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Field Evaluation of Coffee Grounds Application for Crop Growth Enhancement, Weed Control, and Soil Improvement

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Abstract: The use of coffee grounds in crop fields were evaluated in terms of crop growth enhancement, soil improvement, and weed control during four successive cropping seasons for two years. Six summer and three winter green manure crops were grown from June 2009 to May 2011. In the first cropping season, the growth of all green manure crops was significantly inhibited by the application of 10 kg m⁻² of coffee grounds. However, the inhibitory effects spontaneously diminished after the second cropping season (about 12 months later), and the growth of guinea grass, sorghum and sunflower was about 2-fold higher than that of the control. The application of horse manure at 10 kg m⁻² effectively alleviated the inhibitory effects, even though the high concentration of coffee grounds was included. Although top dressing application of coffee grounds at 16 kg m⁻² permitted weed control, the impact maintained enough only for half a year. Coffee grounds application effectively increased both carbon and nitrogen contents of soil and reduced CN ratio. The soil amendment effects were significantly higher in terms of nitrogen enrichment and CN ratio improvement as compared with the horse manure application. These results indicated that coffee grounds are useful to enhance long term crop growth, short duration weed control, and soil improvement in agricultural fields by considering the inhibitory effects on the plant growth for half year after the application. Agricultural use of coffee grounds was also discussed in term of fallow periods in crop rotation.

Key words: CN ratio, Coffee grounds, Green manure crops, Horse manure, Soil amendment, Weed control.

Coffee is one of the most important agricultural commodities in the world. Currently, about one million tons of coffee is produced yearly in more than 50 countries (ICO, 2011). The consumption of coffee has increased worldwide and coffee residues such as coffee pulp, husk and grounds are generated in more than two million tons per year (Pandey et al., 2000). In Japan, the consumption of ready-to-drink coffee in bottles, packs and cans has increased remarkably in recent years (Morikawa and Saigusa, 2011). The amount of coffee grounds, the residue obtained during the preparation of ready-to-drink coffee, also tends to increase year by year. Therefore low-cost and effective strategies for recycling coffee grounds have become important.

Some attempts have already been made to use coffee grounds. Silva et al. (1998) reported that coffee grounds are used as a fuel in the boilers of the Brazilian soluble coffee industry. Morikawa and Saigusa (2011) reported that top-dressing application of coffee grounds increased

in Fe and Zn levels of rice grains because the residue acted as Fe and Zn chelating agents in soils. In addition, coffee grounds contain more N and K than common organic materials such as cow manure and chicken manure (Pandey et al., 2000; Kasongo et al., 2011). These results suggest that coffee grounds have the potential to use for energy and agriculture. However, coffee grounds contain chlorogenic acid that inhibits plant growth (Pandey et al., 2000). Kitou and Yoshida (1997) examined the growth of 12 crop species in pots filled with soil containing coffee grounds. As a result, high concentrations of coffee grounds inhibited plant growth.

The inhibitory activities may disappear by composting coffee grounds. However, Wakasawa et al. (1998a) reported that plant growth was inhibited even though coffee grounds were composted for six months. In the case of mixture of coffee grounds and other organic materials such as bark (Wakasawa et al., 1998b), the composting period was shortened and the inhibitory effects

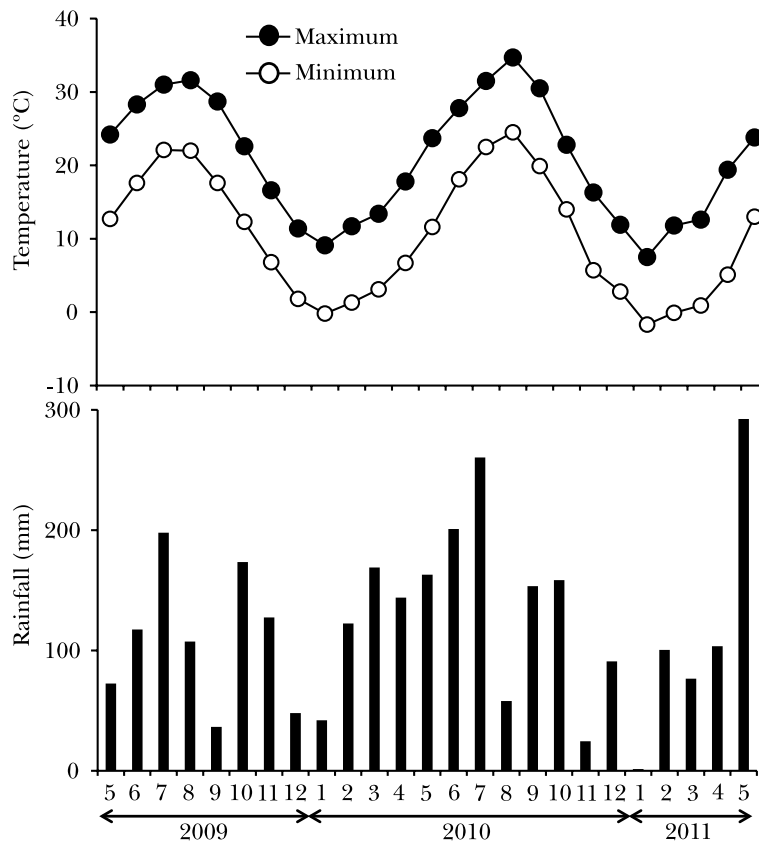


Fig. 1. Monthly maximum and minimum temperature, and rainfall at the experimental site, Nara, Japan during the experimental period. Sources; Local Meteorological Observatory of Nara.

disappeared within 3 months. These results suggest that mixed application of coffee grounds and organic materials into soil is effective to alleviate the inhibitory activities of coffee grounds. However, the inhibitory effects on plant growth were examined using extraction liquids from the compost *in vitro* (Wakasawa et al., 1998a). There is no long term field study on the availability of the mixed application of organic materials and raw coffee grounds into fields. Another inhibitory effect of coffee grounds is the reduction of mineral N content of soil (Wakasawa et al., 1998a). Thus, the authors suggested the necessity of 15 to 20 g m⁻² of nitrogen fertilization into soil when 2.5 kg m⁻² of coffee grounds was applied. However, N addition from animal manures or inorganic fertilizers results in a high potential for NO₃-N leaching from fields (Dinnes et al., 2002). Gómez-López and del Amor (2013) demonstrated that the use of horse manure for supplying N showed better results in minimizing NO₃⁻ leakage and enhancing plant growth and yield of pepper compared with poultry or sheep manures. Therefore, we hypothesized that the mixed application of coffee grounds and horse manure in fields would be effective to diminish the inhibitory effects of coffee grounds and minimize NO₃⁻ pollution. Even though the possibility of weed control by the application of

coffee grounds has been demonstrated (e.g., Kitou and Yoshida, 1997), the impact and stability of weed control in fields have not been demonstrated before.

