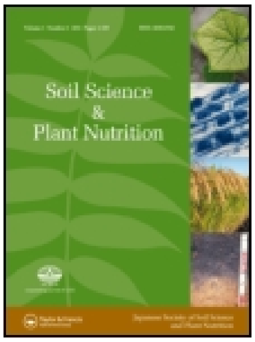

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ORIGINAL ARTICLE

Effects of reduced tillage, crop residue management and manure application practices on crop yields and soil carbon sequestration on an Andisol in northern Japan

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Abstract

Soil carbon sequestration in agricultural lands has been deemed a sustainable option to mitigate rising atmospheric CO_2 levels. In this context, the effects of different tillage and C input management (residue management and manure application) practices on crop yields, residue C and annual changes in total soil organic C (SOC) (0–30 cm depth) were investigated over one cycle of a 4-year crop rotation (2003–2006) on a cropped Andisol in northern Japan. For tillage practices, the effects of reduced tillage (no deep plowing, a single shallow harrowing for seedbed preparation [RT]) and conventional deep moldboard plow tillage (CT) were compared. The combination of RT, residue return and manure application (20 Mg ha^{-1} in each year) increased spring wheat and potato yields significantly; however, soybean and sugar beet yields were not influenced by tillage practices. For all crops studied, manure application enhanced the production of above-ground residue C. Thus, manure application served not only as a direct input of C to the soil, but the greater crop biomass production engendered enhanced subsequent C inputs to the soil from residues. The SOC contents in both the 0–5 cm and 5–10 cm layers of the soil profile were greater under RT than under CT treatments because the crop residue and manure were densely incorporated into the shallow soil layers. Comparatively, neither tillage nor C input management practices had significant effects on annual changes in SOC content in either the 10–20 cm or 20–30 cm layers of the soil profile. When soil C sequestration rates, as represented by annual changes in total SOC (0–30 cm), were assessed on a total soil mass basis, an ANOVA showed that tillage practices had no significant effect on total C sequestration, but C input management practices had significant positive effects ($P \leq 0.05$). These results indicate that continuous C input to the soil through crop residue return and manure application is a crucial practice for enhancing crop yields and soil C sequestration in the Andisol region of northern Japan.

Key words: Andisol, crop residue, manure application, reduced tillage, soil carbon sequestration.

INTRODUCTION

Agriculture contributes to 10–12% of total global anthropogenic greenhouse gas emissions (Smith *et al.* 2007). Closely associated with crop and animal production, CH_4 and N_2O are the major greenhouse gases emitted through agricultural activities (Johnson *et al.* 2007; Smith *et al.* 2007). In modern highly mechanized and material-intensive cropping systems, CO_2 is also emitted from a number of fuel-consuming operations (Koga *et al.* 2006). In contrast, soil organic C (SOC) sequestration in agricultural lands has recently drawn growing attention for its promise in mitigating rises in atmospheric CO_2 concentrations (Paustian *et al.* 1997; Smith *et al.* 2007). In principal, agricultural soils can provide a large C sink and their SOC can be increased through the implementation of efficient agronomic practices (Johnson *et al.* 2007; Ogle *et al.* 2005; Paustian *et al.* 1997).

The quantity of SOC in agricultural ecosystems is influenced by a number of factors, such as climate, soil

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conditions, crops and field management practices (Franzluebbers 2004; Ogle *et al.* 2005). These factors influence the formation and decomposition of SOC in soil and, thereby, determine soil C sequestration rates. Crop residues, plant roots and organic amendments represent significant sources of C inputs for soil C sequestration. As crop type and agronomic practices such as tillage, fertilization and application of organic amendments influence plant biomass production (Kundu *et al.* 2007; Sainju *et al.* 2008), it is important to understand how residue biomass production is influenced by different field management practices and how this impacts on soil C sequestration. Meanwhile, SOC is constantly lost from the soil to the atmosphere through heterotrophic soil respiration. As deep tillage increases CO_2 release from the soil (Reicosky and Archer 2007), the implementation of conservation tillage (no till or reduced tillage) appears to be a practice that can enhance soil C sequestration. Collectively, increasing annual C inputs into soil and/or reducing tillage intensity are crucial in determining soil C sequestration rates. Over the wide range of agro-ecosystems worldwide, optimal field management practices to enhance soil C sequestration have been studied in terms of tillage (Angers *et al.* 1997; Bayer *et al.* 2006; Hermle *et al.* 2008), fertilization (Jagadamma *et al.* 2007; Kundu *et al.* 2007), residue management (Duiker and Lal 1999), application of organic amendments (Agbenin and Goladi 1997), crop rotation (Campbell *et al.* 2000; Su 2007) and combinations thereof (Dolan *et al.* 2006; Halvorson *et al.* 2002; Sainju *et al.* 2008).

Located in the northern part of Japan, the Tokachi region of Hokkaido prefecture is Japan's main center of production for wheat (*Triticum æstivum* L.), potato (*Solanum tuberosum* L.), beans [adzuki bean, *Vigna angularis* (Willd.) Ohwi & Ohashi; kidney bean, *Phaseolus vulgaris* L.; soybean, *Glycine max* Merr.] and sugar beet (*Beta vulgaris* L. subsp. *vulgaris*). In this region, where these crops are cultivated in rotation, harvest is followed by the conventional tillage practice of deep tillage (to a depth of roughly 25 cm) with a moldboard plow, effecting both residue incorporation and improving soil structure. The soil structure is also altered as a result of the harvesting of root crops (potato and sugar beet) and by ridge construction for potatoes. Although local government extension agents recommend manure application to maintain soil fertility and crop productivity, compound fertilizers containing inorganic forms of N, P and K are typically used in crop production. Consequently, intensive field management systems, such as those implemented in the Tokachi region of Hokkaido, may rapidly reduce SOC to contribute to CO_2 emissions from the soil.

