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Soil organic carbon and total nitrogen in intensively managed arable soils

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ABSTRACT

The conversion from cereal fields to vegetable production in the last three decades represents a significant shift in land use in China. Here, we studied the effects of conversion form cereal fields to vegetable production in north China on soil organic carbon (SOC) and total nitrogen (TN) in both bulk soil and soil aggregates. We used two approaches: (1) measurements of paired soil samples from wheat (*Triticum aestivum* L.) – maize (*Zea mays* L.) fields and adjacent greenhouses vegetable fields in three vegetable production areas representing various management intensities in terms of C and N inputs and frequency of tillage; (2) fractionating soil to distinguish intra-aggregate particulate organic matter (iPOM) and organo-mineral complexes (silt + clay). Our results indicated that converting cereal fields to greenhouse vegetable production with intermediate and high management intensity led to increases in SOC and TN and decreases in C:N ratios in the top soil. The accumulation rates of C and N in the surface soil (0–30 cm) were estimated to be 1.37 Mg C ha^{-1} yr^{-1} and 0.21 Mg N ha^{-1} yr^{-1} over an average period of 8 years after cereal fields to greenhouse vegetable production conversion. At the soil aggregate level, only the coarse (>250 μm) and fine (53–250 μm) iPOM fraction contributed to the increases in soil C (e.g., 49% and 51% of total C increases, respectively), while the coarse and fine iPOM, and silt + clay fraction accounted for 22%, 30% and 48%, respectively, of total N increases. This illustrates how the addition of readily available C (manure) and N (manure and inorganic N) leads to a temporary stabilization of C in relatively labile SOM fractions, but to a preferential stabilization of N in organo-mineral SOM fractions. In conclusion, the conversion to highly intensive vegetable systems in China leads to marked differences in C and N stabilization dynamics.

1. Introduction

Land use changes are one of the most important anthropogenic perturbations, which affects both the quality and quantity of soil organic carbon (SOC). The loss of SOC by conversion of natural vegetation to cultivated systems is well known. For example, the conversion of forest to agricultural land has led to an global average loss of 24% of SOC and 15% of total nitrogen (TN), hence showing a decrease in the average soil C:N ratio (Murty et al., 2002). The conversion of pasture to conventional cropland has led to a decrease in SOC averaged by 59% worldwide (Guo and Gifford, 2002). Much of these losses in soil C and N can be attributed to reduced inputs of organic matter (OM), increased decomposition of crop residues, and tillage effects that increase soil aeration and decrease the amount of physical protection of soil organic matter (SOM) (Post and Kwon, 2000).

Due to economic development and increased consumer demand as incomes rise, farmers in China have been encouraged to convert cereal fields to vegetable production since 1980s. Today China is the world leader in vegetable production and consumption with an area of 18.4 million ha dedicated solely to vegetable production, accounting for 11.6% of the area under cultivation in China (China Statistical Yearbook, 2010) and about 1.0% of total harvested area globally (FAO, 2009). Therefore, changes in SOC in response to land use conversion from cereal fields to vegetable production have significant implications on both national and global scales. Recently, challenges in enhancing soil and environmental quality for sustainable vegetable production in China have received increasing attention (Cao et al., 2004; He et al., 2009; Shi et al., 2009; Lei et al., 2010; Zhu et al., 2011). Nevertheless, no studies on SOC dynamic in Chinese croplands over the last two or three decades have

Abbreviations: SOC, soil organic carbon; SOM, soil organic matter; TN, total soil nitrogen; iPOM, intra-aggregate particulate organic matter.

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considered the recently established vegetable production systems (Huang and Sun, 2006; Xie et al., 2007; Lu et al., 2009; Piao et al., 2009).

Vegetables require more intensive management than cereals, including more frequent tillage operations and larger inputs of external nutrients (especially N) and irrigation (Power and Schepers, 1989). This is especially true for greenhouse vegetable systems. Therefore, a significant conversion in land use from cereal fields to vegetable production may lead to shift in agricultural resources distribution. For example, Chinese farmers traditionally used organic fertilizers, such as farmyard manure, in cereal fields; however, most organic fertilizers are being applied now for the production of vegetables rather than cereals (Chen et al., 2004; Lei et al., 2010). As a result, vegetable production fields account for only 11.6% of the total cultivated area but 34% of total use of organic materials in China (Li Yanming, 2008, personal communication). Furthermore, inputs of C and N have did not always increase proportionately in response to land use conversion, e.g., in some agricultural production areas in China the conversion from cereal fields (typically wheat–maize rotation) to greenhouse vegetable production has led to a 4.9-fold increase in N inputs but only a 1.4-fold increase in C inputs (Lei et al., 2010). The increased N and C inputs, combined with more intensive tillage and frequent irrigation, may result in profound effects on C and N cycling, stabilization and losses to the environment.

Soil organic matter has a complex structure consisting of various fractions characterized by different physical and chemical properties, microbial degradability and turnover times (Paul and Clark, 1996). Fractionation of soils by particle size implies the separation of the total OM into pools that are thought to be more functionally homogeneous with respect to physicochemical properties and turnover rates (Six et al., 2002; DeGryze et al., 2004). Most research efforts have focused on the effects of C associated with different physical fractions in response to land use conversion (e.g., afforestation and deforestation) (Van Dam et al., 1997; Post and Kwon, 2000; Six et al., 2002), and agricultural management practices (e.g., tillage and dry-wet cycles) (Six et al., 1999; Denef et al., 2001, 2004). In contrast, the dynamics of aggregate-level N have received less attention (Dorodnikov et al., 2009; Kong et al., 2009). In modern intensive agriculture, the supply of large quantities of external N is considered a key factor controlling vital ecological processes (Vitousek et al., 1997). This is especially true for vegetable production systems with higher management intensity in China. However, we still lack a fundamental understanding of how this N interacts with SOM and even much less how they have changed following the land use conversion.