The objectives of the present study were to investigate the potential of coffee grounds for agricultural use through the series of field experiments; the inhibitory and/or growth enhancement effects for different green manure crop species, the effects of mixture with horse manure, the duration of weed control, and soil improvement effects in agricultural fields.

Materials and Methods

The experiments were conducted for two years in the Experimental Farm of Kinki University in Nara, Japan (latitude 34°40' N, longitude 135°43' E). The experimental farm was opened in the hill side of shrub natural forest in 1988, and weeds such as hogweed and common reed had grown gregariously until 2007. In 2008, the experimental site was cultivated and was sown with the first summer (alfalfa, crotalaria, guinea grass, hairy vetch, sorghum and sunflower), the second summer (buckwheat and bitter buckwheat) and winter green manure crops (barley, italian rye grass, oat and rye). Compound chemical fertilizer (N : P₂O₅ : K₂O = 60 : 60 : 60 : kg ha⁻¹) was applied to the soil.

The green manure crops were mixed-seeded in fields, and harvested before ear emergence. The plant residues were incorporated into soil by tractor.

The experiment was started in the cropping season of 2009 and continued through 2011. The temperature and rainfall during the experimental period were shown in Fig. 1. The top soil on the farm was sampled at 29 May 2009 before experiments. The soil is classified as sandy clay loam (sand : silt : clay = 75.7 : 7.8 : 16.5) with a pH (H₂O) of 5.4, electrical conductivity of 9.78 mS m⁻¹; total C, 5.4 g kg⁻¹ and total N, 0.5 g kg⁻¹. Nine green manure crops, alfalfa (*Medicago sativa* L. cv Neotachiwakaba), crotalaria (*Crotalaria juncea* L. cv Nekobu-killer), guinea grass (*Panicum maximum* Jacq, cv Natsukaze), hairy vetch (*Vicia villosa*, cv Mamesuke), sorghum (*Sorghum bicolor* (L.) Moench, cv Metersorugo) sunflower (*Helianthus annuus* L. cv Ryokuhi himawari), oat (*Avena sativa* L, cv Heiotsu), barley (*Hordeum vulgare* L. cv Wasedorinjyo) and rye (*Secale cereale* L. cv Haruichiban) were used. The summer and winter green manure crops were grown for four successive cropping seasons from June 2009 to May 2011. The same green manure crops were used in the third and fourth cropping season (the second year), and the experiments were conducted in the same manner as in the first year. After the growth of the green manure crops in each cropping season, the crop residue was not incorporated into the soil. Immediately after sampling of the shoot of green manure crops in each plot, the soil was cultivated up to 15 cm depth by hand-tilling. Pest management and irrigation were not conducted and weeds were plowed manually once a month through the experiment.

Coffee grounds were provided by UCC Ueshima Coffee Co., Ltd. as the experimental material. The contents of total C and N in coffee grounds were 523 and 24 g kg⁻¹, respectively, and water content was 65%. The coffee grounds were surface broadcasted and incorporated to 15 cm depth by hand-tilling on May 2009. Coffee grounds were applied to the soil only before sowing of summer green manure crops in the first cropping season. No additional organic materials and no chemical fertilizers (basal fertilization and top dressing) were supplied in soils through the experiments.

1. Species comparison of green manure crops

The effects of coffee grounds on plant growth were analyzed in fields. In the first cropping season, each seed of six summer green manure crops; alfalfa, crotalaria, guinea grass, hairy vetch, sorghum and sunflower, was surface broadcasted in each plot at a rate of 2.0, 2.0, 1.0, 6.0, 2.0 and 2.0 g m⁻², respectively and incorporated manually on 10 June 2009 (12 days after incorporation of coffee grounds (DAI)). The size of each plot was 1 m × 2 m. Three different concentrations of coffee grounds were used: control (0 kg m⁻²), low (1 kg m⁻²) and high (10 kg

m⁻²). Fifty four plots (6 cultivars × 3 treatments × 3 replications) were arranged in a complete randomized block design. Total area in the experimental field was 7 m × 40 m (280 m²). The shoot of the green manure plant in each plot was sampled and the fresh weight was measured on 25 August 2009 (88 DAI). In the second cropping season, each seed of three winter green manure crops; oat, barley and rye, was surface broadcasted in each plot at a rate of 8.0, 10.0 and 8.0 g m⁻², respectively and incorporated manually on 10 November 2009 (165 DAI). Fifty four plots (3 cultivars × 3 treatments × 6 replications) were arranged in the same manner as in the first cropping season. The shoot of green manure plants in each plot was sampled and the fresh weight was measured on 18 May 2010 (354 DAI). In the third cropping season, summer green manure crops were seeded on 10 June 2010 (377 DAI) and harvested on 27 September 2010 (486 DAI). In the fourth cropping season, winter green manure crops were seeded on 6 November 2010 (526 DAI) and harvested on 17 May 2011 (718 DAI).

