Soil & Tillage Research 107 (2010) 80–87

Contents lists available at ScienceDirect

Soil & Tillage Research

journal homepage: www.elsevier.com/locate/still

Changes in soil carbon and nitrogen pools after shifting from conventional cereal to greenhouse vegetable production

S.J. Qiu [a,b], X.T. Ju [a,*], J. Ingwersen [b], Z.C. Qin [a], L. Li [c], T. Streck [b], P. Christie [a,d], F.S. Zhang [a]

[a] Key Laboratory of Plant Nutrition, Ministry of Agriculture, College of Resources and Environmental Sciences, China Agricultural University, Beijing 100193, China
[b] Institute of Soil Science and Land Evaluation, University of Hohenheim, Stuttgart 70593, Germany
[c] Shandong Province Key Laboratory of Eco-Environmental Science for Yellow River Delta, Binzhou University, Binzhou 256603, China
[d] Agri-Environment Branch, Agri-Food and Biosciences Institute, Belfast BT9 5PX, UK

ARTICLE INFO

Article history:
Received 8 July 2009
Received in revised form 25 November 2009
Accepted 20 February 2010

Keywords:
Carbon pools
Nitrogen pools
Natural isotopic signatures
SOC/TN ratio
Conventional cereal production
Greenhouse vegetable production

ABSTRACT

In recent years large areas of conventional cereal production in China have been transferred to greenhouse production with huge excessive nitrogen (N) fertilizer application and massive irrigation. However, the effects of this change in land use on soil carbon and nitrogen pools remain to be explored. Here we report a comparative study in which paired soil samples were taken from four greenhouses and from adjacent conventional cereal fields. Soil organic carbon (SOC), carbonate carbon (IC), total nitrogen (TN) and mineral nitrogen (N_{min}) to 100 cm depth and the soil active organic pools, including particulate organic matter (POM), soil microbial biomass (SMB) and dissolved organic matter (DOM), to 0–40 cm depth were determined. The natural isotopic signatures of SOC, TN and POM were also analyzed. In both production systems all of the carbon and nitrogen pools in the surface soil (0–10 cm) were greater than deeper in the soil profile except for dissolved organic nitrogen (DON) and NH_4-N. SOC and TN and dissolved organic carbon (DOC) concentrations were higher in the greenhouse system than in conventional cereal soils ($P > 0.05$). A similar trend was found for POM ($P < 0.05$) and NO_3-N ($P < 0.05$, below 20 cm depth) pools but the opposite trend was found for soil IC, soil microbial biomass carbon (SMBC) and nitrogen (SMBN) ($P > 0.05$) and IC in the greenhouse system showed a dramatic decline. The SOC/TN ratios of different pools in the greenhouse soils were lower than in the conventional cereal system ($P > 0.05$). The SOC/TN ratio ranged from 8.4 to 10.0 in greenhouse soils and 8.5 to 11.7 in the cereal soils. At each depth POM content in the greenhouses (1.5–7.1 g kg^{-1}) was significantly greater than that in the field soils (0.8–2.9 g kg^{-1}) ($P < 0.05$). Application of large amounts of manure increased SOC stocks, but the total carbon stock (SOC plus IC) was lower in the greenhouse system by tradeoff effect on declining IC in this calcareous soil due to soil acidification induced by excessive N fertilization plus massive irrigation. The higher nitrate concentrations found due to massive N fertilization combined with large amounts of irrigation water represent a considerable threat to groundwater quality and may be harmful to local residents.

1. Introduction

Soils play an important role in the global carbon (C) and nitrogen (N) cycles. The amount of C stored in soils is about twice that stored in the atmosphere (Davidson et al., 2000). The functioning of soils as a C sink or source has moved into the focus of research within the scope of the scientific debate on global climate change (Lal et al., 1995; Schlesinger and Lichter, 2001; Huang and Sun, 2005; Knorr et al., 2005). Storage of soil organic carbon (SOC) and carbonate carbon (IC) in agricultural land can be influenced by management practices such as tillage, fertilizer N inputs and crop rotations (Halvorson et al., 2002; Russell et al., 2005). Optimizing fertilizer N inputs, for instance, may increase SOC content by increasing crop yields and hence the amount of residues returned to soils (Janzen et al., 1998; Halvorson et al., 1999; Huang and Sun, 2005). Excessive fertilizer N may block SOC sequestration through suppression of the microbial population or stimulation of mineralization of old native organic C (McCarty and Meisinger, 1997). Indeed, long-term over-use of fertilizer N in agricultural systems has resulted in substantial nitrate leaching (Ju et al., 2007) and soil carbonate has become depleted (Barak et al., 1997) as a result of soil acidification (Barak et al., 1997; Malhi et al., 1998; Ju et al., 2007). Hence, changes in SOC and carbonate content with N fertilization can affect soil C stability and soil SOC/TN ratio.

