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Effects of Long-Term Fertilization on Light and Heavy Fractions of Soil Organic Matter in Single Cropping Paddy Soils in Korea

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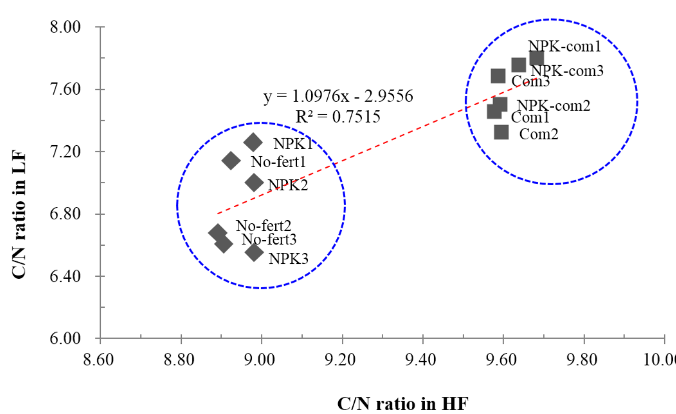
ABSTRACT

Advanced understanding of SOC still requires further studies on diverse soils including a wide spectrum of paddy soils and agricultural practices. The objectives of this study were to investigate the effects of long-term fertilization on both light fraction (LF) and heavy fraction (HF) of soil organic matter and the relationships among total C, C/N ratio, clay content, and fertilization type in paddy soils. Compost application led to a significant increase in HF and consequently in C and N contents. Compost plots had a higher C/N ratio compared to those of treatments without compost in HF as well as LF. Correlation of C/N ratio to LF and HF was clearly separated into two groups as a boundary of about 9.5 of C/N ratio. These results clearly show that balanced fertilization together with composting could lead to synergic effects on enhancing C sequestration as well as plant nutrition in plow layer of paddy soils in Korea.

Keywords: Long-term fertilization, Korean paddy soils, Soil carbon, C/N ratio



Correlation between C/N ratios of LF and C/N ratio of HF with long-term treatment of different fertilizers.

Introduction

Agricultural soils are not only nutrient resource for plant growth but also carbon sink for removal of anthropogenic CO_2 from the atmosphere (IPCC, 2000; Wagai et al., 2009; Zhang et al., 2012). Among various soil components, soil organic matter (SOM) is one of the most important materials to perform these roles well. It is well known that easily decomposable organic materials (labile forms) are potential plant nutrients whereas stabilized ones (recalcitrant forms) are the forms sequestrated (McLauchlan and Hobbie, 2004). Therefore, there have been incessant researches to characterize SOM and to provide critical understandings for sustainable agricultural land management (Six et al., 2002; Kölbl and Kögel-Knabner, 2004; McLauchlan and Hobbie, 2004; Zimmermann et al., 2007; Gulde et al., 2008; Moni et al., 2012).

Physical fractionation, especially density fractionation, is a powerful approach to evaluation of SOM dynamics including their quality and quantity in response to management practices (Christensen, 1992; McLauchlan and Hobbie, 2004; Heitkamp et al., 2011). Floatation method with dense liquids such as colloidal silica, NaI and sodium ploytungstate (SPT) have been generally used to separate light and heavy fractions from soils (Moni et al., 2012). A light fraction (LF) mainly includes both newly incorporated and partially decomposed plant debris, while a heavy fraction (HF) consists of the organic matters absorbed on inorganic surface or sequestrated within soil aggregates. The mineral associated organic matter and free LF had positively correlated with the clay content in forest according to Grüneberg et al. (2013), although some studies showed little relationship of clay concentration to SOC content (Mclauchlan, 2006). HF is physically protected against microorganisms (Kölbl and Kögel-Knabner, 2004; McLauchlan and Hobbie, 2004; Wagai et al., 2009). Actually, light fraction (mainly particulate organic matter) has been an indicator of land use chronicle (Janzen et al., 1992; Kölbl and Kögel-Knabner, 2004; McLauchlan and Hobbie, 2004).

