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Short Communication

Optimizing the harvesting stage of rye as a green manure to maximize nutrient production and to minimize methane production in mono-rice paddies

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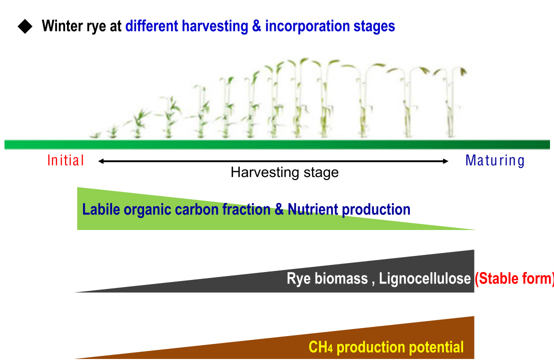
HIGHLIGHTS

- We tested different rye harvesting stages on CH4 and nutrient production in rice soil.
- Chemical composition and rye biomass were significantly varied over the harvesting.
- CH4 production potential was significantly influenced in different harvest seasons.
- Controlling the harvesting time could be a new strategy to mitigate the CH4 impact.

GRAPHICAL ABSTRACT



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ABSTRACT

Rye (*Secale cerealis*) has been widely cultivated to improve soil quality in temperate paddies. However, its biomass incorporation can significantly increase greenhouse gas emissions, particularly the emission of methane (CH_4), during rice cultivation. The chemical composition and productivity of cover crop biomass may vary at different growing stages. Therefore, nutrient productivity and CH_4 production potential might be controlled by selecting the optimum harvesting stage. To investigate the effect of rye harvesting stage on nutrient productivity and CH_4 production potential, rye was harvested at different growing stages, from the flowering stage to the maturing stage, for seven weeks. The chemical composition and biomass productivity of rye were investigated. CH_4 production was measured by laboratory incubation, and CH_4 production potential was estimated to determine the real impact on CH_4 dynamics in rice soils. Rye biomass increased with plant maturation, but nutrient productivities such as N (nitrogen), P_2O_5, and K_2O were maximized at the flowering stage. The contents of cellulose and lignin increased significantly as plants matured, but the total N, labile organic carbon (C), and hot and cold water-extractable organic C clearly decreased. Soils were mixed with 0.3% (wt wt^{-1} on dry weight) air-dried biomass and incubated to measure the maximum CH_4 productivity at 30 °C under flooded conditions. Maximum CH_4 productivity was significantly correlated with increasing labile organic C and protein content, but it was negatively correlated with total organic C, cellulose, and lignin content. CH_4 production potentials were significantly

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increased up to the pre-maturing stage (220 DAS) and remained unchanged thereafter. As a result, CH_4 production potential per N productivity was the lowest at the late flowering stage (198–205 DAS), which could be the best harvesting stage as well as the most promising stage for increasing nutrient production and decreasing GHG emissions in temperate mono-rice paddy soils.

1. Introduction

Cover crops are usually grown to cover the ground and protect the soil from erosion and loss of plant nutrients through leaching and runoff (Reeves, 1994). Because crop residues are mostly removed for livestock feeding in many Asian regions, cover crop cultivation during the fallow season is strongly recommended to improve soil quality. In temperate countries such as Korea, the winters are characterized by long, dry and cold weather. Winter cover crops that can tolerate such harsh weather conditions are critically important (Haque et al., 2013). The main cover crops include barley, hairy vetch and rye. Winter rye is considered the most viable in this region, due to its high tolerance against drought and extreme weather conditions (Kim et al., 2013). Another advantage of rye is its high biomass yield compared to other cover crops. It grows rapidly and is adapted to low temperatures, so it provides a higher input of organic matter into the soil (Kim et al., 2013) and can be an excellent source of animal feed when other green forages are not available (Oelke et al., 1990). In addition, rye is known to have a very strong and long root system that can hold the soil in place, thus preventing soil erosion and loss of nutrients (Smith et al., 2011).

The mineralization of organic substrates controls the availability of nutrients to the field crops, and soil microorganisms play an important role in determining the mineralization rate of organic matter. The kinetics of decomposition of organic substrates in soil and their C and N mineralization could be strongly influenced by the quality of the materials (Heal et al., 1997). It is quite clear from the literature that N content or the C/N ratio of green manures is the principal determinant of biomass application effects on soil N availability after incorporation into soil (Hargrove, 1986; Smith et al., 1987; Ranells and Wagger, 1996). Therefore, the C/N ratio of cover crop biomass could be a crucial factor to consider in determining the value of green manure because it affects the nutrient content of the soil and may starve a crop of N if the incorrect plants were used as a green manure.