The natural abundance of stable isotopes can been used as a measure to reflect soil C and N cycling and storage (Clapp et al.,

* Corresponding author. Tel.: +86 10 62733459; fax: +86 10 62731016.
E-mail address: juxt@cau.edu.cn (X.T. Ju).

0167-1987/$ – see front matter
doi:10.1016/j.still.2010.02.006

2000; Lynch et al., 2006; Watzka et al., 2006). Differences in plant $\delta^{13}C$ can be attributed to differences in photosynthesis between C_3 and C_4 plants (Clapp et al., 2000; Lynch et al., 2006) and differences in soil $\delta^{15}N$ can result from discrimination against ^{15}N during N loss processes (Lynch et al., 2006; Watzka et al., 2006). Values of $\delta^{13}C$ of C_3 plants range between −23 and −30‰ and of C_4 plants from −9 to −17‰ (Mariotti and Peterschmitt, 1994; Lynch et al., 2006). Similarly, the $\delta^{15}N$ of chemical N fertilizers range between −3 and 2‰ and that of composted manure is larger than 8% (Choi et al., 2003). It is therefore possible to quantify changes in soil C and N pools after long-term changes in crop species and fertilizer regimes.

Soil organic matter (SOM) can be differentiated into active and passive pools. The active SOM fractions respond very sensitively to management practices and affect nutrient (including N) supply (Mrabet et al., 2001; Wander, 2004). The character of the active SOM can be denoted by particulate organic matter (POM), soil microbial biomass C and N and dissolved organic matter (DOM) because these pools bring together the physical, biological and chemical functions of SOM (Wander, 2004). POM is regarded as a nucleus for aggregates (Bongiovanni and Lobartini, 2006; Marriott and Wander, 2006a,b) and represents a substantial fraction of the fresh plant residues or those at various stages of decomposition (Lehmann et al., 2001). Soil microorganisms are the drivers of SOM turnover and soil microbial biomass (SMB) is the source and sink of nutrients (Perelo and Munch, 2005; Perelo et al., 2006). On one hand, microorganisms make full use of the energy provided by C sources to increase N immobilization (Zogg et al., 2000; Perelo et al., 2006) and on the other hand microbial decomposition and C turnover can also be activated by increasing N availability (Körner and Arnone, 1992; Hu et al., 2001). DOM is mainly derived from root excretion, plant debris, and living and dead microorganisms (Kalbitz et al., 2000; Park et al., 2002) and is greatly influenced by C or N addition (Park et al., 2002; Sinsabaugh et al., 2004) because microorganisms are able to assimilate DOM. In addition, POM provides a C source for microorganisms (Christensen, 2001; Marriott and Wander, 2006a,b) and may attach to microbial tissues (Mendham et al., 2004). There is thus a close connection among POM, SMB and DOM.

Greenhouse vegetable production has played an important role in increasing farming incomes during the last two decades. Accordingly, many farmers have shifted from conventional cereal cropping to greenhouse production systems. In Shouguang county, Shandong province, more than 65% of the arable land is now used for intensive greenhouse production, with 2220 kg fertilizer N ha^{-1} and 1800 mm irrigation water per year applied for some crops (He et al., 2007). However, the effects of these excessive N application rates and massive irrigation on the C and N pools of the local soils, which are low in SOC, have not yet been determined. The present study was conducted to investigate changes in different soil C and N pools and their $\delta^{13}C$ and $\delta^{15}N$ signatures in greenhouse vegetable production compared with conventional cereal soils, to examine the stocks of C and N in the soil profile some years after the shift to greenhouse production, and to elucidate how soil management controls these changes.