Andisols, derived from volcanic ash, although not widely distributed worldwide, are typical of the Tokachi region, where they constitute a staple soil in Japanese arable crop production (Shoji *et al.* 1993). Andisols have unique chemical (e.g. high organic C contents, presence of metal–humus complexes and high P sorption capacity) and physical (e.g. low bulk density and high porosity) properties. Given the nature of Japanese Andisols, they may display unique C dynamics in terms of soil C sequestration. In fact, in optimizing a soil organic matter turnover model (Rothamsted Carbon Model) for Japanese Andisols, special modifications were necessary (Shirato *et al.* 2004). Therefore, it is important to identify the effects of field management practices on total C inputs to the soil and soil C sequestration, so that Japanese agricultural soils can contribute to mitigating global warming. However, at present, lacunae exist in our understanding of the relationships between different field management practices and soil C sequestration in Japanese Andisols. In the present study, optimal field management practices for soil C sequestration under a spring wheat–potato–soybean–sugar beet rotation on an Andisol in northern Japan were identified.

MATERIALS AND METHODS

Study site

A field experiment to assess the effects of different tillage and C input management practices on total SOC and other relevant parameters was conducted (crop cultivation in 2003–2006 and soil sampling in 2003–2007) at the National Agricultural Research Center for Hokkaido Region (42°53′N, 143°03′E), located in the Memuro township near the center of the Tokachi region of Hokkaido prefecture, northern Japan (Fig. 1). The soil in the field was an Andisol (Typic Hapludands), a well-drained volcanic ash-derived soil, typical of this region (Soil Survey Staff 2006). The soil texture was a clay loam (sand, 53.1%; silt, 21.9%; clay, 25.0%), and the initial (2003) mean soil pH was 6.0.

Figure 2 shows the monthly precipitation and mean air temperatures over the study period. The annual mean precipitation and air temperature over the study period were 902 mm and 5.8°C, respectively. Based on the annual precipitation and mean air temperature at the site, the climate zone was categorized as Cool Temperate Moist (Intergovernmental Panel on Climate Change 2006). In winter, the field was covered with snow throughout the study period. The Tokachi region of Hokkaido is an area where soils freeze in winter (Hirota *et al.* 2006). In the winters of 2002–2003, 2005–2006 and 2006–2007, the soils froze, and the

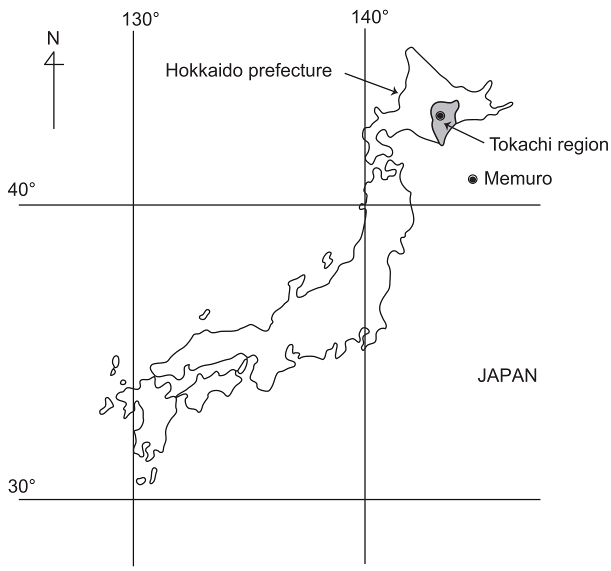

Figure 1 Location of the study site.

maximum soil frost depths were 19, 17 and 25 cm, respectively, whereas the soils hardly froze in the winters of 2003–2004 and 2004–2005 (Iwata *et al.* 2008). Prior to the field experiment, the entire field was cropped to Phacelia (*Phacelia tanacetifolia* Benth.) in 1998 and to cabbage (*Brassica oleracea* L.) in 1999. Both conventional tillage (CT) and reduced tillage (RT) treatments began in 2000 as part of a previous study (Miyazawa *et al.* 2004).

Experimental design and field management

Over the 4-year period of 2003–2006, spring wheat (*T. æstivum*), potato (*S. tuberosum*), soybean (*G. max*) and sugar beet (*B. vulgaris* subsp. *vulgaris*) were cultivated in rotation with four different crop sequences (Table 1). In each crop sequence, the field experiment was set up in a split-plot design with two blocks (Table 2), where the main plot factor was tillage with two tillage treatments: (1) conventional tillage (CT), (2) reduced tillage (RT). Under CT, following the autumn harvest, deep (25 cm) moldboard plow tillage incorporated the residue and manure (when applied). In early spring, seedbed preparation included two shallow (10 cm) harrowings prior to sowing or transplanting. Under RT, moldboard plowing was omitted and only a single shallow harrowing was carried out in early spring for crop residue and manure incorporation as well as for seedbed preparation. Therefore, under RT, crop residues, which overwintered on the ground surface, were incorporated into the soil by shallow harrowing.

Table 1 Crop sequences used in the present study[†]

Spring wheat/potato/soybean/sugar beet
Potato/soybean/sugar beet/spring wheat
Soybean/sugar beet/spring wheat/potato
Sugar beet/spring wheat/potato/soybean

[†]2003/2004/2005/2006.