Most studies on density fractionation had biased towards upland and forest soils (Golchin et al., 1994; Hassink, 1997; Kölbl and Kögel-Knabner, 2004; Sollins et al., 2006; Zimmermann et al., 2007; Gulde et al., 2008; Gong et al., 2009; Heitkamp et al., 2011; Moni et al., 2012). On the other hand, less attention has been paid to SOMs of paddy soils although their roles in environment as well as agriculture have steadily expanded. In fact, there are only a few studies. Yin et al. (2005) investigated the contents of LF and HF respectively in two-cropping system treated with chemical fertilizers in China. Wang et al. (2012) evaluated the effect of pig-manure compost application (continuous 4-year treatment) on the composition of SOM in rice-wheat cropping system in China. Huang et al. (2014) showed that continuous rice cropping system, especially single and double rice cropping, led to higher SOC concentrations than corresponding upland cropping system at three long-term soil monitoring sites (27, 21, and 18 years in single, double rice cropping, and rice-wheat cropping respectively) in China. Most of organic C (about 70%) in paddy topsoil is LF from tangled roots and microorganisms (Zhang and He, 2004). These scattered studies are still not enough to comprehend the relationship of SOC to diverse farming practices like crop system, fertilization and composting in paddy soils. Therefore, advanced understanding of SOC still requires further studies on diverse soils including a wide spectrum of paddy soils and agricultural practices.

Paddy soils of South Korea has the largest portion (~964,000 ha in 2013) of agricultural land because rice has been the most important staple food. Although intensive farming with chemical fertilizers has been practiced to increase rice yield in paddy soils, their application has steadily decreased partially due to public concern over the environment. Furthermore, Korean paddy soils undergo alternate turn of summer (wet period) and winter (dry period). In order to evaluate the long-term effects of fertilization patterns on crop yield and soil physicochemical properties in Korea paddy soils, an experimental field has been operating since 1967 at Institute of Crop Science, Milyang (Lee at el., 2004; Daquiado et al., 2013; Lee at el., 2013). The objectives of this study were to 1) investigate the effects of long-term fertilization on both LF and HF of soil organic matter, 2) to elucidate the relationships among total C, C/N ratio, clay content, and fertilization type in paddy soils.

Materials and Methods

Experimental site and cultivation background The field experiments with different types of management were installed in 1967 at National Institute of Crop Science, Milyang (36º36' N and 128º45' E, elevation 12 m) Korea. The experimental field with different types of fertilization was classified into Pyeongtaeg series (somewhat poorly drained fine silty mixed mesic, Typic Haplaquepts). The detailed experiment design and cultivation background were described by Lee et al. (2004) and Daquiado et al. (2013). Four plots were selected in this study (see a Table 1): a) no fertilization (No-fert.), b) only rice straw compost at a rate of 10 Mg ha^{-1} (Com), c) only chemical fertilization with N-P-K (NPK), d) chemical fertilization along with rice straw compost (NPK+Com.). All plots were cultivated with rice (*Oryza sativa* L.) under a paddy field condition. The average contents of total C, N, P and K of straw composts used during 2001- 2013 were ca. 430, 19, 5, and 28 g kg^{-1} respectively.

Separation of heavy and light fractions Soil samples were collected from the plow layer (0 - 15 cm) in November 2013 after harvest. The soils were air-dried, crushed gently by hand, and sieved < 2 mm. To separate LF and HF, density fraction method described by John et al. (2005) was slightly modified (Fig. 1); 5 g soil was placed in a 50 mL centrifuge tube with 25 mL of sodium polytungstate [$Na_6(H_2W_{12}O_{40})H_2O$] solution adjusted to a density

Table 1. Fertilizer management history of fields used in the study.

Treatment	Fertilization detail
No-fert.	Fertilizer was not applied.
Com.	Rice straw compost mixed with cow manure composted for more than six months in the outdoor was applied annually at the rate of 10 $Mgha^{-1}$ before flooding in early May.
NPK	Chemical fertilizers were applied with the rates of N-P_2O_5-K_2O=120-80-80 kg ha^{-1} in 1967-1976 and 150-100-100 kg ha^{-1}. The basal fertilizer application was made to supply 50%, 100% and 70% of nitrogen, phosphorus and potassium, respectively. At tillering 20% of the nitrogen was top-dressed on the 15th day after transplanting, and the remainder (30%) of N and K were treated on the late July during panicle forming time.
NPK+Com.	Applied both Com & NPK treatment.

