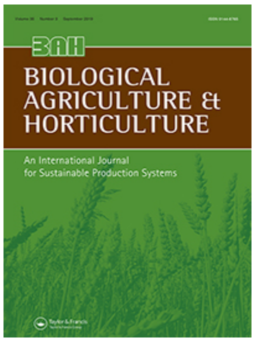

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Potential for no-tillage and clipped-weed mulching to improve soil quality and yield in organic eggplant production

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ABSTRACT

Deep-inversion tillage for weed control and residue incorporation can have a detrimental effect on agroecosystems. Despite the potential for no-tillage (NT) organic farming to improve soil quality, the yield response of NT can vary. This study compared the effects of NT and conventional rotary tillage (CT), leafmould application (LM+) and no leafmould (LM–), clipped-weed mulch application (CM+) and no weed mulch (CM–) on eggplant yield and crop residue (*Solanum melongena* L.) and on soil chemical and physical properties under standard organic farming conditions. In both years, NT CM+ resulted in higher yield and crop residue than in NT CM–. Soil bulk density was 34 and 32% lower in 2014 and 2015, respectively, in NT compared with CT. In both years, CM+ had a significant impact on the water content in the surface-layer in both tillage systems. Soil organic carbon and active carbon concentrations, at 0–2.5 cm depth, were 85 and 20% higher in NT than in CT. In October, NO_3-N, exchangeable Mg^{2+}, Ca^{2+} (in 0–2.5 cm only) and available P (in 0–2.5 cm only) were higher in NT than in CT in soil layers 0–2.5 cm and 2.5–7.5 cm. CM+ resulted in increased soil inorganic nitrogen in NT plots during the growing season. The results suggested that NT with CM+ application can be a valuable conservation practice for increasing yield and soil carbon in organic farming by reducing tillage intensity.

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No-tillage; conventional tillage; clipped-weed mulch; soil carbon; eggplant production

Introduction

Organic farming can provide diverse ecosystem services along with food production. Organic farmers avoid using inorganic fertilizers and instead use compost, green manures, and crop rotations including legumes to maintain soil fertility. However, their reliance on deep-inversion tillage for weed control and residue incorporation can have a detrimental effect on the agroecosystem (Kühling and Trautz 2013; Larsen et al. 2014; Lehnhoff et al. 2017).

No-tillage (NT) has been reported to improve soil quality by increasing soil organic carbon (SOC), water infiltration rate, and soil water retention, as well as by reducing soil bulk density, thus promoting greater aggregate stability and minimizing soil erosion (Ghuman and Sur 2001; Franzluebbers 2002; Dikgwatlhe et al. 2014). In conventional farming, however, this practice often requires the use of herbicides to prevent the invasion of perennial weeds (Fabrizzi et al. 2005).

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Supplemental data for this article can be accessed here.

Organic NT also improved soil quality, Arai et al. (2014) for example, reported that long-term NT without inorganic fertilizer input increased water-stable aggregates >2 mm by 34%, which may increase soil carbon sequestration and could be a good way for improving soil quality. Yagioka et al. (2015) reported that after conversion to organic NT farming, soil carbon at the surface layer down to 2.5 cm increased linearly over the years.

In NT farming, the use of inorganic fertilizers for nutrient availability and herbicides for weed control increased the yield of summer maize (*Zea mays* L.) by 1.4% (He et al. 2011) and provided equal or higher yield of marketable broccoli (*Brassica oleracea* L.) compared with CT (Infante and Morse 1996). Organic NT practices doubled total carbon and light-fraction particulate organic matter in the upper 15 cm layer compared with CT, but the yield of sweet corn (*Zea mays* cv. Saccharata) was less than 50% of that of CT (Larsen et al. 2014). These results suggested that NT can increase crop yield when practiced together with the use of inorganic fertilizers and herbicides, but organic farming requires a different approach to increase yields (Carr et al. 2013; Yagioka et al. 2014).

For NT in organic farming, the challenge is to eliminate soil disturbance while growing crops using the resources available in the agroecosystem. In Japan, the natural farming system (NT with weed cover mulching) is a unique practice that was developed by Fukuoka (2009) and later modified by Kawaguchi and Toriyama (2000). This practice produced adequate yields of daikon radish (*Raphanus sativus var. longipinnatus cv.* Taibyousoufutori) and turnip (*Brassica rapa subsp. Rapa*) (Yagioka et al. 2014) in the autumn-winter growing season, but yields of summer crops, such as eggplant (*Solanum melongena* L.) and green pepper (*Capsicum annuum*), were poor (Yagioka et al. 2015).

The yield response of NT in organic farming is a subject of debate among farmers who practise it. Constraints of organic NT farming include maintenance of nitrogen availability, increased competition from grassy weeds, and inferiority compared with CT for soil that is not well drained, as well as a reduced choice of crops (Peigné et al. 2007). Application of appropriate amounts of clipped-weed mulch (CM+) might be effective for increasing inorganic nitrogen through mineralization and for reducing weed pressure. The rate of nitrogen mineralization depends strongly on the chemical and physical characteristics of the residue (Kuo and Jellum 2002). Generally, incorporation of plant residue with a low C:N ratio results in a rapid release of inorganic nitrogen for crop uptake (Drinkwater et al. 2000). In this regard, CM+ application could be a good alternative for increasing crop nutrient availability, especially soil inorganic nitrogen, in NT organic farming systems.