2. Materials and methods

2.1. Site description

Shouguang county is located in Shandong province at 36°41′–37°19′N, 118°32′–119°10′E and has a typical continental monsoon climate. Annual average air temperature and precipitation (1993–2003) are 12.4 °C and 558 mm. Conventional maize/wheat rotations have been practiced since 1978 and greenhouse vegetable production has developed rapidly in place of the cereal rotation since the 1990s. In conventional cereal systems summer maize and winter wheat are sown in the middle of June and the beginning of October of the same year and there are two fertilizer applications for each crop. Irrigation is combined with fertilizer N application during the wheat season but little irrigation is applied during the summer because there is sufficient rainfall. The wheat straw is returned to the soil under no-tillage conditions and the maize straw is harvested for silage. In greenhouse vegetable systems, from October to June of the next year double or triple cropping is practiced with up to 13 irrigation events and 7 fertilizer applications followed by a fallow period until October (Table 1).

2.2. Soil sampling

Paired soil samples were taken from four greenhouses and adjacent conventional cereal fields at the end of April 2007 for direct comparison of the two production systems (Table 1). Two pairs of samples were collected from Yingli village (118°48′N, 37°03′E) and the other two from Tianliu village (118°47′N, 36°59′E). The sampling distance between each greenhouse and the adjacent field was <50 m and was >200 m between greenhouses at each site. Samples were composites of at least 8 soil cores in each field of approximately 400 m^2 area. The 100 cm deep sample cores were divided into 0–10, 10–20, 20–40, 40–60, 60–80, 80–100 cm depth increments. A 100 cm deep soil profile under conventional cereals was selected at each village for the measurement of soil bulk density. As soil depth increased, soil bulk density was 1.42, 1.45, 1.47, 1.45, 1.43, 1.43 g cm^{-3} at the Yingli site and 1.48, 1.50, 1.46, 1.42, 1.41, 1.50 g cm^{-3} at Tianliu. Samples were passed through a 2 mm sieve and a portion of each sieved sample was stored at 4 °C for subsequent analysis for mineral nitrogen (N_{min}), SMBC, SMBN and DOM, and the remaining portion was air-dried for analysis of SOC, TN, IC and POM. The content and natural abundance of SOC and TN, and the content of

Table 1
Farm management, crop yields and pH distribution in the soil profiles of the sampling sites.

Cropping system[a]	Site	Year started	Crop rotation	Fertilizer/manure[b] (kg N ha^{-1} yr^{-1})	Irrigation[b] (mm yr^{-1})	Yield[b] (t ha^{-1} yr^{-1})	pH at different depths (cm) in the soil profile					
							0–10	10–20	20–40	40–60	60–80	80–100
G1[c]	Yingli	1996	Tomato/cucumber	1634/1300	1400–1700	171.0	7.71	7.87	8.07	8.13	8.05	8.14
C1	Yingli	1978	Maize/wheat	600/0	<300	16.5	7.97	8.15	8.22	8.28	8.51	8.55
G2	Yingli	1996	Tomato/cucumber	1572/1246	1500–1700	175.6	7.38	7.67	8.20	8.17	8.15	8.11
C2	Yingli	1978	Maize/wheat	600/0	<300	17.0	7.84	7.97	8.18	8.22	8.23	8.35
G3	Tianliu	1993	Tomato/cowpea	1829/1318	1300–1700	168.4	5.59	5.53	5.58	7.21	7.31	7.60
C3	Tianliu	1978	Maize/wheat	500/100	<300	18.0	7.89	8.22	8.30	8.22	8.02	8.02
G4	Tianliu	1993	Tomato/sweet pepper	1620/1866	1400–1600	150.0	6.87	6.90	7.26	7.45	7.56	7.56
C4	Tianliu	1978	Maize/wheat	500/100	<300	18.0	7.89	7.99	8.11	8.24	7.96	7.83

[a] G, greenhouse system; C, conventional cereal system.
[b] Data acquisition: April 2007.
[c] Yield in greenhouse system refers to fresh weight and that in conventional cereal system to air-dried weight.

N_{min}, IC and soil bulk density were determined at each depth increment and the content and natural abundance of POM, and the content of SMBC, SMBN and DOM were determined in 0–10, 10–20 and 20–40 cm depth categories.

