recovered on the sieve were thoroughly washed with water to remove remaining fine mineral particles. After this washing, the roots were separated from remaining sand particles and organic debris by flotation. However, the root biomass could not be separated between hairy vetch and barley. In the 1st year, total belowground biomass productivity was 1.0–1.2 Mg ha^{-1} dry weight. The belowground biomass had a mean total C content of 387 g kg^{-1}, and the range of C/N ratios was 23.1–24.5. In the 2nd year, the belowground biomass yields of the cover crop increased slightly with increased levels of biomass for recycling, with yields that ranged from 1.1 Mg ha^{-1} in the complete biomass removal plots to 1.2 Mg ha^{-1} in the complete biomass recycling plots. However, the chemical properties of the belowground biomass were not significantly different among the treatments.

The harvested aboveground biomass was manually chopped (5–10 cm), applied at different recycling ratios (0, 25, 50, 75 and 100%) of the total biomass, and then mixed mechanically into the surface soil one week before the transplanting of rice. Each treatment plot was 10 m × 10 m, and the plots were arranged with three replications in a randomized block design. A concrete barrier was placed between each treatment to provide buffer zones (0.6 m) and to avoid the effects of mixing.

Twenty-one-day-old rice (Dongjinbyeo cultivar, Japonica type) seedlings were transplanted at 15 cm × 30 cm spacing in mid-June. The recommended rates of chemical fertilizers ($N–P_2O_5–K_2O$ = 90-45-58 kg ha^{-1}) were applied (RDA, 1999). Throughout the rice growing season, the water level was maintained at a depth of 5–7 cm above the soil surface with an automatic water level controller; the water was drained three weeks before the rice harvest. The rice was harvested in mid-October. The growth and yield characteristics were determined at the maturing stage following Korean standard methods (RDA, 1995). The belowground biomass productivities of rice were determined by the same method with cover crop sampling. However, different with cover crop sampling, the soil samples were separately collected in row and between row positions at three representative points.

2.2. Assessment of organic carbon budgeting

The instantaneous level of the SOC pool can be assessed with computing the balance between inputs and outputs (Eq. (1)) (Lal, 2002). The depletion of the SOC pool occurs when inputs of solid residues of C are less than the outputs of C.

$$SOC_g = C_o + (C_r + C_b + C_f) - C_m \quad (1)$$

where SOC_g is the gross SOC pool, C_o is the antecedent SOC pool, C_r is the addition of C in crop residue, and C_b and C_f are the additions of C as other biosolids and fertilizers, respectively. However, in this study, because the organic C balances were investigated during rice cultivation, the cover crop biomass and urea application were the

Table 1
Productivities and chemical properties of cover crop biomasses incorporated as green manure.

Parameters	2011			2012		
	Total	Barley	Hairy vetch	Total	Barley	Hairy vetch
Biomass (Mg ha^{-1}, dry weight)	12.0	5.5	6.5	11.5	5.3	6.2
Total C (%, wt wt^{-1})	42.0	41.5	42.9	42.3	41.6	43.0
Total N (%, wt wt^{-1})	2.09	0.83	4.0	2.0	0.84	4.0
C/N ratio	20.12	50.0	10.72	21.15	49.52	10.75
Total P (%, wt wt^{-1})	0.23	0.13	0.39	0.24	0.13	0.40
Total K (%, wt wt^{-1})	1.36	1.0	1.9	1.36	1.01	1.91