2. Effects of coffee grounds mixed with horse manure

Horse manure provided by Riding Club CRANE in Nara was applied to the soil containing coffee grounds as the experimental material. The contents of total C and N in horse manure were 390 and 10 g kg⁻¹, respectively, and water content was 32%. Horse manure was surface broadcasted and incorporated to 15 cm depth by hand-tilling on the same day as coffee grounds were incorporated. Both coffee grounds and horse manure were supplied at three levels in each plot; control (0 kg m⁻²), low (1 kg m⁻²) and high (10 kg m⁻²). Twenty seven plots (9 different combinations × 3 replications) were arranged in a complete randomized block design. The size of each plot was 1 m × 4 m, and in total 17 m × 14 m (238 m²). In the first cropping season, alfalfa, crotalaria, guinea grass, hairy vetch, sorghum and sunflower were mixed-seeded in each plot at a rate of 1.33, 1.33, 0.67, 4.0, 1.33 and 1.33 g m⁻², respectively, and incorporated manually on 23 June 2009 (25DAI). The shoot of green manure crops in each plot was sampled and the fresh weight was measured on 26 August 2009 (89 DAI). In the second cropping season, three winter green manure crops; oat, barley and rye, were mixed-seeded in each plot at a rate of 10.7, 13.3 and 10.7 g m⁻², respectively, and incorporated manually on 10 November 2009 (165 DAI). The shoot of green manure plants in each plot was sampled and the fresh weight was measured on 18 May 2010 (354 DAI). In the third cropping season, summer green manure crops were seeded on 13 August 2010 (441 DAI) and harvested on 19 October 2010 (508 DAI). In the fourth cropping season, winter green manure crops were seeded on 6 November 2010 (526 DAI) and harvested on 17 May 2011 (718 DAI).

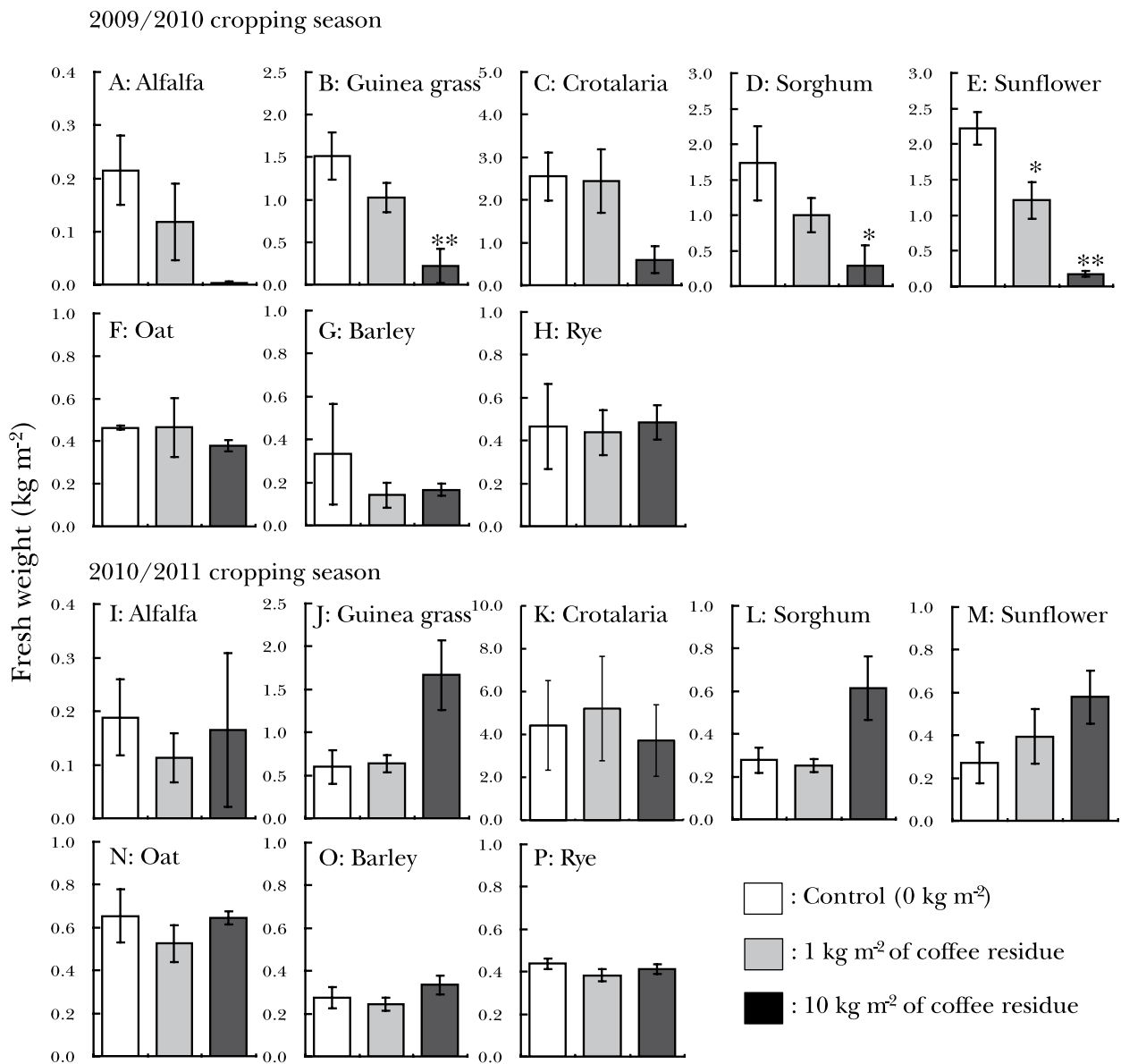


Fig. 2. The growth of green manure plants on the soil incorporated with coffee grounds. (A – E) First summer cropping from 12 to 88 DAI. (F – H) First winter cropping from 165 to 354 DAI. (I – M) Second summer cropping from 377 to 486 DAI. (N – P) Second winter cropping from 526 to 718 DAI. Data are means \pm standard error (SE) ($n = 3$ replicated fields). One-way analysis of variance (ANOVA) was used to compare means among groups. If the ANOVA was significant, post-hoc analyses were conducted using Dunnett's multiple comparison test, with the level of statistical significance taken as $P < 0.05$ and $P < 0.01$. * and ** above the bars indicate significant differences from control at $P < 0.05$ and $P < 0.01$, respectively.

3. Weed control effects

The effects of coffee grounds on weed control were investigated. All weeds in the plot were mowed, and as top dressing, coffee grounds was applied to the soil at 26 June 2009. Green manure crops were not cultivated in all the plots. Three different concentrations of coffee grounds were used: control (0 kg m^{-2}), low (4 kg m^{-2}) and high (16 kg m^{-2}). Eighteen plots (3 treatments \times 6 replicates) were arranged in a complete randomized block design. The size of each plot was $1 \text{ m} \times 1 \text{ m}$, and in total $5 \text{ m} \times 11 \text{ m}$ (55 m^2). The fresh weight of weeds in a plot was measured at

171, 419, 565 and 694 days after the top dressing.