Furthermore, each main plot was divided into four subplots with different C input management systems (Table 2): (1) removal of all above-ground residue biomass from the field, no manure application (–R), (2) return of residue biomass into soil, no manure application (R), residue return and manure application in (3) autumn (R+FM) or (4) spring (R+SM). In the R+FM

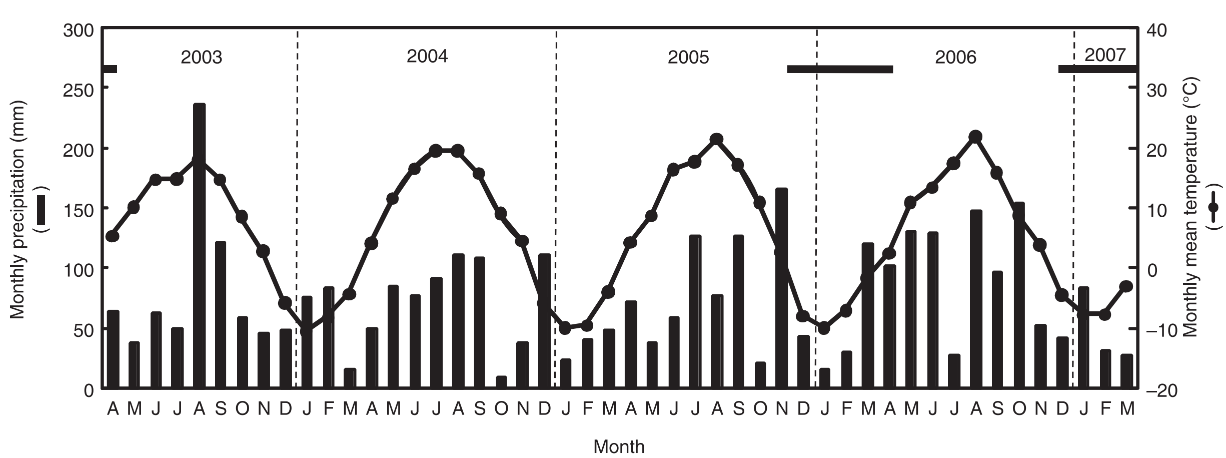

Figure 2 Monthly precipitation and mean air temperature over the study period. Weather data were measured at a meteorologicalobservation site at the National Agricultural Research Center for Hokkaido Region (200 m distant from the experimental field). Horizontal bars indicate the duration of soil freezing. The annual mean precipitation and air temperature over the study period were 902 mm and 5.8°C, respectively.

Table 2 Tillage and carbon input management factors

Factor	Treatment
Tillage (main plot factor)†	Conventional tillage (CT)
	Reduced tillage (RT)
Carbon input management (subplot factor)	Removal of above-ground crop residues (−R)
	Return of all crop residues (R)
	Return of all crop residues + manure application in autumn (R+FM)
	Return of all crop residues + manure application in spring (R+SM)

†Both the CT and RT treatments began in 2000 as part of another study (Miyazawa *et al.* 2004).

Table 3 Crops, varieties, planting densities, fertilizer application rates and times of sowing and harvesting

				Fertilizer application rate‡				
		Row spacing	Planting density†	N§	P_2O_5	K_2O		
Crop	Variety	(cm)	(plant m^{-2})	(kg ha^{-1})			Sowing or transplanting	Harvesting
Spring wheat	Haruyutaka	30	16.0	80	200	120	Late April	Early August
Potato	Kita-akari	72	4.6	64 (12)	160	336	Early May	Early September
Soybean	Toyomusume	66	15.2	30	250	130	Late May	Early October
Sugar beet	Abend	66	7.6	144 (66)	240	144	Late April	Mid October

†In g seeds m^{-2} for spring wheat. ‡All subplots received granular compound fertilizer, depending on the crop. §The main form of N applied was ammonium-N. Numbers in parentheses are the rates of N applied as nitrate-N (kg ha^{-1} of the total).

and R+SM subplots, wheat straw mixed composted cattle dairy manure, purchased from a nearby dairy farm, was applied at a rate of 20 Mg ha^{-1} $year^{-1}$ on a fresh-weight basis. Standard field management practices for the Tokachi region of Hokkaido were followed, with all subplots receiving granular compound fertilizer (Table 3). A paper-pot transplanting system was used in sugar beet production, where 5–6-week-old seedlings raised in paper pots (13 cm high × 2 cm in diameter) were transplanted into the field. In 2003 and 2006, some portions of the sugar beet crops were damaged owing to a foliar disease. The area of each subplot was 16 m^2 (4 m × 4 m). In total, 64 subplots (four crop sequences × two blocks × two levels of tillage × four levels of C input) were implemented in the field experiment.

Plant and manure analysis

In 2003–2006, crop yields and dry-weight basis above-ground residue biomass production at harvest were recorded. The residue biomass and manure samples were oven-dried at 80°C for 3 days and ground to a fine powder. The C and N contents of these samples were measured by a dry combustion method using an NC analyzer (Sumigraph NC-900; Sumika Chemical Analysis Service, Tokyo, Japan). The annual C inputs from wheat seeds, seed potatoes, soybean seeds and sugar beet seedlings were equivalent to 60, 200, 25 and 1 kg C ha^{-1}, respectively. The paper pots used for transplanting sugar beet seedlings contributed 16 kg C ha^{-1}. Carbon inputs from fungicides, insecticides and herbicides were not considered.

Soil sampling and analysis

Soil samples, taken between planted rows in early June of each year from 2003 to 2007, were drawn from four different layers of the soil profile: 0–5, 5–10, 10–20 and 20–30 cm. In each subplot, five soil subsamples were taken from each depth using a hand auger (4 cm diameter) and bulked in the field. The composite samples were then passed through a 2 mm sieve and air-dried in a dark and cool room for 1 month. After visible plant and manure debris were removed using forceps, air-dried soil samples were ground to a fine powder. For these samples, the moisture contents were determined by drying at 105°C, and the C contents were measured using an NC analyzer (Sumigraph NC-900). As the soil was slightly acidic (pH 6.0), and lime had not been applied to the field, the total C in the soil was considered to be equivalent to SOC. For measuring soil bulk densities, irrespective of crop sequences and C input management treatments, 10 subplots were randomly selected from each CT and RT treatment. In each selected subplot, soil core samples were taken annually for the four soil layers (0–5, 5–10, 10–20 and 20–30 cm) in early June of every year.