The objectives of this study were to (1) assess the impacts of land use conversion from cereal fields to greenhouse vegetable production on SOC, TN and soil C:N ratio, (2) determine relative contributions of different SOM fractions to soil C and N changes, and (3) evaluate the effects of land use conversion on SOM fractions for C and N accumulation potentials in intensively managed arable soils of north China. We first compared SOC and TN using paired samples from the top 90 cm of the soil profiles from wheat–maize fields and adjacent vegetable greenhouse fields at three typical vegetable production areas representing low, intermediate and high management intensity in terms of the amount of C and N inputs and tillage frequency. Paired soil samples then were fractionated (Six et al., 2000) to distinguish coarse (>250 μm) intra-aggregate particulate organic matter (iPOM), fine (53–250 μm) iPOM, and organo-mineral complexes in size < 53 μm (silt + clay) in order to evaluate the effects of land use conversion on these specific SOM fractions.

2. Materials and methods

2.1. Study areas

Published information on nutrient and C inputs (Chen et al., 2004; Lei et al., 2008) and our preliminary survey were used to

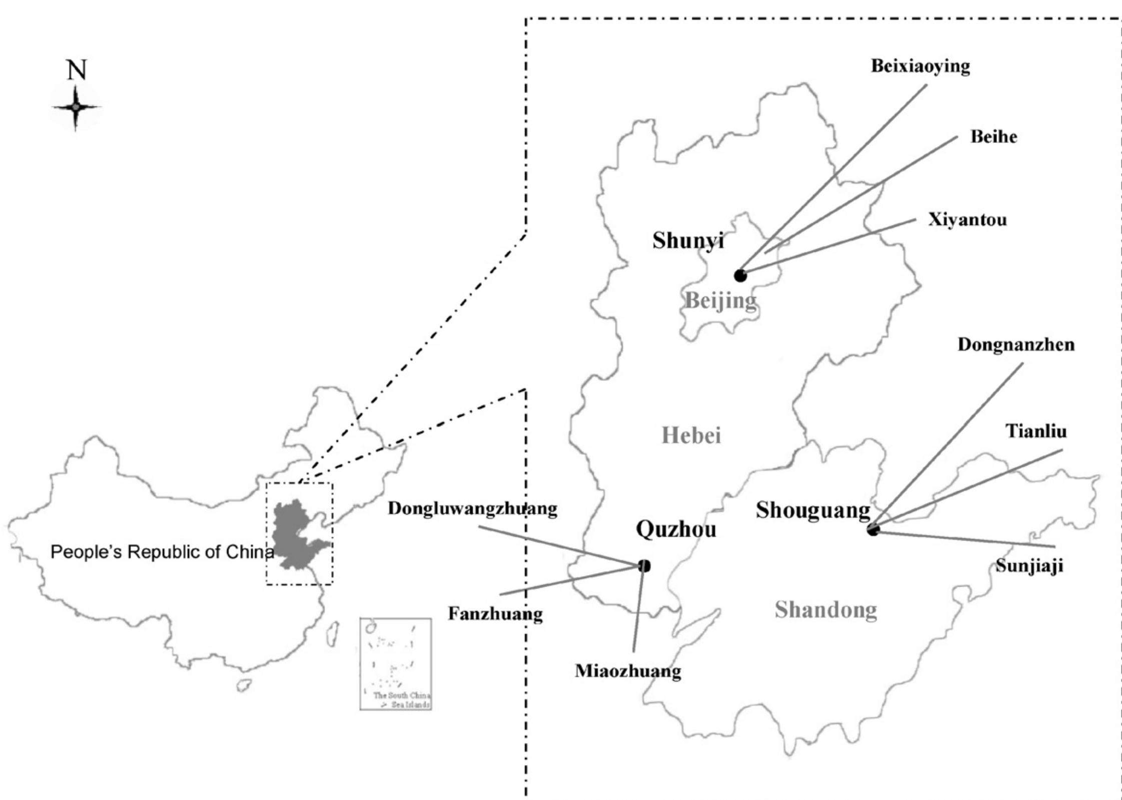

Fig. 1. Study areas of Quzhou, Shunyi and Shouguang and sampling locations within each area.