4. Soil improvement effects

Soil improvement effects were evaluated in all the three experiments during two years periods after the application of coffee grounds and horse manure application. Top soil collected from 0 – 15 cm depth was sampled from each plot on 24 May 2011 after the experiment. The soil samples in the experiment of species comparison of green manure crops were collected randomly from 6 places in each treatment. The soil samples in other experiments

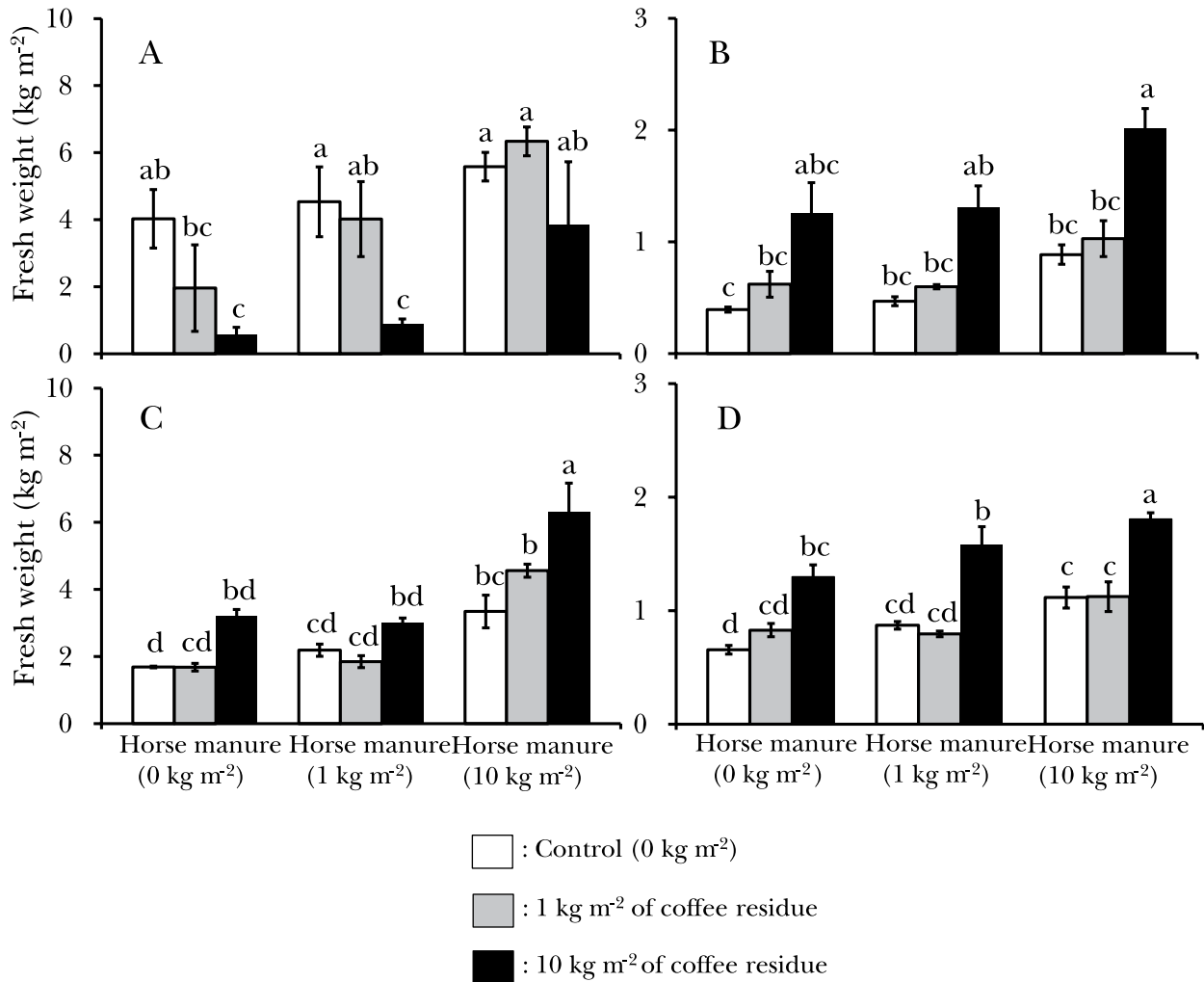


Fig. 3. The growth of green manure crops on the soil incorporated with coffee grounds and horse manure. (A) First summer cropping from 25 to 89 DAL. (B) First winter cropping from 165 to 354 DAL. (C) Second summer cropping from 441 to 508 DAL. (D) Second winter cropping from 526 to 718 DAL. Data are means \pm SE ($n = 3$ replicated fields). ANOVA was used to compare means among groups. If the ANOVA was significant, post-hoc analyses were conducted using Tukey's test, with the level of statistical significance taken as $P < 0.05$. Different letters above the bars indicate significant differences.

were collected from a place in each treatment. The soil samples were passed through a 2 mm sieve, and oven dried at 80°C for 2 days. After drying, the samples were ground into a powder and total C and N contents were analyzed by CN analyzer (Yanako, MT-700 II). Changes of carbon and nitrogen contents in soil, and CN ratio were evaluated.

Data were statistically analyzed using one-way analysis of variance followed by Tukey's or Dunnett's multiple comparison tests. Significant differences were analyzed based on $P < 0.05$ (Tukey) and $P < 0.05$ and 0.01 (Dunnett) between the means among treatments.