Table 4 Mean crop yields under different tillage and carbon input management practices (Mg ha^{-1} $year^{-1}$)[†]

	Conventional tillage				Reduced tillage			
Crop	–R	R	R+FM	R+SM	–R	R	R+FM	R+SM
Spring wheat[‡]	2.90	3.42	3.66	3.72	3.19	3.87	4.13	3.97
Potato	33.6	33.7	39.3	38.2	37.1	37.0	44.1	42.5
Soybean[‡]	3.22	3.33	3.53	3.50	3.30	3.35	3.39	3.45
Sugar beet	50.5	53.0	54.3	54.7	50.9	51.0	55.4	55.4

[†]Means of 2003–2006. [‡]Grain yields for spring wheat and soybean were based on 13.5 and 15.0% moisture contents, respectively. –R, removal of above-ground crop residues; R, return of all crop residues; R+FM, return of all crop residues + manure application in autumn; R+SM, return of all crop residues + manure application in spring.

Table 5 ANOVA results for the crop yields

Crop	Y	T	CI	Y × T	Y × CI	T × CI	Y × T × CI
Spring wheat	*	*	***	ns	ns	ns	ns
Potato	*	**	***	ns	ns	ns	ns
Soybean	*	ns	*	ns	ns	ns	ns
Sugar beet	ns	ns	*	ns	ns	ns	ns

*P < 0.05; **P < 0.01; ***P < 0.001; ns, not significant; CI, carbon input; T, tillage; Y, year.

The area-based total SOC at 0–5, 5–10, 10–20 and 20–30 cm depth ranges was calculated by multiplying soil bulk densities and C contents, depth by depth. The total SOC at a depth of 0–30 cm was calculated on a soil-mass-weighted basis (Ellert and Bettany 1995) by summing total SOC for all soil depths. As soil bulk densities were influenced by tillage treatments and sampling years in the field experiment, it was necessary to eliminate the effect of such changes in soil bulk densities on the calculations of total SOC over the study period. For this purpose, the length of the 20–30 cm layer was changed for the 2004–2007 soil samples so that the total soil mass in 2004–2007 would equal the mean total soil mass (0–30 cm) in 2003 (2,601 Mg ha^{-1} for CT and 2,765 Mg ha^{-1} for RT). Annual changes in SOC contents (0–5, 5–10, 10–20 and 20–30 cm) and total SOC (0–30 cm) over the period of 2003–2007 were calculated from the relationship between sampling years, and SOC contents or total SOC in the corresponding years by linear regression analysis for each subplot.

Statistical analyses

For each crop, the effects of cultivation year, tillage (CT and RT) and C input management practices (–R, R, R+FM and R+SM) on crop yields and the annual production of above-ground residue biomass C were tested by ANOVA. The effects of sampling years and tillage practices on soil bulk densities were tested for each soil depth by ANOVA. Annual changes in SOC contents (0–5, 5–10, 10–20 and 20–30 cm) and total SOC (0–30 cm) were also tested with crop sequences, tillage and C input management by ANOVA. All statistical analyses were carried out using R (R Development Core Team 2008).

RESULTS

Crop yields

Carbon input management practices (i.e. residue incorporation and manure application) significantly influenced the harvestable yield biomass production in spring wheat ($P \leq 0.001$), potato ($P \leq 0.001$), soybean ($P \leq 0.05$) and sugar beet ($P \leq 0.05$) (Tables 4,5). In R+FM and R+SM, manure application increased yield biomass production. Yield reduction resulting from residue removal was more pronounced in spring wheat than in the other three crops. The effects of tillage on crop yields were significant for spring wheat ($P \leq 0.05$) and potato ($P \leq 0.01$). Spring wheat and potato yields were improved by RT. These crops have a relatively short growing period (3–4 months) from planting to harvesting, and yields in such crops may be vulnerable to soil nutrient status (e.g. N and P) at planting. Given that crop residues and manure were densely incorporated into the surface soil layer in the RT treatments, it was expected that the nutrient concentrations in the soil surface would be higher in RT soils than CT soils at planting. One possible reason for the improved yields

Table 6 Above-ground residue biomass carbon production under different tillage and carbon input management practices (Mg C ha^{-1} year^{-1})[†]

Crop	Residue biomass	Conventional tillage				Reduced tillage			
		–R[‡]	R	R+FM	R+SM	–R[‡]	R	R+FM	R+SM
Spring wheat	Straw, stubble and husks	1.73	1.95	2.05	2.02	1.80	1.94	2.26	2.18
Potato	Stems and leaves	0.16	0.15	0.21	0.19	0.17	0.17	0.18	0.18
Soybean	Stems, leaves, stubble and pods	1.12	1.14	1.22	1.23	1.13	1.17	1.24	1.26
Sugar beet	Leaves	1.92	1.99	2.14	2.10	1.87	1.73	1.99	1.96
Annual mean[§]		1.23 (0.69)	1.31 (0.75)	1.41 (0.78)	1.39 (0.77)	1.24 (0.68)	1.25 (0.69)	1.42 (0.81)	1.40 (0.78)

[†]Means of 2003–2006. [‡]It is important to note that the actual C inputs from above-ground residue biomass were zero in –R. [§]Mean (± standard deviation) over the four crops. –R, removal of above-ground crop residues; R, return of all crop residues; R+FM, return of all crop residues + manure application in autumn; R+SM, return of all crop residues + manure application in spring.

Table 7 ANOVA results for the above-ground residue biomass carbon production

Crop	Y	T	CI	Y × T	Y × CI	T × CI	Y × T × CI
Spring wheat	ns	ns	***	ns	*	ns	ns
Potato	*	ns	**	*	ns	ns	ns
Soybean	*	ns	**	*	ns	ns	ns
Sugar beet	*	ns	*	ns	ns	ns	ns

*P < 0.05; **P < 0.01; ***P < 0.001; ns, not significant; CI, carbon input; T, tillage; Y, year.

in spring wheat and potato with RT might be the better nutrient status in the surface soil in RT than in CT.