Although many studies have examined the effects of tillage on soil quality (e.g. Busari et al. 2015) and yield response (e.g. He et al. 2011; Gözübüyük et al. 2015), there is little information on the effect of tillage systems together with CM+ on soil quality and the yield of eggplant (*Solanum melongena* L.), a crop that is widely grown across Asia. In this study, it was hypothesized that NT with CM+ systems would improve soil quality, especially inorganic nitrogen concentration, and increase eggplant crop yield in organic management. Therefore, a field experiment was undertaken in two years to investigate the effects of different tillage systems together with CM+ on the yield of organic eggplants and soil quality.

Materials and methods

Site description and experimental design

The study was performed at the Centre for Field Science Research and Education, Ibaraki University, Japan. The field had been managed in accordance with organic farming standards since 2009 and the practices used followed the technical guidelines of Japanese agricultural standards for organic products (JMAFF 2012). Since 2009, the experimental field includes areas with tillage inversion and no-tillage management to facilitate studies on the long-term effects of these contrasting approaches. The soil type is typical volcanic ash Andosol (Soil Survey Staff 2009), with a sandy loam texture in the surface layer, changing to clay with increasing depth. The soil had a cation exchange capacity of 17.2 cmol kg^{-1}, pH of 6.5, 3.4% total soil carbon, 0.35% total soil nitrogen, 20.7 mg kg^{-1} soil inorganic nitrogen, 238.4 mg kg^{-1} P, and 120.8 mg kg^{-1} K (Brey method) (Gutiérrez Boem et al. 2011). Annual precipitation was 1457.5 mm in 2014 and 1284.5 mm in 2015 and mean annual air temperatures were 14.7 and 15.9°C, respectively (Figure 1). In 2014 and 2015, the field trial was carried in different locations in the same field and in both years the proceeding crop was daikon radish (*Raphanus sativus* var. *longipinnatus*) that had been grown in both the tillage and no-tillage management system.

The field experimental design was a split-split plot design with four replications. The study used three factors: two tillage systems as the main factor, two leafmould treatments as the sub-factor, and two clipped-weed mulch treatments as the sub-sub-factor. The two tillage systems were no-tillage (NT) and conventional rotary tillage (CT). The two sub-factor treatments were leafmould application (LM+) at 5.6 Mg ha^{-1} dry matter (C:N ratio: 43.1 in 2014 and 43.6 in 2015) and no leafmould application (LM–). The two sub-sub-factor treatments were application of clipped-weed mulch (CM+) at 7.2 Mg ha^{-1} dry matter (C:N ratio: 20.7 in 2014 and 25.5 in 2015) and no clipped-weed mulch (CM–). The clipped-weed mulch, which was cut and collected from around the experimental site, consisted of natural weeds such as *Echinochloa crus-galli, Eleusine indica, Digitaria ciliaris, Cyperus microiria, Chenopodium album, Persicaria longiseta*, and *Commelina communis* in 2014 and young fresh wheat (*Triticum aestivum*) in 2015. The leafmould had been made from oak leaves that had decomposed for one year. The study consisted of a total of 32 plots, each measuring 12.5 m^2 (2.5 m × 5 m).

Farming practices

Cultivation for the CT treatment was carried out twice using rotary tiller to a depth of 15 cm on 15 April and 22 May in 2014 and on 14 April and 20 May in 2015 before transplanting, incorporating the weeds present. In mid-May in both years, weeds in NT plots were mowed by a flail mower and left on the soil surface. Eggplant (*Solanum melongena* L.) seedlings were transplanted at a 1 m × 1 m spacing on 29 May in 2014 and 27 May in 2015. Farming practices followed the standard practices of Japanese organic farmers. Leafmould was applied before the eggplants were transplanted (Table 1). CM+ was applied in strips 120 cm wide and 12 cm thick on

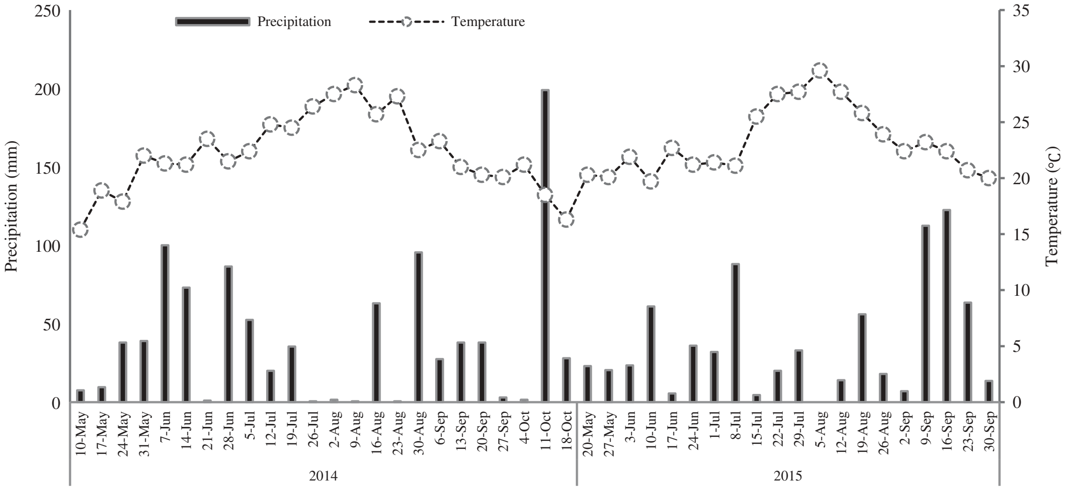

Figure 1. Weekly temperature and precipitation at the study site (2014–2015). treatments at the 5% significance level using the Tukey–Kramer test.

Table 1. Chemical properties of leafmould and clipped-weed mulch in 2014 and 2015.