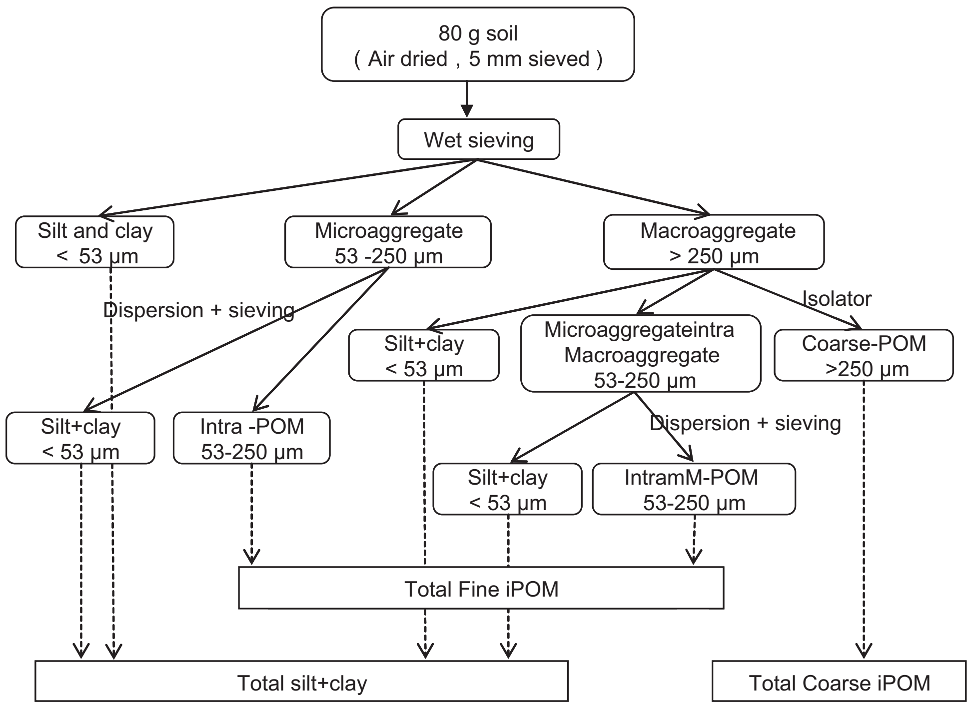

Fig. 2. A fractionation scheme to isolate coarse (>250 μm) intra-aggregate particulate organic matter (iPOM), fine (53–250 μm) iPOM and (<53 μm) organomineral complexes (silt + clay).

select three greenhouse vegetable production areas in north China representing three levels of management intensity in terms of the amount of soil C and N inputs and tillage frequency (Fig. 1). Quzhou county in Hebei province was considered to represent low management intensity, Shunyi district in Beijing for intermediate management intensity, and Shouguang county in Shandong province for high management intensity. All cereal fields under the wheat–maize rotation had a similar level of management intensity across the study areas (Table 1). Within each selected area, three locations were determined as sampling sites (Fig. 1). These areas are characterized by a typical continental monsoon climate with a mean annual air temperature and precipitation of 13.1 °C and 556 mm in Quzhou, 11.2 °C and 620 mm in Shunyi and 12.7 °C and 594 mm in Shouguang.

2.2. Paired soil sampling

Three paired sampling locations of greenhouse vegetable fields and adjacent cereal fields within a distance of less than 50 m were selected in Quzhou, Shunyi and Shouguang in July 2008. Detailed information on locations, soil texture, cultivation history and crop types are shown in Table 2. In each field, we set up a 30 m × 20 m plot for soil sampling. Twelve random soil cores (2.5 cm in diameter × 90 cm deep) were collected within the plot and composited by 0–30, 30–60, and 60–90 cm depth increments. The field-moist soils were passed through a 5-mm sieve and then were air dried for aggregate fractionations and determination of SOC and TN. In addition, three other soil cores were collected for bulk density measurements.

2.3. Soil aggregate separation

Because SOC and/or TN in top 0–30 cm of bulk soil at Shunyi and Shouguang showed significant increases following the conversion from cereal fields to greenhouse vegetable production, aggregate size separation was performed using a wet sieving method adapted

Table 1
Management information of greenhouse vegetable production (VF) and cereal fields (wheat–maize, CF) in selected study areas of Quzhou, Shunyi, and Shouguang, north China.

Land use	C, N input and tillage frequency [a]
Quzhou, Hebei Province	
CF	C input: 6300 kg C ha^{-1} (crop residues: straw and root) N input: 550 kg N ha^{-1} (N fertilizer 430 kg N ha^{-1}, crop residues, 120 kg N ha^{-1}) Tillage, 1 time before wheat season start
VF	C input: 3100 kg C ha^{-1} (manure) N input: 670 kg N ha^{-1} (N fertilizer 330 kg N ha^{-1}, manure, 340 kg N ha^{-1}) Tillage, 1–2 times
Shunyi, Beijing	
CF	C input: 6900 kg C ha^{-1} (crop residues: straw and root) N input: 490 kg N ha^{-1} (N fertilizer 360 kg N ha^{-1}, crop residues, 130 kg N ha^{-1}) Tillage, 1 time before the wheat season start
VF	C input: 6600 kg C ha^{-1} (manure) N input: 1300 kg N ha^{-1} (N fertilizer 570 kg N ha^{-1}, manure, 730 kg N ha^{-1}) Tillage, 2 times
Shouguang, Shandong Province	
CF	C input: 6900 kg C ha^{-1} (crop residues: straw and root) N input: 440 kg N ha^{-1} (N fertilizer 310 kg N ha^{-1}, crop residues, 130 kg N ha^{-1}) Tillage, 1 time before wheat season start
VF	C input: 9500 kg C ha^{-1} (manure) N input: 2180 kg N ha^{-1} (N fertilizer 1120 kg N ha^{-1}, manure, 1060 kg N ha^{-1}) Tillage, 2 times

[a] Values are the amounts of C and N inputs and tillage frequency annually based on published information (Chen et al., 2004; Lei et al., 2008) and our survey in 2006 and 2008. The amounts of C and N inputs include crop residue C and N (straw and root) and N from fertilizer application for the cereals fields and C in manures and N in manures and fertilizer applications for the greenhouse vegetable production, respectively. Biomass of root in cereal systems were estimated by ratio of root to shoot (Huang et al., 2006). Most of above- and belowground residues in greenhouse vegetable fields were removed during harvest. Carbon and N inputs and tillage frequency of the cereal fields refer only to similar time periods as in the greenhouse vegetable systems.

Table 2
Sampling location information on selected greenhouse vegetable production (VF) and cereal fields (wheat–maize, CF) for paired comparisons in Quzhou, Shunyi and Shouguang, north China.