2.3. Measurements

Soil samples for SOC analysis were soaked for 24 h in excess 0.3 mol L^{-1} HCl solution to remove calcium carbonate ($CaCO_3$). The wet soil was cleaned with deionized water until the solution pH was above 6 and oven-dried at 60 °C. POM was determined as described by Bronson et al. (2004). Briefly, 25 g air-dried soil was dispersed in 100 ml of sodium hexametaphosphate solution (5 g L^{-1}) for 1 h on a reciprocal shaker and the suspension was washed over a 53 μm sieve until the rinsing water was clear. The remaining material (except for visible stones and roots on the sieve) was oven-dried in a beaker at 60 °C. TN, SOC, POM-C and POM-N of soil passed through a 0.15 mm mesh were determined with a CN analyzer (Vario Max CN, Elementar, Germany). Their $\delta^{13}C$ and $\delta^{15}N$ were determined with a mass spectrometer (Delta Plus XP, Thermo Finnigan, Germany). $\delta^{13}C$ values were expressed relative to Pee Dee Belemnite and $\delta^{15}N$ to atmospheric N_2 for N in terms of ‰ value according to the equation:

$$\delta X\,(‰) = 1000 \times \left(\frac{R_{\text{sample}}}{R_{\text{standard}}} - 1\right)$$

where X is ^{13}C or ^{15}N and R is the molar ratio of the $^{13}C/^{12}C$ or $^{15}N/^{14}N$ working standard defined as 0.011237 or 0, respectively.

Mineral N was extracted with 1 mol L^{-1} KCl at a soil:water ratio of 1:5 (w/v) and measured with a continuous flow analyzer (TRAACS 2000, Bran and Luebbe, Germany). SMBC and SMBN were determined by the $CHCl_3$ fumigation-extraction (FE) method (Brookes et al., 1985). The C in fumigated and unfumigated samples in 0.5 M K_2SO_4 solution (1:4, w/v) were determined with a TOC analyzer (Phoenix 8000, Tekmar, USA), and their N contents were determined by continuous flow analyzer (FIA Star 5000, Foss, Sweden) following Kjeldahl digestion. SMBC and SMBN were calculated as: SMBC or SMBN = (total C or N in fumigated extracts−total C or N in unfumigated extracts)/K_E, where K_E = 0.45 (Wu et al., 1990; Jenkinson, 1988). DOC was the amount of TOC in the unfumigated extract (Cookson et al., 2007; Ghani et al., 2007) and DON was the difference between N and NH_4-N in unfumigated extracts (Cookson et al., 2007; Ghani et al., 2007). Soil carbonate C was determined by the pressure calcimeter method (Loeppert and Suarez, 1996). Soil pH was measured by electrode using a soil:water ratio of 1:2.5. Soil bulk density was calculated using dry weights and the volumes of soil sampled.

2.4. Statistical analysis

Data are expressed on oven-dried soil basis. Statistical analysis was performed using the SPSS 11.0 for Windows software package. Student's *t*-test was used to assess differences at the 5% level between greenhouse and conventional cereal systems. Data are reported as mean ± one standard error of the mean (SEM).

3. Results

3.1. SOC and TN and their natural abundance

In both greenhouse soil and cereal soil profiles, SOC and TN decreased in the surface soil above 40 cm depth. Below 40 cm only little change was observed (Fig. 1a and b). In the profile of the greenhouse soils, for example, the SOC content declined from 1.4% in the 0–10 cm layer to 0.5% at 80–100 cm depth. The concentrations of SOC and TN in the greenhouse soils tended to be higher than in the cereal soils (Fig. 1a and b). Due to the large variation between the two sites, however, statistically significant differences between the two production systems were only found in SOC in the 20–40 and 40–60 cm layers and in TN in the 10–20 cm layer ($P < 0.05$). In both production systems the SOC/TN ratio increased with soil depth and was slightly higher in the conventional cereal system than in the greenhouse production system (Fig. 1c). In the greenhouse soil profiles the SOC/TN ratio ranged between 8.4 and 10.0 and in the cereal system between 8.5 and 11.7. Similarly, because of the high variability between replicates, differences in SOC/TN ratio between the two production systems were not significant at the 5% level.

$\delta^{13}C$ of SOC and $\delta^{15}N$ of TN increased with soil depth above 40 cm depth (Fig. 1d and e) with little change below 40 cm. The differences in both $\delta^{13}C$ and $\delta^{15}N$ between the two production systems were largest in topsoil but were not significant ($P > 0.05$). A similar trend was found in $\delta^{13}C/\delta^{15}N$ ratio (Fig. 1f). $\delta^{13}C$ ranged from −17.8 to –20.9% in the greenhouse soil profiles and from −17.9 to –21.9‰ in the cereal rotations (Fig. 1d). Similarly, $\delta^{15}N$ varied between 6.3 and 6.9% in the greenhouses and 5.6 and 7.2‰ in the cereal soils (Fig. 1e).