Results

1. Species comparison of green manure crops

Figure 2 shows the growth of green manure crops on the soil with or without the application of coffee grounds. In the first cropping season (Fig. 2A – E), the fresh weights

of alfalfa, sorghum and sunflower grown on the soil containing 1 kg m⁻² of coffee grounds decreased about 50% compared with the control. The fresh weight of guinea grass was about 65% compared with the control. However, the fresh weight of crotalaria did not significantly decrease. The growth of all plants grown under the soil including 10 kg m⁻² of coffee grounds was drastically decreased. The fresh weights of guinea grass, sorghum and sunflower significantly decreased (Fig. 2B, D, E). In the second cropping season (Fig. 2F – H), the fresh weights of barley under the soil containing 1 kg m⁻² and 10 kg m⁻² of coffee grounds decreased. The values were lower by 50% compared with that of the control. However, the fresh weights of oat and rye were similar to those of the control. In the third cropping season (Fig. 2I – P), the plant growth inhibitory activities of coffee grounds completely disappeared and the fresh weights of guinea grass,

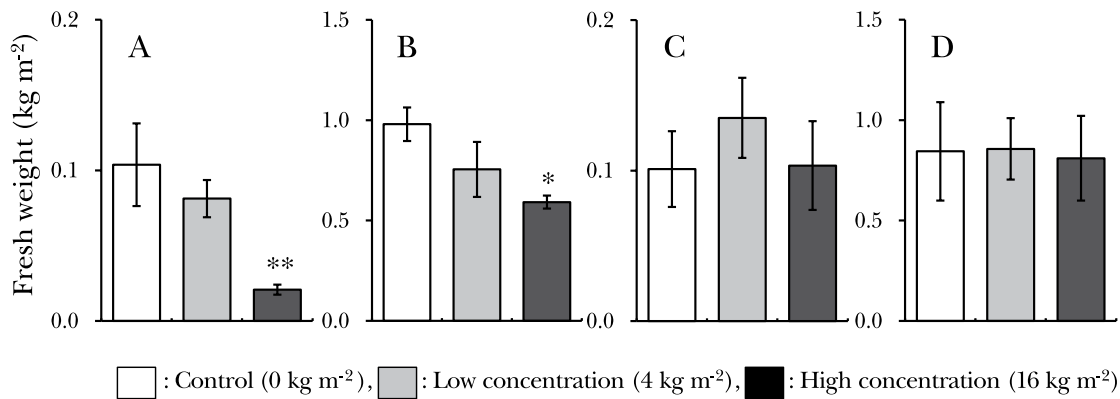


Fig. 4. Effects of the top dressing of coffee grounds on weed growth at (A) 171, (B) 419, (C) 565, (D) 694 DAI. Data are means \pm SE (n = 6 replicated fields). ANOVA was used to compare means among groups. If the ANOVA was significant, post-hoc analyses were conducted using Dunnett's multiple comparison test, with the level of statistical significance taken as $P < 0.05$ and $P < 0.01$. * and ** above the bars indicate significant differences from control at $P < 0.05$ and $P < 0.01$, respectively.

sorghum and sunflower were 2.7, 2.2 and 2.1 fold that of the control, respectively. The fresh weights of other plants tested were similar to those of the control.

2. Effects of horse manure mixture

Figure 3 shows the fresh weight of green manure crops in a plot incorporated with coffee grounds or horse manure or both materials at various concentrations. In the first cropping season, the fresh weights of green manure crops in the plots incorporated with 1 kg m⁻² and 10 kg m⁻² of coffee grounds without the application of horse manure decreased about 50% and 10% compared with the control, respectively (Fig. 3A). The application of horse manure to the soil containing coffee grounds suppressed the decrease. The fresh weight in the plot incorporated with both coffee grounds and horse manure at 1 kg m⁻² was similar to that of the control and was similar to that in the plot without the application of organic materials (Fig. 3A). However, the fresh weight in the plot incorporated with 1 kg m⁻² of horse manure and 10 kg m⁻² of coffee grounds significantly decreased (Fig. 3A). The fresh weight in the plot incorporated with 1 kg m⁻² of coffee grounds and 10 kg m⁻² of horse manure was the highest among all treatments (Fig. 3A). The application of horse manure at 10 kg m⁻² effectively suppressed the decrease in the growth, even though 10 kg m⁻² of coffee grounds was included in the soil. The value was similar to that in the plot without the application of organic materials. Although the mechanisms dissolving the inhibitory effects by the application of horse manure are still unclear, microbes could be related to the detoxification of plant growth inhibitory activities in coffee grounds (Fujii and Takeshi, 2007). However, further studies are needed to elucidate the relation between the application of horse manure and the activity of microbes in soils incorporated with coffee

grounds. In the second cropping season, the inhibitory effects of coffee grounds on the growth of green manure crops were dissipated (Fig. 3B). The growth of green manure crops in the plots incorporated with coffee grounds at 10 kg m⁻² along with the application of horse manure at 0, 1 and 10 kg m⁻² was 3.2, 2.8 and 2.3-fold that of the control, respectively (Fig. 3B). After the third cropping season, the more organic materials the soil included, the better was the growth of green manure crops (Fig. 3C, D).

3. Weed control effects

Figure 4 shows the fresh weight of weeds in a plot with or without top dressing of coffee grounds. At 171 days after top dressing, the weed growth in the plot top dressed with 16 kg m⁻² of coffee grounds was severely inhibited compared with that of the control (Fig. 4A). Although the weed growth in the plot top dressed with 4 kg m⁻² of coffee grounds was slightly low, a significant decrease was not observed (Fig. 4A). At 419 days after top dressing, the weed growth in the plot top dressed with 16 kg m⁻² of coffee grounds significantly inhibited (Fig. 4B). However, the extent of the inhibition was lower than that at 171 days after top dressing. At 565 and 694 days after top dressing, the inhibitory effects of coffee grounds on weed growth disappeared even in the soil top dressed with a large amount of coffee grounds (Fig. 4C, D).