Year	Type	Total C (%)	Total N (%)	C/N Ratio	CaO (%)	MgO (%)	K_2O (%)	P_2O_5 (%)
2014	Leafmould	43.5	1.0	43.1	0.26	0.11	0.44	0.08
	Clipped-weed mulch	40.9	1.9	20.7	0.38	0.18	1.12	0.25
2015	Leafmould	22.6	0.5	43.6	0.17	0.09	0.18	0.04
	Clipped-weed mulch	39.4	1.5	25.5	0.13	0.11	0.75	0.18

5 June 2014 and on 1 June 2015. During the growing period, weeds in the CT plots were removed from field once a month using a hoe and in the NT plots weeds were cut with a bush cutter and left on the soil surface in the inter row spaces. A data logger (Em50, Decagon, Pullman, WA, USA) was installed to record annual rainfall and air temperature. No herbicides or pesticides were applied during the experiment.

Organic matter, carbon and nitrogen input

In both years, above-ground weed biomass was collected within a 50 cm × 50 cm quadrat in early April and mid-May before tillage inversion in the CT plots. In the NT plots, weed biomass was sampled in the same way in mid-May before mowing. Samples of weeds, leafmould and clipped-weed mulch were dried at 65°C for 72 h and weighed. These samples were then ground into 1 mm fragments, and their carbon and nitrogen concentrations were measured using a CN analyser (JM3000N/CN, J Science Lab Co. Ltd, Kyoto, Japan). Carbon and nitrogen inputs from the weeds, leafmould and clipped-weed mulch were calculated by multiplying the organic matter input by the carbon and nitrogen concentrations.

Crop growth and yield measurement

The height (from the soil surface to the top of the plant) of three eggplants from each replicate plot was measured at 2-week intervals throughout the growing season. Eggplant fruits were harvested from the whole plot (12.5 m^2) once a week from late June to early October. Marketable yields were based on the criterion that harvested fruits weighing less than 100 g were not marketable. Eggplant crop residue was harvested from and area of 1.25 m^2 in each plot at the time of the final fruit harvest. The residue was dried at 65°C for 72 h and weighed.

Soil sampling and measurements

One soil sample was taken from each plot by sinking a steel cylinder, 5 cm diameter, to a depth of 30 cm twice each year, in June (spring) and October (autumn). Each soil core sample was then sliced with a sharp knife into four layers at depths of 0–2.5, 2.5–7.5, 7.5–15 and 15–30 cm. Fresh soil samples of approximately 5 g were weighed for inorganic nitrogen (NO_3-N and NH_4-N) measurement immediately after sampling. The remaining soil samples were placed in paper bags and dried at room temperature for 1 week. The dry samples were passed through a 2 mm sieve to prepare them for later measurement of soil chemical properties (total carbon, active carbon, K, Mg, Ca, and P). For carbon content, sub-samples were further dried at 105°C for 72 h and measured by using a CN analyser (JM3000N/CN, J Science Lab Co. Ltd, Kyoto, Japan).

To assess the bulk density and water content, sub-samples were taken from the fresh soil samples (the fresh weight of which was recorded when sliced). The sub-samples were weighed, dried at 105°C for 72 h, and weighed again. Bulk density was calculated as dry soil weight (g)/soil volume (cm^3) (McKenzie et al. 2002).

To determine the soil active carbon (*AC*) concentration, 2.5 g air-dried samples were extracted with 20 ml of 0.02 mol $KMnO_4$ solution and shaken for 2 min. Each sample's absorbance was then recorded by mass spectrometry at 550 nm (Weil et al. 2003). *AC* was determined as:

$$AC = \ [C_i - \ (a + b \times \text{absorbance})] \ \times M_C \times \ (V_{\text{sol}}/W_{\text{s}}), \tag{1}$$

where C_{i} is the initial solution concentration (0.02 mol L^{-1}), a is the intercept and b is the slope of the standard curve, M_{C} is the mass of carbon (9000 mg, 0.75 mol) that is oxidized by 1 mol of MnO_4 changing from Mn^{7+} to Mn^{4+}, V_{sol} is the volume of $KMnO_4$ solution reacted (0.021 L), and W_{s} is the weight of soil used (0.0025 kg).

In both years (August and September), to measure soil inorganic nitrogen, three soil samples from each plot were taken to a depth of 0–30 cm, using a soil sampling probe and combined to make one sample. Then, 5 g fresh soil sub-samples were extracted with 40 ml of 1 mol L^{-1} KCl and shaken for 1 h. Absorption by UV-visible absorption spectrophotometry (Yamaki 2003) and the indophenol blue method (Editorial Committee of Soil Environmental Analysis 2008) were used to measure soil NO_3-N and NH_4-N, respectively.

To measure soil exchangeable K^+, Mg^{2+}, and Ca^{2+}, 2 g air-dried soil samples were extracted with 40 ml of 1 mol L^{-1} ammonium acetate and shaken for 1 h. To measure soil available phosphorus, 0.2 g air-dried soil samples were extracted with 40 ml of 0.002 mol sulphuric acids and shaken for 30 min. The nutrient concentrations were then measured on a soil and plant clinical analyser (SPCA-6210, Shimadzu, Kyoto, Japan).

Statistical analysis

Analysis of variance was conducted in StatView software (SAS Institute 1998). A split-split experimental design was used to test for soil quality and eggplant yield, with tillage system as a main factor, LM+ as a sub-factor, and CM+ as a sub-sub-factor. Year and sampling dates (2014 and 2015 in June and October) were used as a repeated measure in the model. Organic matter, carbon and nitrogen inputs were compared for the main effect of tillage, LM+, and CM+, with year as a repeated measure. Soil total carbon and active carbon in soil were compared between tillage treatments only if there was no significant effect of CM+ and LM+ or interaction between tillage, CM+, and LM+ in both years, with year and sampling dates as a repeated measure. Eggplant yield and crop residue, eggplant height, soil bulk density, water content, and soil inorganic nitrogen were compared between tillage and CM+ treatments if there was no significant effect of LM+ or interaction between tillage and LM+ applications, with year and sampling dates as a repeated measure. Multiple analyses were performed using the Tukey–Kramer test as a *post hoc* test if significant differences were found between treatments in the analysis of variance.