3.2. Storage of SOC, IC, total carbon (TC) and TN

The storage of TC in the greenhouse soils was less than in the conventional cereal system except for the 4th pair of samples because of the distinct difference in IC content between the Yingli and Tianliu sites (Table 2). IC showed a dramatic decline in the greenhouse system. At site G4, for example, more than 78% of the former IC had been lost by acidification. Over the four pairs of samples the SOC summed up over the whole profile was significantly different between the two production systems ($P < 0.05$; greenhouses: 101.0 ± 9.9 t C ha^{-1}; cereals: 83.0 ± 9.8 t C ha^{-1}). No significant difference in TN was observed between the production systems ($P > 0.05$; greenhouses: 11.6 ± 2.4 t N ha^{-1}; cereal rotation: 8.5 ± 1.2 t N ha^{-1}).

3.3. N_{min}

The concentration of NO_3-N in the greenhouse soil was much higher than in the conventional system and the difference was significant below 20 cm soil depth ($P < 0.05$; Fig. 2a). The concentration of NO_3-N in the greenhouse system ranged from 51.9 to 130.8 mg kg^{-1}, and that in the cereal system varied between 6.0 and 110.7 mg kg^{-1}. NO_3-N summed up over the whole profile in the greenhouse and conventional cereal systems was 933 ± 265 and 339 ± 192 kg N ha^{-1}, respectively. The concentration of NH_4-N was very low in all soil profiles. The NH_4-N concentration ranged from 0.9 to 2.2 mg kg^{-1} and no significant differences were observed between the two systems ($P > 0.05$; Fig. 2 b).

3.4. Active C and N pools

POM-C, POM-N, POM-C/SOC and POM-N/TN in the top 40 cm of the soil profile were significantly higher in the greenhouse soils than the cereal soils and decreased with soil depth in both production systems ($P < 0.05$; Table 3). POM-C expressed as a percentage of SOC in the greenhouse system ranged between 24.3 and 52.4% and in the conventional system between 16.0 and 27.2%. Similarly, POM-N as a percentage of TN ranged from 14.0 to 31.7% and from 8.3 to 14.6%, respectively. The POM-C/POM-N ratio in the cereal system tended to be higher than in the greenhouses (18.6 versus 13.5) but the difference between production systems was not significant ($P > 0.05$). Although $\delta^{13}C$ of POM-C did not differ significantly between the two systems, $\delta^{15}N$ of POM-N and $\delta^{13}C$/