4. Soil improvement effects

Figure 5 shows the total C and N contents and CN ratio in the soil before and after the experiment comparing green manure crops. The total C and N contents of the soil containing 1 kg m⁻² of coffee grounds were almost equal to that of the initial soil and the control (Fig. 5A, B), and CN ratio was also similar (Fig. 5C). The total C and N contents of the soil containing 10 kg m⁻² of coffee grounds

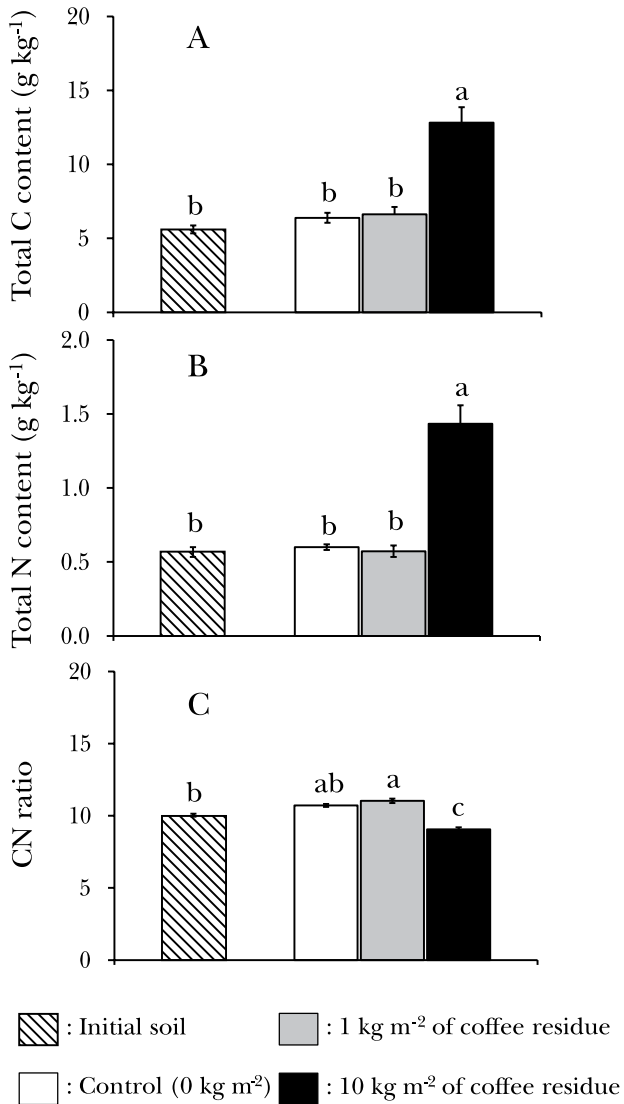


Fig. 5. Total C and N contents and CN ratio in soils incorporated with coffee grounds at 0, 1 and 10 kg m⁻². Initial soils before treatments were sampled on 29 May in 2009. After the growth of green manure crops for two years, soils were sampled at 24 May 2011. The soil samples were collected randomly from 6 places in each treatment. Data are means ± SE (n = 3 replicated fields). ANOVA was used to compare means among groups. If the ANOVA was significant, post-hoc analyses were conducted using Tukey's test, with the level of statistical significance taken as $P < 0.05$. Different letters above the bars indicate significant differences.

increased significantly. The values were about 2-fold those of the initial soil and the control (Fig. 5A, B). In addition, the CN ratio decreased significantly compared with that of the initial soil and the control (Fig. 5C).

Figure 6A and B show the total C and N contents in the soils before and after the application of coffee grounds and horse manure. In the soil without the application of horse manure, the total C and N contents increased only when 10 kg m⁻² of coffee grounds was incorporated (Fig. 6A, B). In the soil incorporated with both materials at 1 kg

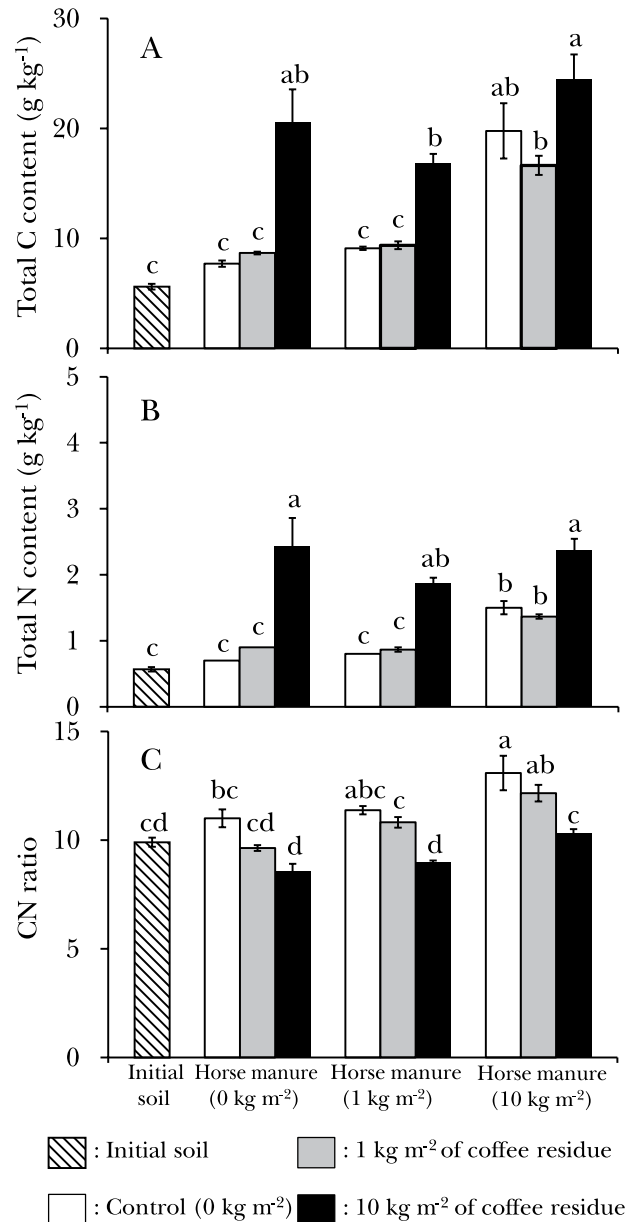


Fig. 6. Total C and N contents and CN ratio of soils incorporated with coffee grounds and horse manure at 0, 1 and 10 kg m⁻², respectively. Initial soils before treatments were sampled on 29 May in 2009. After the growth of green manure crops, soils were sampled on 24 May in 2011. Data are means ± SE (n = 3 replicated fields). ANOVA was used to compare means among groups. If the ANOVA was significant, post-hoc analyses were conducted using Tukey's test, with the level of statistical significance taken as $P < 0.05$. Different letters above the bars indicate significant differences.