Annual carbon inputs from crop residue biomass and manure

The production of above-ground crop residue biomass, which can serve as a significant source of annual C inputs into the soil, is presented in Table 6. Large quantities of residue C were produced by spring wheat (1.73–2.26 Mg C ha^{-1} year^{-1}) and sugar beet (1.73–2.14 Mg C ha^{-1} year^{-1}), whereas very low residue C was noted for potato production (0.15–0.21 Mg C ha^{-1}year^{-1}). Soybean displayed an intermediate residue C production (1.12–1.26 Mg C ha^{-1} year^{-1}). The ANOVA results showed that tillage had no significant effect on residue biomass C, but C input management practices (–R, R, R+FM and R+SM) had significant effects (Table 7). Averaged across the four crops, the quantities of C retained in the residues ranged from 1.23 ± 0.69 Mg C ha^{-1} year^{-1} for CT × (–R) to 1.42 ± 0.81 Mg C ha^{-1} year^{-1} for RT × (R+FM) in a single year (Table 6). Continuous manure application in R+FM and R+SM increased the total C in the crop residue biomass. Mean residue C was 8 and 6% higher for R+FM and R+SM than for R, respectively, under the CT system, whereas it was 14 and 12% higher, respectively, under the RT system. Conversely, decreases in residue C by the removal of crop residues from the field were most pronounced in spring wheat.

In R+FM and R+SM, cattle dairy manure was applied annually at a rate of 20 Mg ha^{-1} on a fresh-weight basis (Table 8). The rate of direct annual C inputs from manure, expressed on a C basis, was equivalent to 1.39 ± 0.22 Mg C ha^{-1} year^{-1}. The C/N ratios of the manure samples used varied from 12.6 to 20.0.

The total annual C inputs from crop residue biomass and dairy manure are summarized in Table 9. As crop residues were removed and no manure was applied in the –R subplots, actual C inputs from residue biomass (except for below-ground biomass) and manure into the soil were assumed to be zero. In R, the annual C inputs were derived from crop residues, accounting for 1.31 ± 0.75 and 1.25 ± 0.69 Mg C ha^{-1} year^{-1} for CT and RT, respectively (these yearly variations were derived from the variations between crops). Larger total C inputs, approximately 2.8 Mg C ha^{-1} year^{-1}, occurred because of direct C inputs from composted dairy manure and increased C inputs as a result of improved above-ground residue biomass production.

Soil bulk densities under CT and RT

The effect of different tillage practices on soil bulk densities was tested by ANOVA for soil samples taken

Table 8 Annual carbon inputs from composted manure in the return of all crop residues + manure applications in autumn (R+FM) and spring (R+SM)

Application	Fresh weight (Mg ha^{-1} year^{-1})	Dry weight (Mg ha^{-1} year^{-1})	C content (%)	C/N ratio	Annual C input (Mg ha^{-1} year^{-1})
Autumn in 2003/spring in 2004	20.0	4.93	32.3	20.0	1.59
Autumn in 2004/spring in 2005	20.0	4.84	32.2	20.0	1.56
Autumn in 2005/spring in 2006	20.0	6.53	19.8	12.7	1.29
Autumn in 2006/spring in 2007	20.0	6.81	16.4	12.6	1.12
Annual mean†					1.39 (0.22)

†Mean (± standard deviation) of 2003–2006.

Table 9 Total annual carbon inputs from above-ground crop residue biomass and composted manure (Mg C ha^{-1} year^{-1})†

	Conventional tillage				Reduced tillage			
	–R‡	R	R+FM	R+SM	–R‡	R	R+FM	R+SM
Crop residue biomass	0	1.31 (0.75)	1.41 (0.78)	1.39 (0.77)	0	1.25 (0.69)	1.42 (0.81)	1.40 (0.78)
Manure	0	0	1.39 (0.22)	1.39 (0.22)	0	0	1.39 (0.22)	1.39 (0.22)
Total	0	1.31 (0.75)	2.80 (0.81)	2.78 (0.80)	0	1.25 (0.69)	2.81 (0.84)	2.79 (0.81)

†Means (± standard deviation) of 2003–2006. ‡In –R, all above-ground crop residues were removed from the field. –R, removal of above-ground crop residues; R, return of all crop residues; R+FM, return of all crop residues + manure application in autumn; R+SM, return of all crop residues + manure application in spring.

Table 10 Bulk densities of conventional tillage and reduced tillage soils at different soil depths (Mg m^{-3})†

	0–5 cm		5–10 cm		10–20 cm		20–30 cm	
Year	CT	RT	CT	RT	CT	RT	CT	RT
2003	0.78	0.76	0.82	0.89	0.89	0.96	0.92	0.98
2004	0.79	0.79	0.82	0.89	0.88	0.94	0.95	1.00
2005	0.77	0.79	0.82	0.91	0.86	0.94	0.90	0.96
2006	0.81	0.81	0.94	0.91	0.96	0.93	0.96	0.96
2007	0.85	0.88	0.92	0.95	0.93	0.92	0.91	0.95
Mean‡	0.80	0.81	0.86	0.91	0.90	0.94	0.93	0.97
ANOVA								
Year (Y)		*		**		ns		ns
Tillage (T)		ns		*		*		*
Y × T		ns		ns		*		ns

†Ten soil core samples were taken annually from conventional tillage (CT) and reduced tillage (RT) plots, independent of crop sequences and carbon input management practices. Values are the means of the 10 replicated soil core samples. ‡Means of 2003–2007. *P < 0.05; **P < 0.01; ns, not significant.

from CT and RT plots over the period of 2003–2007 (Table 10). For the 0–5 cm soil layer, the mean bulk densities of CT and RT soils were similar, mainly because both soils were subject to shallow harrowing every spring for seedbed preparation. However, the bulk densities of the 5–10, 10–20 and 20–30 cm soil layers were greater in RT soils than in CT soils ($P \le 0.05$). This difference could be attributed to the continuous moldboard plowing in CT soils. The deeper the soil layers were the greater the soil bulk densities, regardless of tillage practices.