Compared to leguminous plants such as hairy vetch, rye biomass has a low N content and a high C/N ratio. Thus, its residue as a green manure could have some undesirable characteristics that may interfere with planting and growth of the succeeding crop in the short term. The C/N ratio of plant biomass will differ from species to species, depending on age. As plant tissue N increases or tissue C/N ratio decreases, the initial N mineralization potential and N mineralization rate increase (Frankenberger and Abdelmagid, 1985; Kuo and Sainju, 1998), and the crossover time for net N mineralization decreases (Kuo and Sainju, 1998). The tissue C/N ratio of cover crops generally decreases in the vegetative growth stage, is minimized at the flowering stage, and thereafter significantly increases with maturity.

Similar results were obtained by Dalal et al. (2008), who found that methane (CH_4) production increased because of the high C/N ratio of rye cover crop application. Because the productivity and the tissue C/N ratio of cover crop biomass can be affected by the growing stage, control of the harvesting time might be an important management technique for cover crops to increase nutrient productivity and availability.

However, using biomass as a green manure could greatly increase the emissions of greenhouse gases (GHGs) such as CH_4 and CO_2 in arable soils. CH_4 is mainly produced from the decomposition of organic matter by anaerobic archaeal methanogens under extremely reduced conditions (Garcia et al., 2000). Cover crop biomass greatly stimulates CH_4 emissions in flooded paddy soils (Kim et al., 2012, 2013; Haque et al., 2013). CH_4 production from organic substrates mainly depends on substrate availability. The composition and biodegradability play a crucial role in CH_4 production from energy crops.

For example, lignocellulose in plant biomass consists of three biopolymers, cellulose, hemicellulose and lignin, which have a remarkable influence on CH_4 production (Vindis et al., 2010). CH_4 productivity shows a strong positive correlation with labile Cs such as water extractable carbon (C) and hot water extractable C, as well as total N, because rye cover crop application has the highest potential of soil organic C accumulation, which alternatively increases CH_4 emission (Denef et al., 2009). In contrast, CH_4 productivity shows a highly negative correlation with cellulose, hemicellulose, lignin and polyphenol content. These results are similar to those of Kazakou et al. (2009), who stated that decomposition of organic constituents increases with increasing concentrations of cellulose, hemicellulose and lignin, which alternatively will reduce CH_4 productivity. Because the composition of lignocellulose and other organic chemicals in biomass could be markedly different during different cover crop growing periods, the choice of harvest time could be important for reducing CH_4 emissions in rice paddy soil.

We hypothesized that the organic components of the rye cover crop change greatly across growth stages in a way that can influence nutrient availability in the soil as well as CH_4 production in the flooded paddy soil. The aim of this study was mainly to determine whether rye biomass could be harvested at particular stages to mitigate CH_4 production and to enhance nutrient production in paddy soil. In this study, the effects of harvesting time and incorporation of rye cover crop biomass on CH_4 production and nutrient production in rice paddy soil were evaluated to determine the optimum season for rye harvesting in both field and laboratory-scale experiments. For this purpose, winter rye was harvested at different growing stages, and CH_4 production potentials and nutrient input of the biomass were estimated.

2. Materials and methods

2.1. Rye cultivation and harvesting

Winter cover crops were cultivated normally in the late autumn and harvested in the following spring. The cover crop was then incorporated as a green manure to improve the soil quality before rice cultivation in summer. In this study, rye (*Secale cerealis*) seeds were sown at the recommended seed rate (120 kg ha^{-1}) (Kim et al., 2013) after rice harvest in mid-October 2010 in a rice field (Naeback ri, Sudong myeon, Hamyang; South Korea; coordinates 35° 36′ 03.56″ N, 127° 48′ 07.50″ E). The soil in this experimental site belongs to the Pyeongtaeg series (fine-silty, mixed, nonacid, mesic Typic Endoaquept) (USDA, 2010). The soil organic C content was 9.0 ± 0.9 g kg^{-1}, and the soil pH was 5.9 ± 0.3 (1:5 with H_2O) before the cover crop incorporation. The field (40 m × 25 m, 1000 m^2) has been managed under the same farming practices for a rye cropping system over the past several decades. Rye was cultivated without adding any chemical fertilizer and maintained under upland conditions during cultivation. Based on maturation time, the above-ground biomass from three 1-m^2 areas within the experimental field was harvested every week from 191 DAS (days after rye seeding) to 233 DAS, which has typically been recommended for harvesting and incorporating green manure in rice fields (Kim et al., 2012, 2013). The whole above-ground biomass was air-dried, the dry weight was recorded.