Site	Land use	Longitude	Latitude	Sand20–2000 μm	Silt2–20 μm	Clay<2 μm	Land use duration (yr)	Crop[a]
Quzhou								
Location	CF	114°58′57″	36°49′57″	59.9	35.5	4.6	>30	Wheat
1	VF	114°58′57″	36°49′57″	60.72	36.0	3.2	7	Cucumber
Location	CF	114°58′17″	36°48′42″	63.5	33.5	3.0	>30	Wheat
2	VF	114°58′17″	36°48′42″	57.4	39.2	3.4	9	Cauliflower
Location	CF	114°57′51″	36°47′50″	56.7	39.4	3.9	>30	Wheat
3	VF	114°57′51″	36°47′50″	67.0	30.3	2.8	10	Cauliflower
Shunyi								
Location	CF	116°42′45″	40°12′35″	65.3	32.3	2.5	>30	Wheat
1	VF	116°42′45″	40°12′35″	67.5	30.3	2.2	8	Cucumber
Location	CF	116°44′39″	40°14′1″	69.3	28.5	2.2	>30	Wheat
2	VF	116°44′39″	40°14′1″	70.5	27.4	2.1	6	watermelon
Location	CF	116°42′1″	40°04′35″	67.9	29.6	2.6	>30	Wheat
3	VF	116°42′1″	40°04′35″	82.2	16.5	1.3	13	Cucumber
Shouguang								
Location	CF	118°47′8″	36°59′27″	62.5	34.3	3.2	>30	Wheat
1	VF	118°47′8″	36°59′27″	60.5	36.0	3.5	8	Pepper
Location	CF	118°56′11″	36°53′43″	58.2	37.8	4.0	>30	Wheat
2	VF	118°56′11″	36°53′43″	63.3	32.9	3.8	11	Pepper
Location	CF	118°52′4″	36°56′19″	69.1	28.0	2.9	>30	Wheat
3	VF	118°52′4″	36°56′19″	73.9	23.5	2.6	11	Pepper

[a] Refer to grown crops in the season when soil samples were collected. Cucumber (*Cucumis sativus* L.), cauliflower (*Brassica oleracea* L.), pepper (*Capsicum annuum* L. var. *annuum*), waterlemon (*Citrullus lanatus*).

from Elliott (Elliott, 1986). Briefly, air-dried soil (80 g) was slaked with deionized water for 5 min. The slaked sample was passed through a series of two sieves (250 and 53 μm), and all fractions left on each sieve and the bottom pan were thoroughly rinsed and transferred to pre-weighed pans. Macroaggregate (M, >250 μm), microaggregate (m, 53–250 μm), and silt + clay (<53 μm) fractions were oven-dried overnight at 60 °C, weighed, and stored at room temperature for further analyses.

Coarse POM (cPOM, >250 μm), microaggregate (mM, 53–250 μm), and silt + clay SOM fractions held within macroaggregates were separated using a microaggregate isolator (Six et al., 2000). A subsample of the macroaggregate fraction (10 g) was dispersed in deionized water by gentle shaking with 50 glass beads (4 mm in diameter). Continuous and steady water flow through the isolator ensured that released microaggregates were immediately flushed from the 250-μm sieve onto a 53-μm sieve. All fractions were collected and dried at 60 °C.

The m and mM fractions were dispersed by shaking in 0.5% sodium hexametaphosphate solution for 18 h with 10 glass beads. The dispersed samples were thoroughly rinsed over a 53-μm sieve, and intra-aggregate POM (iPOM, 53–250 μm) and silt + clay fractions were transferred to pre-weighed pans and dried at 60 °C (see Fig. 2).

2.4. Soil chemical analysis

Inorganic C within the bulk soil and aggregates were removed using an HCl-fumigation method (Harris et al., 2001). Briefly, 20–30 mg soil samples were weighed in silver capsules, wetted with deionized water to approximately field capacity, and placed in a vacuum desiccator containing a beaker with concentrated (12 *M*) HCl to release carbonates as CO_2. After 4 h, the capsules were dried at 60 °C and then closed. Soil organic C and total N contents in the bulk soil were determined by a dry combustion method using a C/N Analyzer (Vario Macro, Elementar, Germany). Organic C and N contents in the aggregate size fractions were also measured with a C/N Analyzer (Carlo Erba, Milan, Italy). Soil texture was determined by the pipette method (Schlichting et al., 1995).

2.5. Calculations of SOC and TN stock and data analysis

Stocks of SOC and TN in the cereal soils and greenhouse vegetable soils were calculated by multiplying SOC and TN concentrations by bulk density and depth. The total stocks of SOC and TN in the 0–90 cm depth were the sum of SOC and TN of the 0–30, 30–60 and 60–90 cm depths.

The rate of C and N accumulations in the 0–30 cm depth in response to conversion from the cereal fields to greenhouse vegetable production was calculated using paired soil samples from the greenhouse vegetable soils and neighboring cereal soils in each area. Differences in soil C and N stocks between greenhouse vegetable soils and the cereal soils were computed and then divided by the duration (yr) after the land use conversion.

The least significant difference (LSD) analysis was performed for the data of paired-samples in SAS. Differences by land use type were evaluated at the 5% significance level.