Results

Organic matter, carbon and nitrogen input

In both years, tillage, LM+, and CM+ had significant effects on organic matter input and on inputs of carbon and nitrogen from the weeds, leafmould and clipped-weed mulch (Table 2). Organic matter input was 12.1 Mg ha^{-1} in NT and 7.5 Mg ha^{-1} in CT in 2014 and was 12.7 and 7.0 Mg ha^{-1} in 2015. In both years, the highest organic matter input was in the LM+ and CM+ plots, being on average 112 and 115% higher than in the control plots. In both years, the carbon and nitrogen inputs from the organic matter were significantly higher in NT than in CT. LM+ and CM+ also showed higher carbon and nitrogen inputs than LM – and CM–, respectively.

Table 2. Effect of tillage system, leafmould application, and clipped-weed mulch application on organic matter, carbon and nitrogen input in 2014 and 2015.

		Organic matter† (Mg ha^{-1} DM)		C input (Mg ha^{-1})		N input (kg ha^{-1})	
Treatments		2014	2015	2014	2015	2014	2015
Tillage	NT	12.1 a	12.7 a	5.1 a	4.6 a	211 a	168 a
	CT	7.5 b	7.0 b	3.1 b	2.3 b	126 b	84 b
Leafmould	LM+	13.5 a	13.2 a	5.7 a	4.4 a	209 a	146 a
	LM–	6.1 b	6.5 b	2.5 b	2.6 b	128 b	106 b
Clipped-weed mulch	CM+	13.4 a	13.5 a	5.6 a	4.9 a	239 a	181 a
	CM–	6.2 b	6.3 b	2.6 b	2.1 b	98 b	71 b
ANOVA significance							
Tillage (T)		***	***	***	***	***	***
Leafmould (LM)		***	***	***	***	***	***
Clipped-weed mulch (CM)		***	***	***	***	***	***
T × LM		ns	ns	ns	ns	ns	ns
T × CM		ns	ns	ns	ns	ns	ns
LM × CM		ns	ns	ns	ns	ns	ns
T × LM × CM		ns	ns	ns	ns	ns	ns

Note: *, **, *** indicate significant differences at the 5%, 1%, and 0.1% significance levels, respectively, and ns indicates no significant difference. Values in columns followed by different letters indicate significant differences between treatments at 5% using the Tukey-Kramer test.

†Organic matter included weed biomass present before eggplant transplanting, leafmould, and clipped-weed mulch.

Eggplant growth and yield

Tillage and CM+ had significant effects on plant height at 1 month (30-June) after transplanting (Supplemental Table 1). CM+ had a significant effect on plant height in NT, but not in CT. Plant heights were greater in CT CM – and NT CM+ plots than in CT CM+ and NT CM – plots, but in both years the heights were lowest (⅓ of others) in NT CM – plots (Supplementary Table 1).

Tillage × CM interaction significantly affected eggplant yield in both years, whereas LM+ had a significant effect only in 2014 (Table 3). In both years, CM+ significantly increased eggplant yield in NT plots. NT CM+ plots had 361 and 1525% higher yields than NT CM – plots in 2014 and 2015, respectively. CM+ had no significant effect on eggplant yield in CT plots. In both years, tillage and CM+ had a significant effect on eggplant crop residue, with a significant tillage × CM

Table 3. Eggplant yield and crop residue in relation to tillage system, leafmould application and clipped-weed mulch application in 2014 and 2015.

		Eggplant yield (Mg ha^{-1} of FM)		Eggplant crop residue (Mg ha^{-1} of DM)	
Treatment		2014	2015	2014	2015
NT	CM+	14.3 a	6.5 a	1.3 a	1.1 a
	CM–	3.1 b	0.4 b	0.3 b	0.1 b
CT	CM+	13.1 a	6.8 a	1.2 a	0.8 a
	CM–	13.9 a	9.1 a	1.3 a	0.9 a
Leafmould	LM+	13.2 a	6.3 a	1.2 a	0.8 a
	LM–	9.0 b	5.1 a	0.9 a	0.6 a
ANOVA Significance					
Tillage (T)		***	***	*	*
Leafmould (LM)		**	ns	ns	ns
Clipped weed mulch (CM)		***	**	*	***
T × LM		ns	ns	ns	ns
T × CM		***	***	**	***
LM × CM		ns	ns	ns	ns
T × LM × CM		ns	ns	ns	ns

*, **, *** indicate significant differences at the 5%, 1%, and 0.1% significance levels, respectively, and ns indicates no significant difference. Values in columns followed by different letters indicate significant differences between treatments at 5% using the Tukey–Kramer test.

interaction. CM+ significantly increased eggplant crop residue in NT plots but not in CT plots. In both years, NT CM+ plots had higher eggplant crop residue than NT CM – plots.

Soil bulk density and water content

In both years, tillage had a significant effect on soil bulk density in the surface layer. Bulk density was lower in NT than in CT plots, though differences between CM+ and CM – treatments were not significant (Table 4).

In both years, tillage and CM+ had a significant effect on soil water content in the surface layer. NT plots had higher water content than CT plots. CM+ also had a significant effect on soil water content in both tillage systems in both years.