Annual changes in SOC contents and storage

The dry-weight basis SOC contents in the initial year (2003) and annual changes in the SOC contents from 2003 to 2007 are presented in Table 11. In 2003, the

Table 11 Effects of different tillage and carbon input management practices on annual changes in soil organic carbon contents

	Conventional tillage				Reduced tillage			
Soil depth	–R	R	R+FM	R+SM	–R	R	R+FM	R+SM
Soil organic carbon content in 2003 (g C kg^{-1})†								
0–5 cm	33.7 (5.5)	34.2 (6.0)	35.0 (6.3)	35.2 (6.4)	35.4 (4.2)	36.5 (3.3)	38.0 (5.5)	40.3 (4.9)
5–10 cm	33.5 (5.9)	34.2 (5.5)	34.9 (6.0)	34.9 (6.4)	34.8 (3.8)	35.4 (3.2)	34.8 (3.9)	36.9 (3.9)
10–20 cm	33.9 (5.9)	34.2 (5.8)	35.3 (6.5)	34.5 (6.0)	34.8 (3.9)	35.1 (3.5)	34.6 (4.1)	35.9 (3.8)
20–30 cm	32.8 (5.4)	33.6 (6.1)	34.6 (8.0)	34.6 (7.4)	30.8 (8.3)	32.4 (9.1)	32.9 (6.2)	33.4 (6.0)
Annual change in soil organic carbon content from 2003 to 2007 (g C kg^{-1} year^{-1})‡								
0–5 cm	−0.39 (0.39)	−0.14 (0.28)	−0.08 (0.78)	0.25 (0.37)	−0.22 (0.37)	0.05 (0.15)	0.39 (0.46)	0.15 (0.42)
5–10 cm	−0.25 (0.28)	0.03 (0.52)	−0.10 (0.49)	−0.05 (0.42)	−0.21 (0.28)	0.08 (0.42)	0.46 (0.56)	0.31 (0.48)
10–20 cm	−0.27 (0.37)	0.03 (0.55)	−0.17 (0.51)	0.11 (0.17)	−0.24 (0.23)	−0.10 (0.28)	0.05 (0.40)	−0.27 (0.46)
20–30 cm	−1.28 (1.50)	−0.95 (1.09)	−0.50 (0.72)	−0.42 (0.67)	−1.31 (0.99)	−0.49 (0.60)	−0.91 (1.11)	−0.59 (0.56)

†Means (± standard deviation) of eight subplots (four crop sequences × two replicates). ‡Means (± standard deviation) of the eight slopes (four crop sequences × two replicates) in linear regression between soil organic carbon contents and the years examined (2003–2007). –R, removal of above-ground crop residues; R, return of all crop residues; R+FM, return of all crop residues + manure application in autumn; R+SM, return of all crop residues + manure application in spring.

Table 12 ANOVA results for annual changes in soil organic carbon (SOC) contents and total SOC (0–30 cm)

Soil depth	CS	T	CI	CS × T	CS × CI	T × CI	CS × T × CI
SOC content							
0–5 cm	ns	ns	*	ns	ns	ns	ns
5–10 cm	ns	ns	*	ns	ns	ns	*
10–20 cm	ns	ns	ns	ns	ns	ns	ns
20–30 cm	ns	ns	ns	ns	ns	ns	ns
Total SOC							
0–30 cm	ns	ns	*	ns	ns	ns	ns

*$P < 0.05$; ns, not significant; CI, carbon input; CS, crop sequence; T, tillage.

mean C contents ranged from 30.8 to 40.3 g kg^{-1} across all soil layers and treatments. Large variations in SOC contents already existed in 2003. The rates of annual changes in soil C contents varied with soil layers and field management practices. As above-ground residues and dairy manure were densely incorporated into the shallow soil layers in RT, the mean SOC contents at 0–5 and 5–10 cm depths increased in the R, R+FM and R+SM subplots. Similarly, the SOC content in the shallow soil layer increased in R+SM under CT because the manure applied in spring was incorporated by shallow harrowing, even with CT. In the –R subplots, where crop residues were withdrawn from the field, the SOC contents decreased rapidly at all soil layers. Even with no physical soil disturbance at the deeper soil layers by deep tillage under RT, the largest decrease in the SOC contents occurred at the 20–30 cm depth. The ANOVA results showed that neither crop sequence nor tillage had significant effects on annual changes in SOC contents at all soil layers (Table 12). Meanwhile, the 0–5 and 5–10 cm depth SOC contents were significant for C input management ($P \leq 0.05$).

In 2003, CT and RT plots bore 2,601 ± 118 and 2,765 ± 104 Mg ha^{-1} of the soil mass, respectively, to a 30 cm depth, and housed 86.9 ± 11.2 to 98.9 ± 10.6 Mg C ha^{-1} in total SOC reserves in a range across CT and RT (Table 13). Given that the annual changes in total SOC (0–30 cm) were evaluated based on the mean soil mass in CT and RT in the initial year, in R under CT (conventional management for this region), the total SOC was declining at a rate of 0.71 ± 1.04 Mg C ha^{-1} year^{-1} (0.8% mean annual reduction). In –R, regardless of the tillage practices, the total SOC decreased at higher rates (−1.45 ± 1.32 Mg C ha^{-1} year^{-1} for CT and −1.58 ± 1.11 Mg C ha^{-1} year^{-1} for RT). Despite the significant annual C inputs from residues and manure (approximately 2.8 Mg C ha^{-1} year^{-1} in total; Table 9), the average annual change in total SOC in R+FM and R+SM was negative. As shown in Table 12, there was no significant difference in annual changes in

Table 13 Effects of different tillage and carbon input management practices on annual changes in total soil organic carbon (0–30 cm)[†]