3. Results

3.1. Soil organic carbon and total nitrogen concentrations of bulk soil

The concentrations of SOC and TN were compared between the cereal soils and greenhouse vegetable soils across three typical vegetable production areas (Table 3). In general, the average levels of SOC in the top 30 cm depth were similar across the cereal fields (7.5 g C kg^{-1} at Quzhou, 8.4 g C kg^{-1} at Shunyi and 7.5 g C kg^{-1} at Shouguang). Conversion from the cereal fields to greenhouse vegetable production led to an increase trends in topsoil SOC, by 42.3% on average across the areas. However, because of variation between the sites, a significant difference was observed only in Shouguang – the area with the most intensive management practices. The greenhouse vegetable soils in Shunyi had an average SOC concentration of 44% that was higher than the adjacent cereal fields, although this difference was not significant. Conversion from the cereal fields to greenhouses vegetable production also increased TN concentrations in the top 30 cm depth by 58.3% on average across the three

Table 3
Soil organic carbon (SOC) and total nitrogen (TN) concentrations, soil C:N ratio, bulk density (BD), pH, and C and N stocks in the 0–30 cm depth for greenhouse vegetable production (VF) and cereal fields (wheat–maize, CF) and C and N accumulation rates following conversion from cereal fields to vegetable greenhouse production in Quzhou, Shunyi and Shouguang, north China.

Land use	SOC (g C kg^{-1})	TN (g N kg^{-1})	C:N	BD (g cm^{-3})	pH	C stock (Mg C ha^{-1})	N stock (Mg N ha^{-1})	C accumulation rate (Mg C ha^{-1} yr^{-1})	N accumulation Rate (Mg N ha^{-1} yr^{-1})
Quzhou ($n=3$)									
CF	7.54a[a]	0.93a	8.36a	1.44a	8.27a	32.6a	4.0a	0.19	0.014
VF	8.26a	1.0 a	8.27a	1.38a	8.04a	34.2a	4.1a		
Shunyi ($n=3$)									
CF	8.39a	0.82b	10.28a	1.53a	8.14a	38.5b	3.8b	1.68	0.26
VF	12.08a	1.37a	9.39b	1.48b	7.61b	53.6a	6.1a		
Shouguang ($n=3$)									
CF	7.51b	0.78b	9.62a	1.55a	8.13a	34.9b	3.6b	2.25	0.36
VF	12.93a	1.62a	8.22b	1.48b	6.86b	57.4a	7.2a		
Average									
CF	7.81b	0.84b	9.42a		8.18a	35.3b	3.5b	1.37	0.21
VF	11.09a	1.33a	8.49a		7.50b	48.4a	5.8a		

[a]Mean values followed by the same letters in the same column at each location indicate no significant difference between the cereal soils and greenhouse vegetable soils at the 5% significance level.

study areas. Significant differences between the cereal soils and greenhouse vegetable soils were observed in Shunyi (0.8 g N kg^{-1} in the former vs. 1.4 g N kg^{-1} in the latter) and Shouguang (0.8 g N kg^{-1} vs. 1.6 g N kg^{-1}). In general, concentrations of SOC and TN in both cereal soils and greenhouse vegetable soils decreased with increasing soil depths. No significant differences were found between the cereal soils and greenhouse vegetable soils below 30 cm depths in the soil profile with the exception of SOC at the 60–90 cm depth in Shouguang (data not shown).

The average C:N ratio in the top soils tended to decrease upon conversion from the cereal fields to greenhouse vegetable production (Table 3). However, a significant decrease in soil C:N ratio following land use conversion was found in Shouguang (19.5%) and Shunyi (12.7%), where represent high and intermediate management intensity, respectively. Conversion from the cereal fields to greenhouse vegetable production decreased soil bulk density and pH in the top 30 cm depth in Shunyi and Shouguang.

3.2. Total organic carbon and nitrogen stocks in soil profile

Both SOC and TN stocks to a depth of 90 cm in the soil profiles were quite similar between the cereal soils (69.5 Mg C ha^{-1} and 8.3 Mg N ha^{-1}) and greenhouse vegetable soils (68.9 Mg C ha^{-1} and 8.2 Mg N ha^{-1}) in Quzhou (Fig. 3). In contrast, the land use conversion led to increased soil C and N stocks in the 0–90 cm depth in Shunyi and Shouguang. Specifically, the increases in SOC and TN stocks mostly occurred in the top 30 cm of the soil profile by 39% and 61% in Shunyi and 64% and 99% in Shouguang, respectively (Table 3). The SOC and TN accumulation rates in the top 30 cm depth following the land use conversion increased in the order of Quzhou < Shunyi < Shouguang (Table 3). Average SOC and TN accumulation rates following conversion from GF to VF across the three areas were 1.37 Mg C ha^{-1} yr^{-1} and 0.21 Mg N ha^{-1} yr^{-1} over the period of average 8 years.

3.3. Carbon and nitrogen in water-stable aggregates

Aggregate C and N concentrations of the top soils generally decreased in the following order: microaggregates (53–250 μm) > macroaggregates (>250 μm) > silt + clay (<53 μm) (Table 4). No significant differences in aggregate size distribution were found between the cereal and greenhouse vegetable soils (data not shown). However, the land use conversion significantly increased C and N in microaggregates and macroaggregates. The C:N ratios of all aggregate fractions were significantly lower in the greenhouse vegetable soils than in the cereal soils.