Total and active carbon

Tillage had significant effects on soil total carbon (SOC) and active carbon in both years. The interaction of tillage × LM × CM was significant in the 0–2.5-cm layer for total C in June 2015 and active C in June 2014 and Oct 2015 (Supplemental Table 2). SOC and active carbon in the 0–2.5-cm and 2.5–7.5 cm layers were significantly higher in NT plots than in CT plots (Figures 2 and 3). SOC and active carbon concentrations were 85 and 20% higher, respectively, in NT than in CT in the 0–2.5-cm layer, and 28 and 17% higher in the 2.5–7.5-cm layer (Figures 2 and 3). In the 7.5–15-cm and 15–30-cm layers, SOC was significantly greater in CT plots than in NT plots, whereas active carbon did not show significant differences between tillage systems in these layers in either year.

Soil chemical properties

In both years, tillage system had a significant effect on soil chemical properties in October (Table 5). Soil NO_3-N in the 0–2.5 cm layer was higher in NT plots than in CT plots. Soil NO_3-N in the 2.5–7.5-cm layer was significantly increased by CM+ in NT plots: NT CM+ plots had 25% more soil NO_3-N than NT CM – plots. On the other hand, in the 7.5–30 cm layers, CT plots had slightly (but not significantly) higher NO_3-N concentration than NT plots.

NT CM+ had a higher concentration of available P than CT CM+ in the surface layer. CM+ increased available soil P in NT plots in the top two soil layers by 25%, comparing NT CM+ with

Table 4. Water content and bulk density in relation to tillage system, leafmould application and clipped-weed mulch application in October 2014 and October 2015.

Treatment		Water Content		Bulk density	
		2014	2015	2014	2015
NT	CM+	45.7 a	48.7 a	0.4 b	0.4 b
	CM–	44.7 b	47.8 b	0.4 b	0.4 b
CT	CM+	42.7 c	42.6 c	0.5 a	0.5 a
	CM–	41.4 d	40.3 d	0.5 a	0.5 a
ANOVA Significance					
Tillage (T)		***	***	***	***
Leafmould (LM)		ns	ns	ns	ns
Clipped weed mulch (CM)		**	**	ns	ns
T × LM		ns	ns	ns	ns
T × CM		ns	ns	ns	ns
LM × CM		ns	ns	ns	ns
T × LM × CM		ns	ns	ns	ns

*, **, *** indicate significant differences at the 5%, 1%, and 0.1% significance levels, respectively, and ns indicates no significant difference. Values in columns followed by different letters indicate significant differences between treatments at 5% using the Tukey–Kramer test

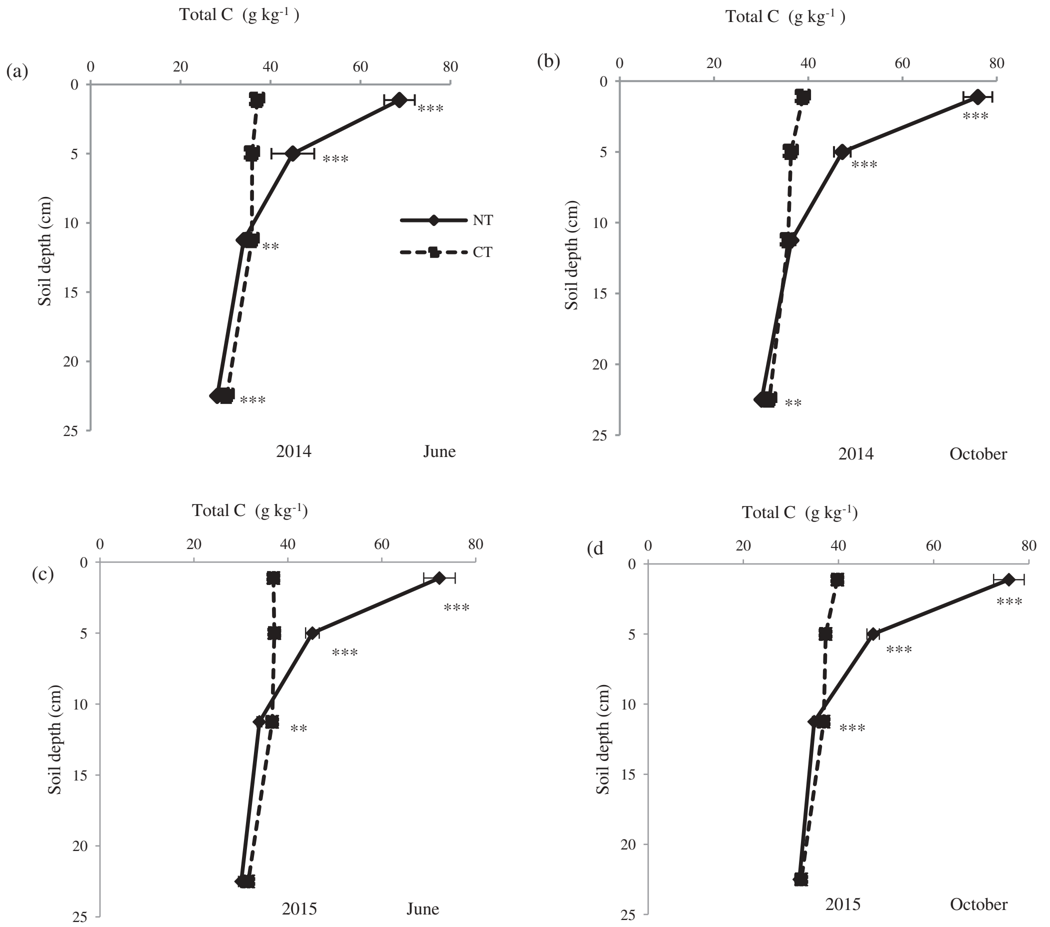

Figure 2. Effect of tillage system (NT, CT) on vertical distributions of total carbon in 0–2.5, 2.5–7.5, 7.5–15, and 15–30-cm soil layers in (a) June 2014, (b) October 2014, (c) June 2015, and (d) October 2015. Asterisks at each soil depth indicate significant differences between the two tillage treatments at the **1% and ***0.1% levels using the Tukey–Kramer test.