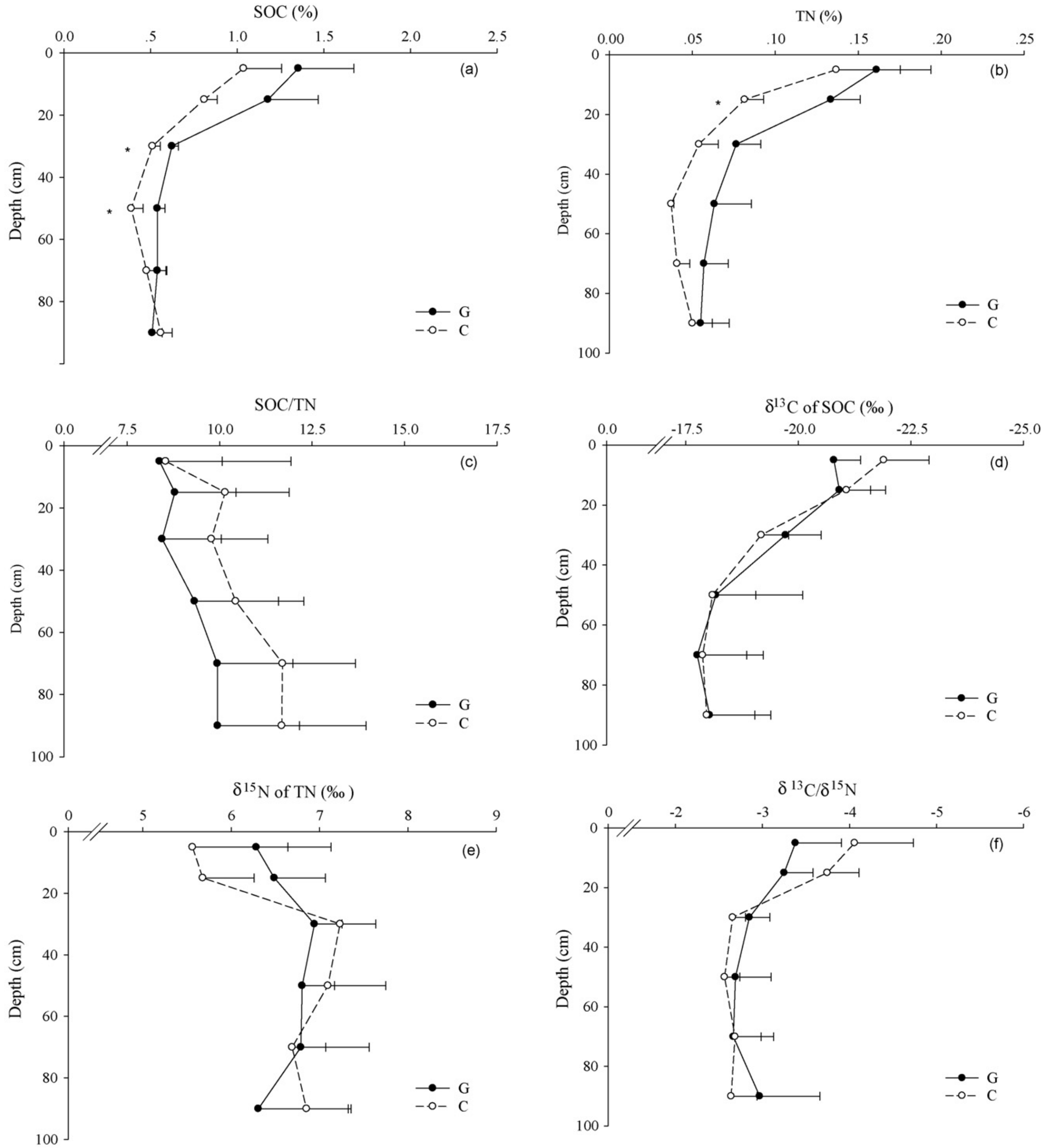

Fig. 1. Soil organic carbon (SOC) and total nitrogen (TN) content, C/N ratio of soil organic matter, and the respective $\delta^{13}C$ and $\delta^{15}N$ abundances in the soil profiles of greenhouse (G) and a conventional (C) production systems. Values at each depth are the means of four replicates. An asterisk represents a significant difference ($P < 0.05$) between greenhouse and conventional production systems.

Table 2
Storage of soil organic carbon (SOC), soil inorganic carbon (IC), total carbon (TC) and total nitrogen (TN) in the soil profile (0–100 cm) of greenhouse (G) and conventional cereal (C) production systems.

Site	SOC (t C ha^{-1})		ΔSOC (t C ha^{-1} yr^{-1})	IC (t C ha^{-1})		ΔIC (t C ha^{-1} yr^{-1})	TC (t C ha^{-1})		ΔTC (t C ha^{-1} yr^{-1})	TN (t N ha^{-1})		ΔTN (t N ha^{-1} yr^{-1})
	G	C	G–C	G	C	G–C	G	C	G–C	G	C	G–C
Yingli 1	95.5	68.6	2.46	360.7	399.3	−3.51	456.2	467.8	−1.05	14.6	8.8	0.53
Yingli 2	109.5	88.9	1.87	343.2	433.8	−8.24	452.7	522.7	−6.37	12.4	9.1	0.12
Tianliu 1	89.8	89.3	0.07	15.1	34.7	−1.40	104.9	124.0	−1.33	9.9	9.2	0.08
Tianliu 2	109.1	85.4	1.69	5.0	23.1	−1.30	114.1	108.6	0.39	9.4	6.7	0.10