	Conventional tillage				Reduced tillage			
	−R	R	R+FM	R+SM	−R	R	R+FM	R+SM
Total SOC in 2003 (Mg C ha^{-1})[‡]	86.9 (11.2)	88.4 (11.4)	90.8 (11.8)	90.2 (11.8)	92.6 (9.9)	95.1 (10.3)	95.3 (10.3)	98.9 (10.6)
Annual change in total SOC (Mg C ha^{-1} $year^{-1}$)[§]	−1.45 (1.32)	−0.71 (1.04)	−0.60 (1.17)	−0.14 (0.66)	−1.58 (1.11)	−0.42 (0.75)	−0.35 (1.16)	−0.49 (1.02)

[†]The total soil organic carbon (SOC) (0–30 cm) in each year was assessed on a soil mass basis. The mean soil masses in conventional tillage (CT) and reduced tillage (RT) plots in 2003 were 2,601 and 2,765 Mg ha^{-1}, respectively. [‡]Means (± standard deviation) of eight subplots (four crop sequences × two replicates). [§]Means (± standard deviation) of the eight slopes (four crop sequences × two replicates) in linear regression between SOC contents and the years examined (2003–2007). –R, removal of above-ground crop residues; R, return of all crop residues; R+FM, return of all crop residues + manure application in autumn; R+SM, return of all crop residues + manure application in spring.

total SOC between CT and RT, but C input management practices (residue management and manure application) had a significant impact ($P \le 0.05$).

DISCUSSION

Crop yields under different field management practices

As crop yields are the major concern for producers, the relationship between mean crop yields (2003–2006) and different field (tillage and C inputs) management practices was assessed (Table 4). The effects of conservation tillage (no till and RT) on crop yields in Japanese Andisol fields have been studied for their benefits in saving costs, labor and fuel (Koga *et al.* 2006; Miyazawa *et al.* 2004). Better crop yields under RT compared with CT have already been reported for spring wheat in Hokkaido (Miyazawa *et al.* 2004) and for summer crops (e.g. maize and soybean) in Tsukuba, central Japan (Tsuji *et al.* 2006). In contrast, similar yields between the two tillage practices have been noted for soybean, maize and sugar beet in Hokkaido (Miyazawa *et al.* 2004; Ogawa *et al.* 1988) and for maize and barley in Tokyo and Niigata prefectures in central Japan (Sakai *et al.* 1994). In our field experiment, higher spring wheat and potato yields were obtained under RT than under CT, whereas soybean and sugar beet yields did not differ significantly between CT and RT (Table 4), even when RT impacted soil properties such as soil bulk densities (Table 10) and vertical SOC content profiles (Table 11). Greater or equal crop yields under RT in various studies in Japan indicate that RT is a promising conservation tillage practice that would not sacrifice crop yields in Japan's Andisol fields. In terms of no-till soil management in Japan, there are some reports on yield reductions owing to germination, weed and soil temperature problems (Sakai *et al.* 1994; Tsuji *et al.* 2006). In the Tokachi region, significant effects of C input management (residue management and manure application) on crop yields were noted in spring wheat, potato, soybean and sugar beet (Tables 4,5). These results indicate that a combination of RT, residue return and manure application is the optimal practice for spring wheat and potato yields. Meanwhile, residue return and manure application, independent of tillage practices, are recommended for soybean and sugar beet to obtain higher yields in this region.

Annual carbon inputs as affected by field management practices

Organic amendments and residue biomass components from crop production are the principal inputs for soil C sequestration, but inputs of the latter are influenced by crop species, cropping systems and a number of agronomic practices (Bolinder *et al.* 2007; Paustian *et al.* 1997). One way to increase C inputs is to use high-residue-producing crops in the cropping system. Johnson *et al.* (2006) reported mean annual residue C production for major field crops in the USA; 3.12, 1.46, 1.07 and 1.49 Mg C ha^{-1} $year^{-1}$ for corn (*Zea mays* L.), wheat, soybean and sorghum (*Sorghum bicolor* (L.) Moench), respectively. Under the crop rotation system implemented in the Tokachi region of Hokkaido, the production of residue C varied widely among the crops (Table 6). Spring wheat and sugar beet represented high residue C production (~2 Mg C ha^{-1} $year^{-1}$), although lower than that of corn in the USA. In contrast, residue C was very low in potatoes (< 0.2 Mg C ha^{-1} $year^{-1}$). Low C inputs from potato residues may illustrate that SOC is lost from the soil rapidly through conventional potato production.

In previous studies, different residue biomass production, depending on fertilization practices, contributed to different soil C sequestration rates (Campbell *et al.*

2000; Kundu *et al.* 2007). Kundu *et al.* (2007) reported that annual C inputs from soybean residues varied widely, depending on fertilization regimes. In their study, no fertilization and a lack of P or K markedly decreased the input of residue C, whereas farmyard manure application increased residue C significantly, resulting in significantly greater soil C sequestration rates. Likewise, annual inputs of residue C in the Tokachi region were significantly influenced by the C input management practices for all crops studied; in particular, manure application increased the C retained in the residue biomass by 6–14% compared with simple residue incorporation (Table 6). These results indicate that manure application serves not only as a practice for direct C inputs into soil, but also as a practice that indirectly increases C input from residue biomass as a result of greater biomass production. Conversely, continuous residue removal was an unfavorable practice. Residue removal not only causes a lack of input of above-ground residue C, but also lowers the production of residue biomass C to be returned to the soil in the following years.

Relationship between tillage and soil carbon sequestration on a Japanese Andisol

Soil tillage has long been widely practiced as a method for controlling weeds, preparing seedbeds and improving soil physical conditions (Franzluebbers 2004). As this practice principally influences the depths to which crop residues and organic amendments are incorporated, as well as physical soil properties, the subsequent formation/decomposition of soil organic matter is also altered. In the context of current global warming issues, alternative tillage practices that would allow the sequestration of more C in soil have been intensively studied. However, few studies have investigated the effects of tillage on soil C sequestration in Japanese soils.