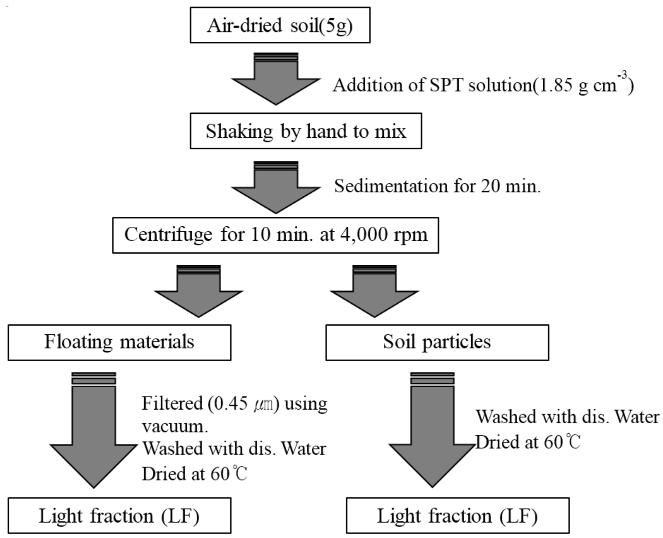


Fig. 1. Flow chart for separation of soil organic matter used in this study.

of 1.85 g cm^{-3}, and the suspension was shaken about 5 min by hand, placed for 20 min, and centrifuged for 10 min at 4,000 rpm. The floating material (LF) was filtered (0.45 ㎛) using vacuum pump, and rinsed with distilled water to remove excess SPT salt. The residual material (HF) was washed with ethanol and distilled water. Each particle was dried at 60°C for 48 h to determine carbon and nitrogen contents. Carbon and nitrogen contents were determined using a CHNS elemental analyzer (vario MAX CN, Elementar Analysensysteme, Germany).Total carbon content was considered as organic because their average pH was near 5.3 indicating the absence of soil carbonate (Mikha et al., 2015).

Statistical analysis Statistical analysis was carried out with R program (ver.3.0.3). Analysis of variance (ANOVA) and least significant difference (LSD) measurements were used for evaluation of significant differences in variables among treatments at level of 0.05. The relationship was analyzed with liner regression technique.

Results and Discussion

Carbon and nitrogen contents in HF and LF Total carbon and nitrogen contents in plow layer (~15 cm) were significantly affected by fertilization type as shown in Tables 2 and 3. NPK-Com showed the highest contents of C and N in all fractions (LF and HF) and No-fert. did the lowest contents. Total C contents for No-fert., Com., NPK, and NPK-Com. were 15.43, 23.20, 17.53, and 25.50 g kg^{-1}, respectively. Total N content increased in the order: NPK-Com (3.10 g kg^{-1}) > Com. (2.90 g kg^{-1}) > NPK (2.30 g kg^{-1}) > No-fert. (2.03 g kg^{-1}). These results are in good agreement with the previous results (Lee et al., 2004; Zhang and He, 2004; Gong et al., 2009; Daquiado et al., 2013; Yang et al., 2015). Carbon content in NPK-Com was somewhat higher compared to the mean equilibrium value (about 20 g kg^{-1}) reported by Zhang and He (2004). This could result from not only a different environmental

Table 2. Carbon contents in HF and LF with long-term treatment of different fertilizers in paddy soil.

Treatment	LFC†	HFC	LFC/TC	HFC/TC
	g kg-1	g kg-1	%	%
No-fert.	6.77b‡	8.66c	43.8	56.2
Com.	6.76b	16.44a	29.1	70.9
NPK	6.86b	10.67b	39.2	60.8
NPK-Com.	8.23a	17.26a	32.3	67.7

†LFC (Light fraction carbon), HFC (Heavy fraction carbon), TC (Total carbon).
‡Means with the different uppercase letters in same column are significantly difference at p<0.05 level by LSD.