3.4. Carbon and nitrogen in intra-aggregate POM and total silt + clay fractions

The average weight distribution of the total silt + clay fractions was 74.2% of the weight of the bulk soil, followed by the fine (19.5%) and coarse iPOM fractions (6.2%) (Fig. 4). The total silt + clay fraction contained the most C and N in both cropping systems (Fig. 5A and B). The coarse and fine iPOM fractions had higher C concentrations in the vegetable soils than the corresponding cereal fields, while no differences were found in the C concentrations associated with the total silt + clay fractions between the cereal and greenhouse vegetable soils (Fig. 5A). The coarse and fine iPOM fractions contributed by 49% and 51% to the total increases in C content in the vegetable soils compared with the cereal soils, respectively. In comparison, the land use conversion increased N concentrations

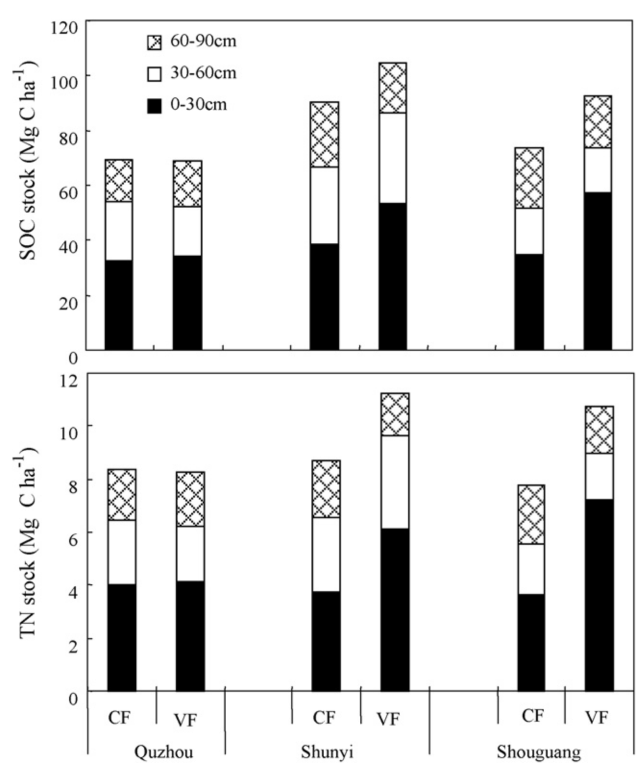

Fig. 3. Soil organic carbon (SOC) and total nitrogen (TN) stocks in the soil profile (0–90 cm) for the cereal soils (wheat–maize, CF) and greenhouse vegetable soils (VF) in Shouguang, Shunyi and Quzhou, north China.

Table 4
Mean soil organic carbon (SOC) and total nitrogen (TN) concentrations, and soil C:N ratio of three water-stable aggregates (macroaggregates, >250 μm; microaggregates, 53–250 μm; and silt + clay, <53 μm) for the greenhouse vegetable production (VF) and cereal fields (wheat–maize, CF) of Shouguang and Shunyi, north China (n = 6).

Land use	Macroaggregates (>250 μm)			Microaggregates (53–250 μm)			Slit + clay (<53 μm)		
	SOC (g C kg^{-1})	TN (g N kg^{-1})	C:N	SOC (g C kg^{-1})	TN (g N kg^{-1})	C:N	SOC (g C kg^{-1})	TN (g N kg^{-1})	C:N
CF	2.54b[a]	0.22b	11.49a	5.58b	0.55b	10.24a	2.53a	0.27a	8.48a
VF	6.14a	0.58a	10.61b	8.77a	0.95a	9.17b	2.46a	0.33a	7.39b

[a] Mean values followed by the same letters in the same column indicate no significant difference in soil properties between the cereal soils and greenhouse vegetable soils at the 5% significance level.

in all the fractions (Fig. 5B). The coarse and fine iPOM, and total silt + clay fractions accounted for 22%, 30% and 48% of the total increases in TN, respectively. The soil C:N ratios of these fractions decreased in the sequence of coarse iPOM > fine iPOM > total silt + clay. In addition, the C:N ratios in the iPOM and total silt + clay fractions were consistently lower in the greenhouse vegetable soils than in the corresponding fractions in the cereal soils (Fig. 5C).

4. Discussion

4.1. Soil organic carbon and total nitrogen of bulk soil

The impacts of agricultural management practices on SOC changes are well documented. There are complex interactions of combined management practices (e.g. tillage, fertilization, change in plant species composition and inputs of organic residues) that affect SOC dynamics in terms of its quantity and quality. Nevertheless, a reduction in soil disturbance and the incorporation of organic materials or manures tend to increase SOC stocks (West and Wilfred, 2002; Huang and Sun, 2006; Triberti et al., 2008). Based on the paired comparisons between the greenhouse vegetable soils and cereal soils, soil C and N accumulation rates in the top 30 cm depth were estimated to be 1.37 Mg C ha^{-1} yr^{-1} and 0.21 Mg N ha^{-1} yr^{-1} over an average period of 8 years (Table 3). This suggests that the land use conversion from the cereal fields to greenhouse vegetable production could increase in SOC and TN concentrations and stocks. Huang and Sun (2006) estimated that C accumulation rates in the topsoil (average 0–20 cm) in Chinese croplands ranged from 2.64 Mg C ha^{-1} to 3.40 t C ha^{-1} since the 1980s. However, these studies did not include vegetable fields that may result in substantial C and N accumulation in the soil and the estimates may have been significantly underestimated the rates.