The relationships between no till and soil C sequestration have been extensively studied globally (Franzluebbers 2005; Paustian *et al.* 1997; West and Post 2002). Greater SOC under no till than under CT was noted in more than 90% of observations in southeastern USA (Franzluebbers 2005). Paustian *et al.* (1997) also reported that in temperate zones SOC was 8% greater, on average, under no till than under CT. The impacts of RT on soil C sequestration have also been assessed in terms of shallow tillage (Halvorson *et al.* 2002; Hermle *et al.* 2008) and chisel-based reduced tillage (Bayer *et al.* 2006; Dolan *et al.* 2006) as opposed to conventional tillage, although the soil depth considered differed from study to study. In previous studies, there are some reports showing no significant positive effects of RT on soil C sequestration, for example, shallow tillage on a Swiss Luvisol (Hermle *et al.* 2008), chisel-based reduced tillage on Brazilian Cerrado soils (Bayer *et al.* 2006) and for a Minnesota soil (Dolan *et al.* 2006). In contrast, Halvorson *et al.* (2002) obtained two different results on the effects of shallow tillage on soil C sequestration: a positive effect for an annual crop rotation system, but no significant effect for a spring wheat–fallow system. This contradictory result arose from the effect of different cropping systems on the levels of total residue return.

In the present study, shallow tillage served as a reduced tillage practice in assessing soil C sequestration. The main reason for shallow tillage was that at least one harrowing was necessary for seedbed preparation and no till is not, therefore, applicable because the soil surface became rough and uneven after harvesting of root crops such as sugar beet and potato in the Tokachi region's crop rotation system. For the Tokachi region's Andisol, RT had no significant positive effects on annual changes in total SOC and soil C sequestration (Table 12).

Reduced tillage increased the SOC contents in the shallow soil layers (0–5 and 5–10 cm depths; Table 11) when crop residues and manure were returned to the field. This may illustrate that more SOC is sequestered under RT than under CT in the shallow soil layers given the significant C input from residues and manure. In contrast, in the deep soil layer of 20–30 cm, the SOC contents under RT decreased rapidly, despite the fact that this deep soil layer did not undergo any physical soil disturbance by plowing. Consequently, this rapid decrease in the SOC contents in the deeper soil layer might deny the positive effects of RT on higher soil C sequestration in the shallow soil layers. The soil at the study site was a well-drained Andisol and the mean soil bulk densities for the 20–30 cm soil layer were low (0.93 Mg m^{-3} for CT and 0.97 Mg m^{-3} for RT) compared with other clayey soils throughout the world. The porous nature of the Andisol might have led to high air permeability, even into the deep soil layer, and an attendant rapid decomposition of soil organic matter through heterotrophic respiration. In terms of implementing RT in the Tokachi region, RT had no positive effects on soil C sequestration, but it should be noted that spring wheat and potato yields were increased by RT (Table 4) and total fuel consumption was significantly reduced by not plowing (Koga *et al.* 2006).

Residue incorporation and manure application for soil carbon sequestration

Increasing the total C input from plant residue biomass (Duiker and Lal 1999; Sainju *et al.* 2008) and organic amendments (Agbenin and Goladi 1997) is crucial to soil C sequestration. Duiker and Lal (1999) demonstrated that SOC contents were positively correlated with the quantity of wheat straw added (0–16 Mg ha^{-1}). As presented in Table 9, in the Tokachi region's Andisol field, total annual C inputs from above-ground residues and manure varied between treatments (0 Mg C ha^{-1} $year^{-1}$ for residue removal, 1.3 Mg C ha^{-1} $year^{-1}$ for residue incorporation and 2.8 Mg C ha^{-1} $year^{-1}$ for residue incorporation and manure application). In the Tokachi region's Andisol field, soil C sequestration was enhanced, according to the increasing annual C inputs from the residue biomass and dairy manure applied (Tables 12,13).

Despite the significant C inputs from crop residues and manure (2.8 Mg C ha^{-1} $year^{-1}$ at the maximum), the mean annual changes in total SOC were all negative (Table 13). This illustrates that further C input is necessary to maintain SOC across the 0–30 cm soil depth in the Tokachi region's Andisol fields. According to the modified Rothamsted C model for Andisols (topsoil, 0–15 or 17.5 cm soil depth), the annual C input needed to maintain the initial SOC at equilibrium was reported to be 2.5–4.1 Mg C ha^{-1} for four sites from Japanese Andisol fields (Shirato *et al.* 2004). The results of this model indicate that more C input is necessary to maintain total SOC if 0–30 cm depth soil is considered in the model. In contrast, in an Indian sandy loam soil (5–10 g kg^{-1} of SOC contents), only 0.3 Mg C ha^{-1} $year^{-1}$ of C inputs was required to maintain SOC (0–45 cm depth; Kundu *et al.* 2007). Hence, Japanese Andisols with relatively high SOC contents might require large quantities of C inputs to maintain total SOC. On this basis, agronomic practices to attain further C inputs to the soil are crucially important to maintain SOC in Andisols in the Tokachi region. For example, possible options under an actual crop rotation system in the Tokachi region are increasing manure application rates, introducing high-residue-producing crops in the rotation system and growing green manure crops in the fallow period. More importantly, the use of a better combination of these possible options would be good practice to ensure that soil in the Tokachi region can be a net sink of C.

Conclusion

In an Andisol field in the Tokachi region of northern Japan, the effects of RT, residue management and manure application practices on soil C sequestration were studied so that Japanese agricultural soil could contribute to both sustainable food production and mitigation of greenhouse gas emissions through soil C sequestration. The response of crop yields to these practices differed from crop to crop. Increases in crop yields under RT were noted in spring wheat and potato crops. Yield biomass production was enhanced by continuous residue return and manure application for all crops. In the Andisol field, RT had no positive effects on overall soil C sequestration (0–30 cm). In contrast, a combination of residue return and manure application exerted a beneficial impact on increasing residue C and decelerating the loss of SOC. These results illustrate the importance of continuous residue return and manure application for sustainable food production and soil C sequestration in an Andisol in the Tokachi region's crop rotation system.

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