m⁻², the total C and N contents did not increase significantly compared with those of the initial soil and the control. However, the total C and N contents were significantly higher in the soil applied coffee grounds and horse manure at 10 kg m⁻² and 1 kg m⁻², respectively. In the soil incorporated with 10 kg m⁻² of horse manure, the total C and N contents significantly increased compared

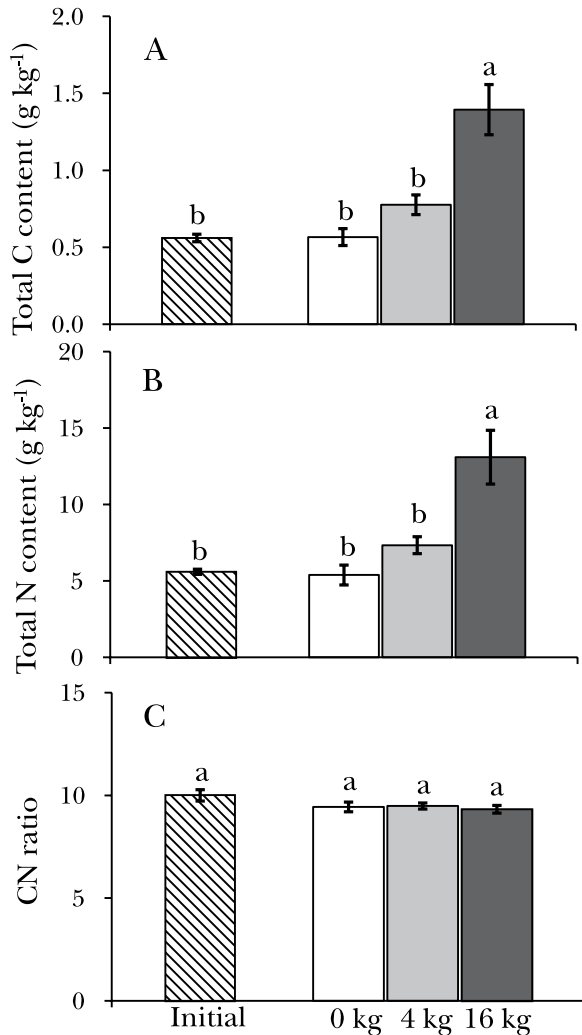


Fig. 7. Total C and N contents and CN ratio in soils top dressed with coffee grounds at 0, 4, 16 kg m⁻². Initial soils before mulching were sampled on 29 May in 2009. After the investigation of weed growth for two years, soils were sampled on 24 May in 2011. Data are means \pm SE (n = 6 replicated fields). ANOVA was used to compare means among groups. If the ANOVA was significant, post-hoc analyses were conducted using Tukey's test, with the level of statistical significance taken as $P < 0.05$. Different letters above the bars indicate significant differences.

with the initial soils, even though no coffee grounds were incorporated. The total C content of the soil incorporated with both materials at 10 kg m⁻² was not significantly higher than that of the control, but the total N content significantly increased. The total N content of the soil applied 10 kg m⁻² of coffee grounds alone was significantly higher than that in the soil incorporated with only 10 kg m⁻² of horse manure. Figure 6C shows the CN ratio in the soil before and after the experiments. The CN ratio in the initial soil was 9.9 (Fig. 6C). The ratio increased by the application of horse manure. The values in the soil incorporated with only horse manure at 1 and 10 kg m⁻² were 11.38 and 13.08, respectively. The values decreased

with increases in the concentration of coffee grounds incorporated in the soil. Especially, the values in the soil incorporated with 10 kg m⁻² of coffee grounds significantly decreased compared with those of the control.

Figure 7 shows the total C and N contents and CN ratio in the initial soil and the soil after the top dressing of coffee grounds. The total C and N contents of the soil applied 4 kg m⁻² of coffee grounds slightly increased compared with those of the initial soil (Fig. 7A, B), but not significantly. The total C and N contents of the soil treated with 16 kg m⁻² of coffee grounds increased greatly (Fig. 7A, B). The CN ratio was similar regardless of the concentration of coffee grounds (Fig. 7C).

Discussion

1. The effects of coffee grounds on green manure crops

The plant growth inhibitory activities of coffee grounds on plant growth has been investigated by several authors before (e.g., Kitou and Yoshida, 1997; Wakasawa et al., 1998a). However, these studies were conducted in pots filled with a soil containing coffee grounds. The effects of coffee grounds on plant growth in fields have not been evaluated. In the first cropping season, all of the growth of green manure crops under the soil incorporated with 10 kg m⁻² of coffee grounds showed negative responses (Figs. 2A – E). Coffee wastes such as coffee pulp, husk and grounds include caffeine, tannins and polyphenols, which show plant growth inhibitory activities (Rizvi et al., 1981; Pandey et al., 2000). Thus, the growth inhibition of green manure crops on the soil containing 10 kg m⁻² of coffee grounds could be due to the inhibitory activities of coffee grounds.

The growth responses on the soil containing 1 kg m⁻² of coffee grounds varied with the crop species (Fig. 2). In the first cropping season, the growth of crotalaria on the soil containing 1 kg m⁻² of coffee grounds was similar to that of the control (Fig. 2C), whereas the growth of other crops was inhibited. Legumes could be relatively tolerant to coffee grounds due to biological N₂ fixation. Rochester et al. (1993) showed that the incorporation of crop residue slightly reduced the mineral N content of soil by encouraging biological immobilization. Wakasawa et al. (1998a) observed with pot experiments that the inorganic N content of the soil decreased 3 months after the incorporation with coffee grounds decreases. Thus, the authors presumed that the application of coffee grounds into soil induces nitrogen starvation. Kitou and Yoshida (1997) reported that legumes such as azuki bean and soybean grow well under the soil containing the low concentration of coffee grounds. These results and implications suggest that it is useful to grow legume species in the soil incorporated with coffee grounds. However, the enhancement of the growth of alfalfa and crotalaria in the third cropping season was not observed (Fig. 2I, K). Thus, the use of legume plants is most effective in the first

cropping season after the application of coffee grounds.