The amounts of residue input are usually lower under vegetables than under cereal production (Kuzyakov et al., 2002), as most of the residues are usually removed after harvest of vegetables (Table 1). Thus, higher SOC accumulation in the greenhouse vegetable production than cereal fields may be attributed mainly to the higher inputs of C from manure additions. Under greenhouse vegetable production compared to the cereal fields, increased tillage intensity was expected to decrease the overall stabilization of C in SOM fractions, particularly labile iPOM fractions (Six et al., 1999), but we found that C associated with the coarse and fine iPOM

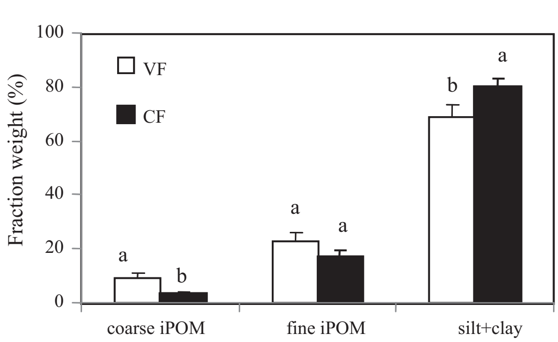

Fig. 4. Mean weight percentages of total coarse (>250 μm) intra-aggregate particulate organic matter (iPOM), total fine (53–250 μm) iPOM, and total (<53 μm) silt + clay fractions in cereal soils (wheat–maize, CF) and greenhouse vegetable soils (VF) in Shouguang and Shunyi, north China (n = 6). Values with the same letters are not significantly different between CF and VF at the 5% significance level. Error bars represent standard deviations.

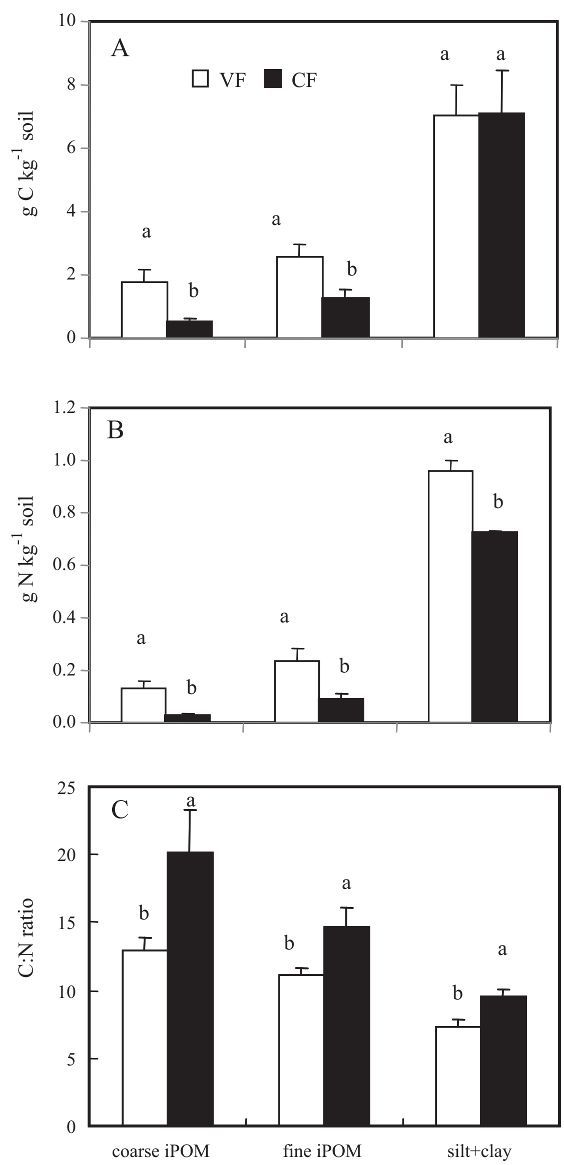

Fig. 5. Mean C, N contents and C:N ratios of total coarse (>250 μm) intra-aggregate particulate organic matter (iPOM), total fine (53–250 μm) iPOM, and total (<53 μm) silt + clay fractions between the cereal soils (wheat–maize, CF) and greenhouse vegetable soils (VF) in Shouguang and Shunyi, north China (n = 6). For each aggregate fraction, values with the same letters are not significantly different between CF and VF at the 5% significance level. Error bars represent standard deviations.

fractions increased. This suggests that the higher manure C input must have offset the negative effects of increased tillage intensity on SOC levels in the greenhouse vegetable systems.

Specifically, the significant build-up in SOC and TN in the 0–30 cm depth after the land use conversion was observed in Shouguang and Shunyi where have received the highest and intermediate levels of manure inputs (Table 3 and Fig. 3). This further supports that the manure application is more effectively increasing SOC stocks rather than the incorporation of crop residues alone. For example, the amounts of C input were similar between the cereal fields and greenhouse vegetable production in Shunyi (6866 kg C ha^{-1} ya^{-1} vs. 6584 kg C ha^{-1} ya^{-1}, Table 1), but the vegetable greenhouse soils had higher SOC stocks. Our results also suggest that C stocks in most crop lands such as cereal fields can potentially increase in the short-time through manure additions in north China where most of them still have low soil fertility and productivity, where manure are being applied even overuse now for the production of vegetable rather than cereal.

In general, agricultural use of soils reduces the soil C:N ratio (Duxbury et al., 1989; Kaffka and Koepf, 1989). For example, the conversion of forest to agricultural land led to a decrease in the average soil C:N ratio, with the underlying explanation that crop residues and its microbial decomposers have lower C:N ratios (Zheng et al., 1999), and consequently lead to a greater loss of C than N (Murty et al., 2002). We found that the soil C:N ratios significantly decreased under greenhouse vegetable production in the areas of high and intermediate management intensity as compared to the cereal fields (Table 3). This suggests that increasing management intensity in agriculture, especially with larger N inputs from fertilizer or manure application, could lead to a faster increase in soil N than C, resulting in lower soil C:N ratios. For example, after the cereal fields were converted to greenhouse vegetable production in Shouguang the N inputs increased 4.9 times on average (i.e., 444 kg N ha^{-1} yr^{-1} in the cereal fields versus 2178 kg N ha^{-1} yr^{-1} in the vegetable greenhouse production), while the amount of C inputs increased 1.4 times only (i.e., 6866 kg C ha^{-1} yr^{-1} in cereal fields versus 9548 kg C ha^{-1} yr^{-1} in greenhouse vegetable production). Furthermore, increased tillage operations in the vegetable systems leading to enhanced decomposition rates of added organic materials and SOM may contribute to the decline in soil C:N ratios. Carbon is released during respiration and some of the mineralized N is lost through leaching or gaseous emissions while some is reincorporated into the SOM pool(s) (Chapin et al., 2002).