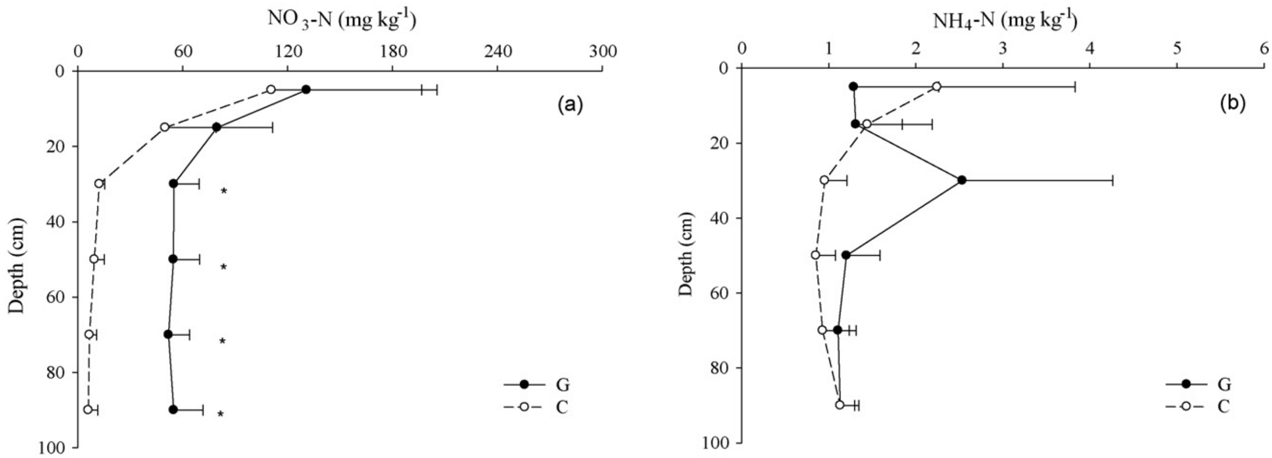

Fig. 2. Concentrations of NO_3-N and NH_4-N in the soil profiles of greenhouse (G) and conventional (C) production systems. Values at each depth are the mean of four replicates. An asterisk represents a significant difference ($P < 0.05$) between greenhouse and conventional production systems.

δ^{15}N ratio of POM were significantly higher in the greenhouses than in the cereal soils at 0–20 cm depth ($P < 0.05$).

In both production systems the concentrations of SMBC and SMBN decreased with soil depth (Table 4). Both SMBC and SMBN were higher in the conventional system than in the greenhouses ($P > 0.05$). The concentration of SMBC ranged between 84.1 and 284.8 mg kg^{-1}, and that of SMBN ranged between 12.4 and 44.8 mg kg^{-1} across both production systems. The percentage of SMBC to SOC and SMBN to TN ranged from 1.3% to 2.8% and 1.6% to 4.6%, respectively. Below 10 cm soil depth, SMBC/SOC and SMBN/TN in the conventional system were significantly higher than in the greenhouses ($P < 0.05$). SMBC/SMBN ranged from 5.8 to 7.1, and

Table 3
Concentration of particulate organic matter C (POM-C) and N (POM-N), natural abundance and their ratio as well as their respective percentage of SOC and TN between greenhouse (G) and conventional cereal (C) systems; values are the means of four replicates; numbers in parentheses indicate standard error.

Cropping system	POM-C (g kg^{-1})	POM-δ^{13}C (‰)	POM-N ($\times 10^{-3}$ g kg^{-1})	POM-δ^{15}N (‰)	POM-C/SOC (%)	POM-N/TN (%)	POM-C/POM-N	δ^{13}C/δ^{15}N
0–10 cm								
G	7.1(2.0)	−21.5(0.9)	511.4(113.9)	6.2(0.8)	52.4(6.1)	31.7(6.0)	13.8(1.8)	−3.5(0.6)
C	2.9(1.3)	−21.5(1.4)	168.9(47.6)	2.6(1.0)	27.2(6.7)	14.4(8.2)	16.7(3.5)	−9.3(4.4)
t-Test	*	ns	**	**	**	*	ns	**
10–20 cm								
G	5.2(1.6)	−21.5(1.4)	385.2(92.7)	6.2(0.8)	44.4(1.6)	28.7(4.5)	13.5(1.5)	−3.5(0.7)
C	2.0(0.4)	−20.9(0.4)	118.9(27.1)	3.0(0.2)	24.7(4.1)	14.6(2.2)	17.2(3.1)	−6.9(0.3)
t-Test	**	ns	**	**	**	**	ns	**
20–40 cm								
G	1.5(0.3)	−19.8(1.6)	105.7(28.6)	7.1(1.5)	24.3(3.3)	14.0(3.4)	14.8(2.3)	−2.9(0.7)
C	0.8(0.3)	−17.6(1.2)	44.9(16.4)	6.2(0.6)	16.0(4.1)	8.3(2.2)	18.6(0.6)	−2.9(0.4)
t-Test	**	ns	*	ns	*	*	ns	ns

* Significant at $P < 0.05$.
** Significant at $P < 0.01$; ns, not significant at $P > 0.05$.