Table 3. Nitrogen contents in HF and LF with long-term treatment of different fertilizers in paddy soil.

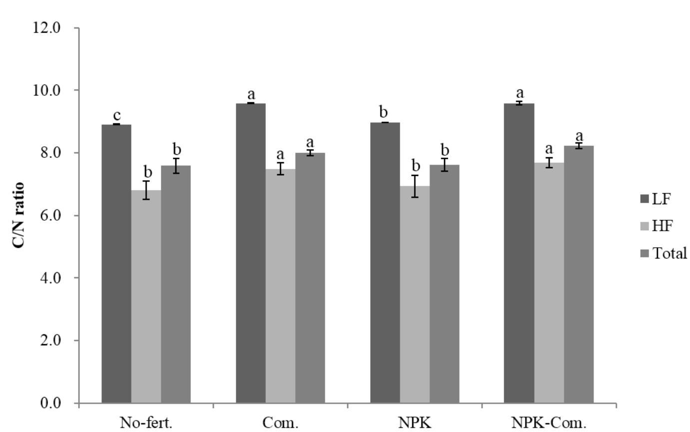
	LFN†	HFN	LFN/TN	HFN/TN
	g kg-1	g kg-1	%	%
No-fert.	0.76ab‡	1.28c	37.3	61.7
Com.	0.70b	2.20a	24.3	75.7
NPK	0.76ab	1.54b	33.2	66.8
NPK-Com.	0.85a	2.25a	27.6	72.4

†LFN (Light fraction nitrogen), HFN (Heavy fraction carbon), TN (Total nitrogen).
‡Means with the different uppercase letters in same column are significantly difference at p<0.05 level by LSD.

conditions (temperature, precipitation, and soil physicochemical properties) but also anthropogenic effects including cropping system, the type of input organic matter, and tillage system (Gulde et al., 2008). In paddy soils under continuous rice-alone cropping, combined treatment of compost and chemical fertilizers enhanced C accumulation in plow layer as expected (Chan, 1997; Rudrappa et al., 2006; Purakayastaha et al., 2008).

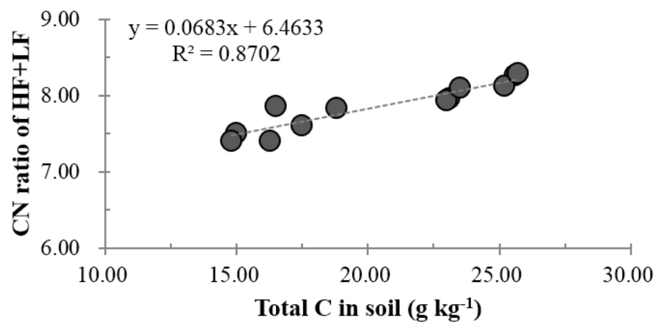
The C amounts of LF and HF (LFC and HFC, respectively) ranged from 6.77 to 8.23 g kg^{-1} and 8.66 to 17.26 g kg^{-1}, while the N contents of both fractions ranged from 0.76 to 0.85 g kg^{-1}and 1.28 to 2.25 g kg^{-1}, respectively. All fertilized plots showed a significant increase in HF compared to No-fert. However, any significant difference in LF was not observed in the study except for NPK-Com plot. Gong et al. (2009) reported that C and N in both fractions (LF and HF) were increased by 18-year fertilization treatments with both of organic matter and balanced chemical fertilizer (NPK application) as N source compared with unfertilized treatment, although their C and N contents were lower than those of this study. The higher contents of C and N in paddy soils seem to result mainly from anaerobic condition (waterlogged state) during its growth stage. It is well known that decomposition of organic matter during flooding is slower than that under dry condition like upland, grassland and forest soils. On the other hand, HF of Com. showed higher C and N contents than NPK plot, whereas no significant difference was observed in LF. A main reason of no significant difference in LF between NPK and Com. may be the result of use of nutrients for plant growth because carbon in LF mainly composed of labile C forms (Six et al., 2002). It was also noticed that compost application led to increase in heavy fraction, as clearly indicated by higher ratio of heavy fraction in both Com. and NPK-Com. plots than in NPK and No-fert. plots. These results clearly show that compost application led to a significant increase in HF and consequently in C and N contents. It is strongly suggested that compost application play a positive role in carbon sequestration of paddy soils.