The decline in C:N ratio, however, may not necessarily indicate increased plant N availability because the 48% increase in TN following the conversion from the cereal fields to greenhouse vegetable production is associated with the total silt + clay fraction (Fig. 5). Other studies have suggested that soils with lower soil C:N ratios are prone to greater N losses through leaching (Dise et al., 1998; Gundersen et al., 1998; Thomsen et al., 2008). Therefore, the excessive rate of N fertilizer application to vegetable crops in many situations, leading to more residual unused nitrate in VF has been main direct reason for nitrate leaching, which has become a major environmental concern (Ju et al., 2006; Yu et al., 2007; Shi et al., 2009; Zhou et al., 2010). The lower soil C:N may partially be responsible for higher nitrate leaching in vegetable production systems in China.

Changes in land use type or management practices may affect subsoil C (Guo and Gifford, 2002; Follett et al., 2009). However, we did not find any significant difference in SOC and TN stocks between the cereal soils and greenhouse vegetable soils in the 30–60 and 60–90 cm depths (Fig. 3). This suggests that the intensive soil management of the greenhouse vegetable production had no effect on SOC and TN in the subsoil within the relatively short period after the land use conversion (6–13 years).

4.2. Carbon and nitrogen in intra-aggregate POM and total silt + clay fractions

Changes in C and N following the land use conversion differed between the aggregate fractions. Among the fractions, the largest proportion of the soil mass and C were found in the total silt + clay fractions (Fig. 4), but no significant SOC difference were found between the cereal soils and greenhouse vegetable soils in the total silt + clay fraction (Fig. 5A). The C contents of iPOM fractions (the sum of the coarse and fine iPOM fractions) were, however, greater in the greenhouse vegetable soils than cereal soils. This showed that the C associated with the iPOM fractions was highly sensitive to the land use conversion. Since the coarse iPOM consists of partially decomposed plant materials around which macroaggregates are formed (Six et al., 2000), the increased manure-C input probably led to the relatively largest C increase in the coarse iPOM fraction among the fractions. Gulde et al. (2008) showed a similar response of coarse iPOM to increased manure additions. The fine iPOM represents a SOM fraction stabilized in the mM fraction (Six et al., 2000), and can serve as an early indicator of C sequestration (Six et al., 2002; Denef et al., 2007). In this study, C changes in the fine iPOM fraction tended to be less sensitive to the land use conversion than those in the coarse iPOM fraction but contributed to 51% of the total increases in SOC and therefore indicates the potential of long-term stabilization by manure additions.

Compared to the C changes in the aggregate fractions, N stocks increased in all the fractions following the land use conversion (Fig. 5B). The coarse and fine iPOM, and total silt + clay fractions contributed to 22%, 30% and 48% of the total increases in N, respectively. Therefore, both the fine iPOM and silt + clay fractions may play an important role in retaining added N in these highly intensively managed arable soils. The increases in N associated with the total silt + clay fraction in the greenhouse vegetable soils may be partially due to the stable sorption of N-containing compounds (e.g., amines, amides, and pyrroles) directly to mineral surfaces (Sollins et al., 2006). In particular, soil organic N typically occurs as proteins (Schulten and Schnitzer, 1997; Schmidt-Rohr et al., 2004), and its significant portion may be in the form of heterocyclic N (Kuzyakov, 1997; Mertz et al., 2005; Smernik and Baldock, 2005). Similarly, in a long-term experiment with ^{15}N-labeled cover crop residues and synthetic fertilizer, Kong et al. (2007) found that the majority of stabilized synthetic fertilizer-derived ^{15}N was associated with the silt + clay fraction. Consequently, relative differences in N associated with the relatively labile iPOM fractions generally followed similar patterns as the C differences, but the differences in N in the silt + clay fraction were significant between the vegetable greenhouse and cereal fields, while the C in the same fraction did not change by the land use conversion. Possibly, C vs. N changes in the slower turning over SOM fractions were determined by different stabilization mechanisms (i.e. organo-mineral complex formation versus simply sorption), hence leading to soil C—N decoupling. Therefore, highly intensive management practices in terms of C and N inputs and tillage frequency do affect the relative contributions of different SOM fractions, such as iPOM and total silt + clay, to the retention of C versus N.

5. Conclusions

Our results showed that a significant shift in land use from the cereal fields to greenhouse vegetable production in China's agriculture increased SOC and TN concentrations and stocks, especially in those areas with high management intensity in terms of C and N inputs and tillage frequencies. In addition, we showed that C and N stabilization occurred simultaneously in the labile fractions but a decoupling of C and N stabilization seems to occur within the slower turning over silt + clay fraction. Despite the increases in SOC and TN, serious environmental consequences such as acidification, nutrient enrichment in the soils and N loss through N_2O emissions and NO_3^- leaching are also apparent in the vegetable production systems (Zheng et al., 2004; Ju et al., 2006; Yu et al., 2007; Guo et al., 2010; Zhou et al., 2010). Therefore, optimizing management strategies, which may be specific for soil C and N management has become one of the most urgent requirements for more sustainable vegetable production in north China.

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