NT CM–, though these differences were not statistically significant. In the same layers, CM+ reduced soil P in CT plots: CT CM – had 60 and 11% higher available P than CT CM+, though the difference was only significant at 0–2.5 cm depth.

Tillage system had a significant effect on exchangeable K^+ in the top three soil layers (0–2.5, 2.5–7.5, and 7.5–15 cm): NT CM+ had a higher concentration than CT CM–. CM+ had no significant effect on exchangeable K^+ in NT plots, but it did have an effect in CT plots in the top two soil layers, where K content was 11 and 26% higher in CT CM+ than in CT CM – plots.

Tillage system had a significant effect on exchangeable Ca^{2+} in the surface layer: with significantly higher concentrations of Ca^{2+} in NT CM+ and NT CM – than in CT CM+ and CT CM–. However, in the 7.5–15-cm and 15–30-cm layers, exchangeable Ca^{2+} was higher in CT plots than in NT plots. Furthermore, NT had significantly more exchangeable Mg^{2+} than CT in the top two soil layers, but significantly less in the lower layers.

Soil inorganic nitrogen

In June 2014, tillage had significant effect on soil inorganic nitrogen, but this was not significant in 2015. In August in both years, the effect of CM+ was significant. Soil inorganic nitrogen was

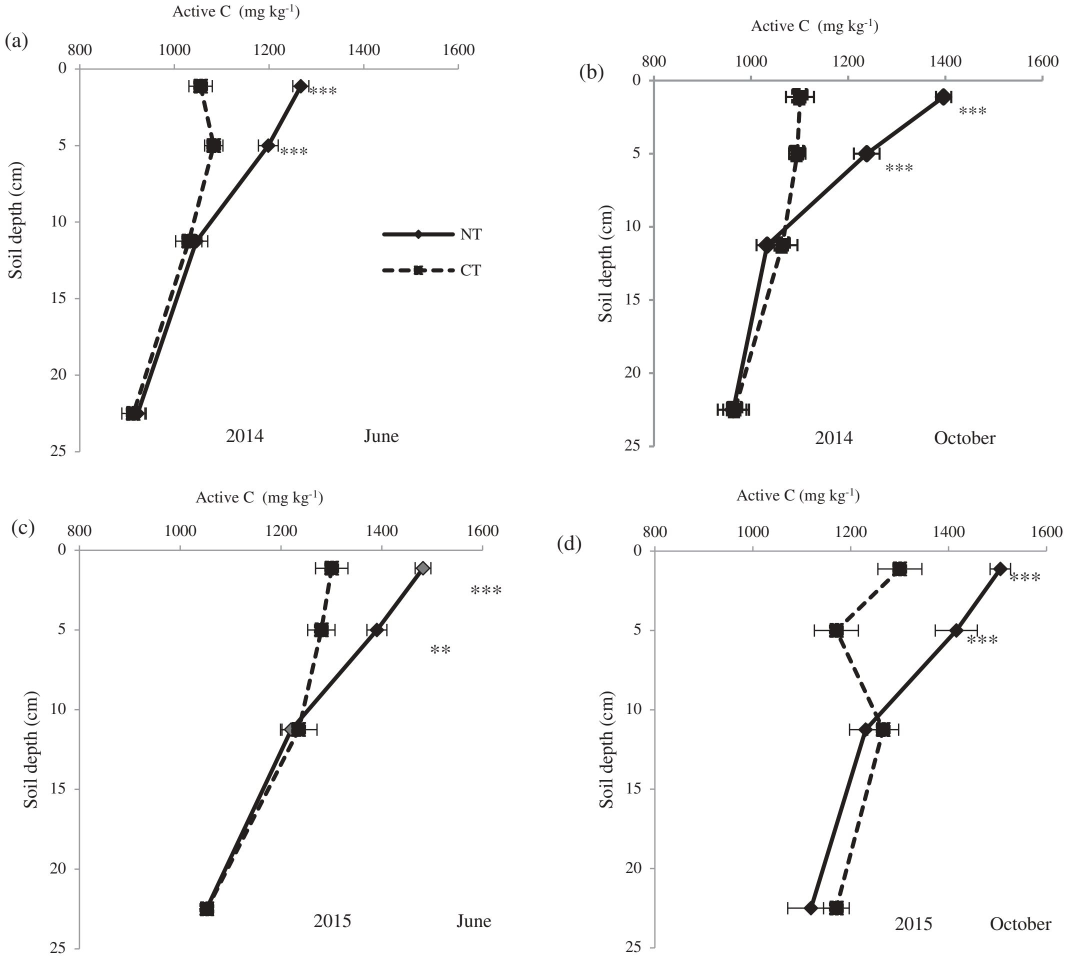

Figure 3. Effect of tillage system (NT, CT) on vertical distributions of active carbon in 0–2.5, 2.5–7.5, 7.5–15, and 15–30-cm soil layers in (a) June 2014, (b) October 2014, (c) June 2015, and (d) October 2015. Asterisks at each soil depth indicate significant differences between the two tillage treatments at the **1% and ***0.1% levels using the Tukey–Kramer test.

increased also in September and October, but not significantly so (Table 6). In August 2014, NT CM+ plots had 108 and 59% more inorganic nitrogen than NT CM – and CT CM – plots, respectively. In August 2015, NT CM+ plots similarly had 30%, 43%, and 21% more inorganic nitrogen than in NT CM–, CT CM–, and CT CM+ plots, respectively (Table 6).