Relationship between total C and C/N ratio of each fraction C/N ratio in soils has used to predict both direction and velocity of mineralization-immobilization of organic materials in soil (Janssen, 1996). C/N ratios of HF, LF, and total fractions in plow layer were depicted in Fig. 2. All treatments in this study had a higher C/N ratio in LF than in HF, as well known (reviewed by Wagai et al., 2009). C/N ratio ranged from 8.91 to 9.59 in LF and 6.60 to 7.21 in HF, somewhat lower values compared to those of forests and/or grasslands (Wagai et al., 2009). The similar results were reported in paddy soils by Zhang and He (2004). The difference in C/N ratio between LF and HF was well explained by the fact that LF has more celluloses and hemicelluloses concentration than HF (Wang et al., 2012). Compost plots including Com. and NPK-Com. had a higher C/N ratio compared to those of treatments without compost (NPK and No-fert.) in HF as well as LF. This result indicates that compost application was also more effective than chemical fertilization for stabilization of soil C in paddy soils. The relationships between the total carbon and C/N ratio of LF, HF and LF+HF in paddy soils with long-term compost application showed a positive correlation and high significance level (Fig. 3). The value of correlation coefficient in LF (R^2=0.9446) was higher than that in HF (R^2=0.8629) and total carbon and C/N ratio of LF+HF had still showed the liner relationship (R^2=0.8702). It is worthy to note that correlation of C/N ratio to LF and HF was clearly separated into two groups as a boundary of about 9.5 of CN ratio (Fig. 4). One was grouped into no compost treatments (No-treat. and NPK) and the other into compost treatments (Com and NPK-com). These results implied that paddy soils with continuous compost application had highly positive effect on increase of organic carbon contents in LF as well as HF. Therefore, combination treatment (NPK-Com.) in plow layer of paddy can be not only the good management for increase of C sequestration but also for nutrient supplement of rice plant.

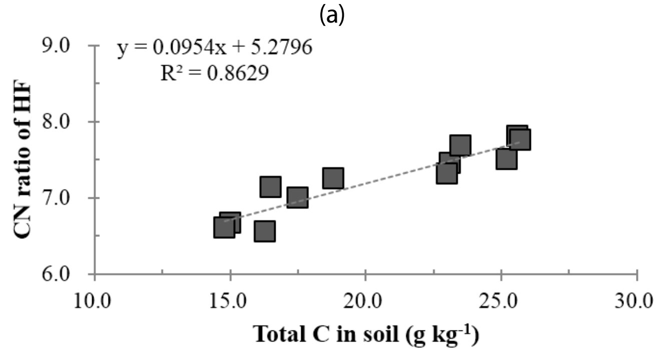


†Means with the different letter in same color bar are significantly difference at p<0.05 level by LSD. Error bars indicate one standard error(n=3). Abbreviation: LF(Light fraction), HF (Heavy fraction).

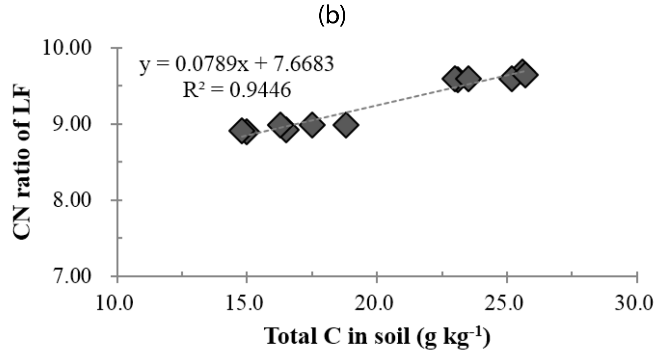
Fig. 2. C/N ratio of HF, LF, and total fraction with long-term treatment of different fertilizers.