The inhibitory effects on the growth of barley remained even at 354 DAI (Fig. 2G). In addition, the enhancement effects of coffee grounds on winter green manure crops were not observed during the experiment. Thus, the inhibitory and enhancement effects of coffee grounds varied with the crop species.

2. Weed control effects

The heavy use of commercial herbicides to control weed induces the evolution of herbicide-resistant weeds (Owen and Zelaya, 2005). Combined application of organic materials such as rice bran (Toga et al., 2006) or allelopathy (Owen and Zelaya, 2005) may help to reduce the development of herbicide resistance in weed ecotypes. Although the use of allelopathy for weed control has been extensively studied and many compounds have been identified (Khanh et al., 2007; Farooq et al., 2011), the effective use of organic materials has rarely been studied. Kitou and Yoshida (1997) speculated that coffee grounds were useful as an agent for weed control due to the inhibitory effects on plant growth. However, there are no field studies on the impact or duration of weed control. In the present study, the application of coffee grounds at 16 kg m⁻² to the field was successful for weed control (Fig. 4A). However, the application at 4 kg m⁻² had little impact on weed control. The growth of all green manure plants tested was inhibited by 10 kg m⁻² of coffee grounds (Fig. 2A – E), and the growth of sunflower, sorghum and barley was inhibited by 1 kg m⁻² of coffee grounds (Fig. 2D, E, G). Although the sensitivity to coffee grounds varied with the plant species, 10 kg m⁻² of the application would be enough for weed control. The effects of coffee grounds on weed control diminished 419 days after top dressing (Fig. 4B) and completely dissipated 565 days after top dressing (Fig. 4C). Thus, the top dressing of coffee grounds at more than 10 kg m⁻² permits weed control for 6 months.

3. Soil improvement effects

The total C content of the soil was increased significantly by the incorporation of coffee grounds or horse manure or both materials at 10 kg m⁻² increased significantly (Figs. 5, 6, 7). Because the carbon compounds in coffee grounds are carbonized in roasting process, the content of decomposable organic C is very low (Kitou and Okuno, 1999). Horse manure has a small fraction of decomposable organic C compared with the other types of manures such as chicken, cow and pig (Ajwa and Tabatabai, 1994). In addition, horse manure contains a large amount of plant fiber, which is decomposed at a slow rate (Ajwa and Tabatabai, 1994). These results suggest that the significant increase in total C content in the soil would be derived from both the insoluble organic C in coffee grounds and plant fibers in horse manure.

The application of coffee grounds but not horse manure largely contributed to the increase in total N content of the soil (Fig. 6B), which resulted in the decrease in CN ratio. Thus, the effects of coffee grounds on soil amendment were significantly stronger in terms of nitrogen enrichment and CN ratio improvement as compared with the horse manure. However, top dressing of coffee grounds did not induce the decrease in CN ratio (Fig. 7). Thus, the incorporation of coffee grounds is more effective than the top dressing to improve soil properties. The high rate of total N in the soil incorporated with coffee grounds is assumed to be due to the accumulation of insoluble N. Kitou and Okuno (1999) demonstrated that the rate of easily decomposable nitrogen is low in coffee grounds, because these N components could be removed by coffee extraction. Maki et al. (2009) reported that the rate of easily decomposable N in cow manure treated at 180°C is lower than that treated at 80°C. The temperature in roasting process of coffee grounds was about 200°C (Clarke, 1987). These results suggest that most of N in coffee grounds is insoluble N. However, Wakasawa et al. (1998a) reported that NO₃⁻-N content of the soil incorporated with coffee grounds gradually increases after 4 months of the application. The nitrogen release to the soil would also have contributed to the enhanced growth of guinea grass, sorghum and sunflower in the third cropping season (Fig. 2J, L, M). Thus, coffee grounds have the potential to improve soil fertility and enhance long term crop growth.

4. Agricultural implication

The effective use of coffee grounds for agriculture has not been proposed so far, because of the inhibitory effects on plant growth after the application. However, the inhibitory effects could be useful for weed control in crop rotation systems with fallow period. In addition, considering the facts that the enhanced growth of green manure crops after one year of coffee ground application (Fig. 2J, L, M), increased total N content and decreased CN ratio in the soil (Figs. 5, 6), the residue could be beneficial for the reduction of N fertilizer application and soil amendment in crop rotation systems. Moreover, legume species would be much safer to grow just after the fallow period. These results lead to the proposal of following crop rotation system. In the crop rotation system with fallow period, more than 10 kg m⁻² of coffee grounds is supplied on the soil for weed control in the period. After the fallow period, say just winter period for warm region, and a year period for the cold district, the coffee grounds are well mixed with soils by chisel plowing, and then legume species can be cultivated. In the crop rotation systems without fallow period, horse manure equal amount of coffee grounds is incorporated into the soil for diminishing the inhibitory effects. To overcome the

drawbacks of direct application of coffee grounds to soil, composting has been considered as a suitable method (Wakasawa et al., 1998a; Kitou and Okuno, 1999). However, the application with the nearly equal amounts of horse manure is enough to overcome the inhibitory effects (Fig. 3A). In both crop rotation systems, legumes relatively tolerant to coffee grounds are available for the cultivation in the first cropping season after the incorporation. In addition, coffee grounds are useful for weed control in furrow or passage during the cropping season of both systems.

Coffee grounds have the potential to increase total N content of soils on a long-term basis, because the soil incorporated with coffee grounds has a high rate of total N. The application of coffee grounds also would enhance plant growth by improving soil chemical and physical properties. Because green coffee beans are roasted at about 200°C, coffee grounds should have a property similar to charcoal. There are some reports that biochar application to soils can enhance plant growth and yields through the amelioration of soil chemical properties (Glaser et al., 2002). Thus, the effects of coffee grounds on soil properties need to be further evaluated in long-term field studies to expand agricultural use of coffee grounds. In addition, coffee grounds have the potential to capture and storage carbon dioxide (CO₂) geologically. Because total C content 2 years after the application of coffee grounds remained at a high level (Fig. 5A, 6A, 7A), carbon derived from the residue would remain longer than that derived from other organic materials. Thus, the application of coffee grounds is suggested to be important to aid mitigation of global climate change.

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