Discussion

NT organic farming has great potential to improve SOC, which is a key indicator of soil quality and productivity. Organic systems usually require frequent soil inversion, resulting in reduced soil organic matter (SOC) due to decomposition (Wang et al. 2007). The results from this study revealed that CM+ application in NT organic farming not only maintained the SOC, but also improved crop yields to a similar level as that in the CT treatments (Figure 4). Matsuura et al. (2018) reported that in conventional farming typical eggplant yields in this area was 60 t ha^{-1}.

In NT farming, stubble management and cover crop residues increased carbon concentrations in the surface soil and increased carbon sequestration rates (Chan et al. 2002; Higashi et al. 2014). However, few studies have reported the use of weed residues as a carbon source for soil carbon

Table 5. Effect of tillage system and clipped-weed mulch application on soil NO_3-N, P, K^+, Ca^{2+}, and Mg^{2+} (2014 and 2015 October average data).

Soil depths (cm)	Treatment	NO_3-N (mg kg^{-1})	P (mg kg^{-1})	K^+ (mg kg^{-1})	Ca^{2+} (mg kg^{-1})	Mg^{2+} (mg kg^{-1})
0–2.5	NTCM+	13.8 a	136.2 a	315.0 a	1603.8 a	365.2 a
	NTCM–	11.4 a	109.0 a	315.1 a	1644.3 a	349.2 a
	CTCM+	7.8 b	43.8 b	312.1 a	1057.9 b	197.7 b
	CTCM–	6.7 b	70.2 a	281.3 b	1137.3 b	175.7 b
2.5–7.5	NTCM+	10.5 a	72.3	300.0 a	1162.9	278.7 a
	NTCM–	8.4 b	57.7	300.0 a	1158.3	230.5 a
	CTCM+	6.5 b	64.3	300.0 a	1089.9	174.5 b
	CTCM–	8.3 b	71.3	237.5 b	1120.9	180.7 b
7.5–15	NTCM+	6.7	53.3	311.9 a	916.3 b	139.5 b
	NTCM–	6.9	44.0	299.6 a	949.8 b	138.2 b
	CTCM+	8.7	65.3	276.1 b	1146.4 a	181.6 a
	CTCM–	6.6	59.4	263.9 b	1122.7 a	182.4 a
15–30	NTCM+	5.0	59.2	228.5	1054.2 b	115.2 b
	NTCM–	4.2	50.4	197.4	1052.3 b	109.9 b
	CTCM+	6.9	47.5	222.4	1193.2 a	171.9 a
	CTCM–	6.6	49.7	195.8	1194.2 a	153.9 a

Values, in columns and within soil depths, followed by different letters indicate significant differences between treatments at 5% using the Tukey-Kramer test

Table 6. Effect of tillage system (NT, CT) and clipped-weed mulch application (CM+, CM–) on soil inorganic nitrogen (NO_3-N and NH_4-N) in 2014 and 2015.

		Soil inorganic N (mg kg^{-1})							
		June		August		September		October	
Treatment		2014	2015	2014	2015	2014	2015	2014	2015
NT	CM+	45.7 a	55.9	163.6 a	163.5 a	80.8	95.5	59.4 a	40.3
	CM–	42.8 b	59.9	78.7 b	126.0 bc	60.0	94.2	50.3 a	40.6
CT	CM+	39.2 b	53.9	121.7 ab	134.6 b	61.1	91.1	42.8 b	42.7
	CM–	32.7 b	55.4	102.6 b	114.4 c	54.7	84.1	42.1 b	45.5
ANOVA Significance									
Tillage (T)		**	ns	ns	*	ns	ns	**	ns
Leafmould (LM)		ns	ns	ns	*	ns	ns	ns	ns
Clipped weed mulch (CM)		ns	ns	***	**	ns	ns	ns	ns
T × LM		*	ns	ns	ns	ns	ns	*	ns
T × CM		ns	ns	*	ns	ns	ns	ns	ns
LM × CM		ns	ns	ns	ns	ns	ns	ns	ns
T × LM × CM		ns	ns	ns	ns	ns	ns	ns	ns

*, **, *** indicate significant differences at the 5%, 1%, and 0.1% significance levels, respectively, and ns indicates no significant difference. Values in columns followed by different letters indicate significant differences between treatments at 5% using the Tukey–Kramer test

sequestration. In this study, SOC and active carbon in the 0–2.5 cm and 2.5–7.5 cm soil layers were significantly higher in NT than in CT, suggesting that weed residue contributed to soil carbon sequestration. Aziz et al. (2013) reported that long-term NT practice increased total carbon and active carbon concentrations in the top two soil layers by 28% and 12%, respectively, relative to CT. Likewise, this study showed that SOC and active carbon in the surface layer (0–2.5 cm) were 85 and 20% higher in NT than in CT. These increases were associated with a greater amount of organic matter input in NT than in CT. Thus, the weed residues appeared to be an adequate source of SOC and active carbon in organic NT agroecosystems.