(a)



(b)



(c)

Fig. 3. Correlation between total C and C/N ration of a) heavy fraction (HF) + light fraction (LF), b) HF, and c) LF with long-term treatment of different fertilizers.

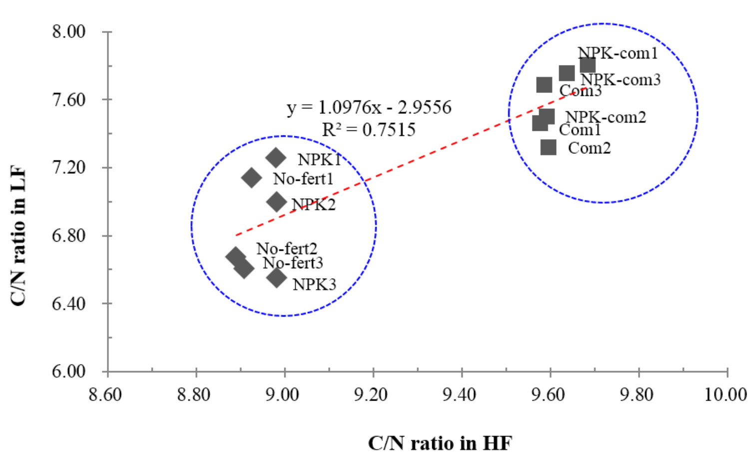


Fig. 4. Correlation between C/N ratios of LF and C/N ratio of HF with long-term treatment of different fertilizers.

Relationship between clay content and C contents of each fraction It is well known that high clay content in soil may have a positive effect on increase of the SOC accumulation, provided that all other factors are equal (Six et al., 2002; McLauchlan, 2006). Contrary to general expectation, there were no relations between clay content in soil and HF as well as LF in the study (Fig. 5). A reason may be originated from the physicochemical properties of sampling site (plow layer), where not only soil aggregate structures were easily destroyed by plowing but also exposed SOM decomposed by microorganism (Six et al., 2002; Kölbl and Kögel-Knabner, 2004). Actually, the experiment field has been plowed two times per year during the experiment. Mclauchlan (2006) also showed the similar result that clay content had little effect on labile or recalcitrant C in 62 former agricultural fields although Zhang et al. (2012) reported a positive correlation between SOC and clay content contents in a certain range of clay content.

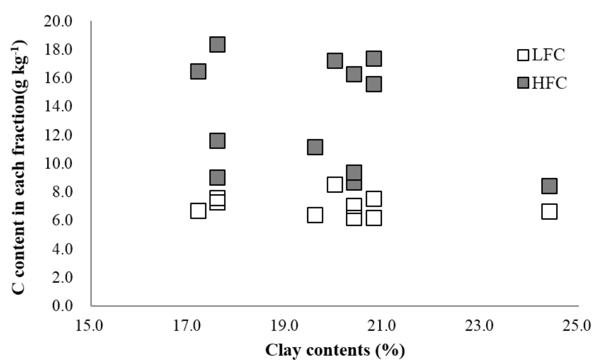


Fig. 5. Relationship between clay content and C contents of each fraction.

Conclusions

Amounts of total C and N in plow layer of paddy soil were increased by long-term incorporation of compost and chemical fertilizer. But compost had higher effect compared to chemical fertilizer on C storage. Only combined application (NPK+Com) increased C and N contents of both LF and HF. All plots in this study had higher C/N ratio in LF than in HF. C/N ratio ranged from 8.91 to 9.59 and 6.60 to 7.21 in LF and HF respectively. The relationships between the total carbon and C/N ratio of LF, HF and LF+HF in plow layer had positive correlation at high significance level in all treatments. Meanwhile, there were no relations between clay content and HFC as well as LFC in the study. These results showed that balanced fertilization together with composting could lead to synergic effects on enhancing C sequestration as well as plant nutrition in plow layer of paddy soils in Korea.

Acknowledgement

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