Other studies have shown that the active carbon concentration in the surface soil was highly correlated with crop productivity, attributable to improved soil structure (Stine and Weil 2002). In general, NT resulted in higher active carbon concentrations than CT (Six et al. 2006), although discrepancies in crop yield responses were reported in NT systems (Videnović et al. 2011). Phillips et al. (1980) reported that NT with no applied nitrogen reduced maize yield, whereas NT with the maximum nitrogen application rate produced high yields. In a 6-year experiment, organic NT resulted

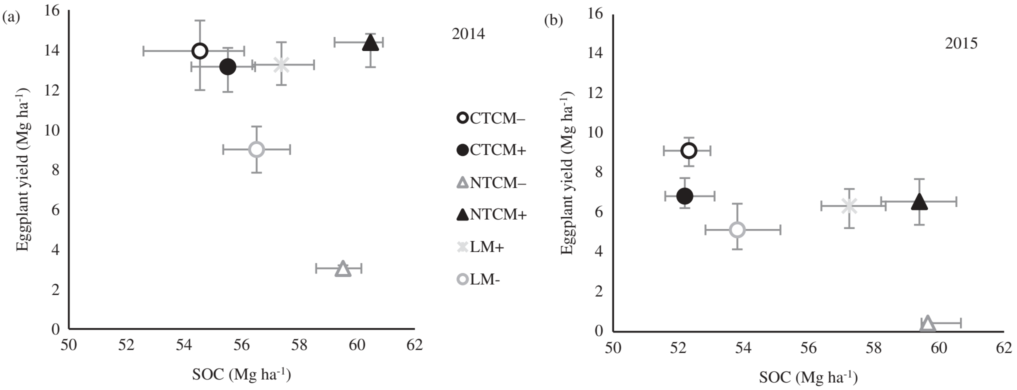

Figure 4. Relationship between eggplant yield and SOC in (a) 2014 and (b) 2015. Results compare tillage system (CT, NT), clipped-weed mulch application (CM+, CM–) and Leaf-mould application (LM+, LM-).

in significantly lower spring wheat yields than organic CT, conventional NT, and conventional CT systems (Halde et al. 2015). These results clearly indicated that NT with an optimum nitrogen supply can increase plant yield. In the study reported here, eggplant yields were significantly higher in NT CM+ than in NT CM – in both years. This yield increase was accompanied by higher soil nutrient availability, particularly soil inorganic nitrogen (NO_3-N and NH_4-N, Table 6), and water content in NT CM+ compared with NT CM–. Aggarwal and Power (1997) reported that using manure and retention of crop residues increased SOC and soil moisture, and improved yield of pearl millet (*Pennisetum typhoides*). Although NTCM- had high SOC, the yield was low due to low concentrations of inorganic N during the growing season (Figure 4 and Table 6). Singh Brar et al. (2015) also reported that organic fertilizers improved SOC and nutrient availability, especially inorganic N, compared with a non-treated control. In the study reported here, October average data showed that NT CM+ had 25% higher soil NO_3-N in the 2.5–7.5-cm layer, compared with in NT CM–. Furthermore, during the growing season (in August) in both years, CM+ had a significant effect on inorganic nitrogen (NO_3-N and NH_4-N) in the surface layer, which was likely the key factor underlying the increase in yield in NT CM+.

Ghuman and Sur (2001) reported that nitrogen uptake was greater in NT systems with crop residue mulch than without mulch. The result of their study suggested that crop residue mulch provided adequate soil conditions for crop growth and yield increases in NT systems. Application of crop residues released inorganic nitrogen after decomposition, retained moisture, facilitated root development, and provided optimal conditions for efficient uptake of nutrients at the soil surface in NT systems (Agehara and Warncke 2005).

In this study, CM+ treatment did not affect the yield in the CT plots, but strongly improved it in the NT plots. The interaction between CM and tillage treatment was obvious in the eggplant yield. The C:N ratios of applied CM+ and LM+ were on average 23.1 and 43.3, respectively. The slow mineralization of LM+ was the main reason for the small effect of LM+ application on eggplant yield and soil parameters. Cheshire et al. (1999) reported decreased NO_3-N concentrations after incorporation of straw mulch with a high C:N ratio into the soil, due to the immobilization of nitrogen, resulting in no effect of the mulch on yield. Nicolardot et al. (2001) also reported that application of plant residue with C:N ratio of 20–25 can cause temporary immobilization of soil nitrogen. In the experiment reported here, the average C:N ratio of CM+ was 23.1, which may explain why the CM+ treatment reduced eggplant yield in CT. The data indicated that CM+ significantly increased the NO_3-N concentration in the 2.5–7.5 cm soil layer in the NT system, but the increase in the 0–2.5 cm layer was not significant. Further research is therefore required to evaluate the effects on soil quality and yield response of long-term CM+ in organic NT farming.

The data showed that NT led to a greater retention of water in the soil surface layer than that in the CT. CM+ also significantly affected surface-layer soil water content in NT plots. By maintaining soil integrity, NT can reduce evaporation from the soil, thus avoiding the development of moisture stress in plants (Blevins et al. 1971). As in this study, Humphreys et al. (2011) also reported that NT with rice straw mulch application supported long-term retention of soil moisture, thus delaying the need for irrigation and increasing crop yield.

The results suggested that NT with CM+ was successful in meeting the need for good crop yield without the use of inorganic fertilizers and pesticides. The results also showed that NT with CM+ has the potential to improve soil quality, especially soil carbon concentrations, in organic farming. Using CM+ in NT organic farming increased the input of organic matter (weed biomass) and had a significant effect on inputs of carbon and nitrogen. NT CM+ significantly increased crop yield and water content in the soil surface layer relative to NT CM−. In both years, NT CM+ increased soil inorganic nitrogen during the growing season, resulting in significantly higher yield than in NT CM−. These results suggested that the combination of NT and CM+ application can be an effective tool in organic farming systems to maintain soil fertility and achieve adequate yield.

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Disclosure statement

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