Table 4
Soil microbial biomass (SMBC and SMBN) concentrations, SMBC/SMBN and their respective percentages in SOC or TN in greenhouse and conventional production systems. Values are the means of four replicates; numbers in parentheses indicate standard error.

Cropping system	SMBC (mg kg^{-1})	SMBN (mg kg^{-1})	SMBC/SOC (%)	SMBN/TN (%)	SMBC/SMBN
0–10 cm					
G	215.0(82.8)	31.6(12.5)	1.60.6)	1.9(0.7)	6.8(1.2)
C	284.8(70.1)	44.8(22.6)	2.8(0.3)	3.4(1.3)	7.0(1.7)
t-Test	ns	ns	*	ns	ns
10–20 cm					
G	163.5(90.6)	27.2(11.6)	1.3(0.5)	2.0(0.7)	5.8(1.6)
C	227.1(40.2)	36.7(3.2)	2.8(0.5)	4.6(1.0)	6.2(1.2)
t-Test	ns	ns	**	**	ns
20–40 cm					
G	84.1(34.5)	12.4(2.4)	1.4(0.6)	1.6(0.2)	6.8(2.8)
C	118.4(23.8)	16.9(3.4)	2.3(0.3)	3.2(0.5)	7.1(1.2)
t-Test	ns	ns	*	**	ns

* Significant at $P < 0.05$.
** Significant at $P < 0.01$; ns, not significant at $P > 0.05$.

Table 5
Dissolved organic matter (DOC and DON) concentration, DOC/DON and their respective percentages in SOC and TN in greenhouse and conventional production systems. Values are the means of four replicates; numbers in parentheses indicate standard error.

Cropping system	DOC ($mg\,kg^{-1}$)	DON ($mg\,kg^{-1}$)	DOC/SOC (%)	DON/SON (%)	DOC/DON
0–10 cm					
G	50.0(20.5)	9.3(4.0)	1.9(0.7)	0.4(0.09)	5.9(2.0)
C	35.2(2.1)	7.9(4.3)	3.4(1.3)	0.4(0.07)	6.0(4.1)
t-Test	ns	ns	ns	ns	ns
10–20 cm					
G	45.5(19.7)	9.5(4.4)	2.0(0.7)	0.4(0.13)	4.9(0.5)
C	31.1(1.8)	10.8(1.1)	4.6(1.0)	0.4(0.05)	2.9(0.1)
t-Test	ns	ns	**	ns	**
20–40 cm					
G	25.0(4.1)	8.4(3.8)	1.6(0.2)	0.4(0.09)	3.4(1.3)
C	20.5(4.1)	8.3(1.3)	3.2(0.5)	0.4(0.04)	2.5(0.6)
t-Test	ns	ns	**	ns	ns

** Significant at $P < 0.01$; ns, not significant at $P > 0.05$.

the ratio in the conventional system was greater than in the greenhouses, though the difference was not significant ($P > 0.05$).

The concentration of DOC at 0–40 cm soil depth was higher in the greenhouse system than that in the conventional system and the concentration of DON in both production systems was largest at 10–20 cm soil depth (Table 5). Differences in DOC or DON were not significant in either production system ($P > 0.05$). DOC as a percentage of SOC and DON as a percentage of TN were 1.6 to 4.6% and 0.4%, respectively. DOC/DON ratio ranged between 2.5 and 6.0. At 10–20 cm depth DOC/DON was significantly higher in the greenhouse system than in the cereal rotation ($P < 0.01$).

4. Discussion

4.1. SOC, IC and TN

The higher SOC concentration in the greenhouse system (Fig. 1a) may be attributable to the numerous different types of manure incorporated into the soil to maintain high vegetable yields. The amount of N applied in manures in the greenhouse system at Shouguang was found by He et al. (2007) to be up to 936 kg N ha^{-1} per year. Higher yields increase root exudation and exudates and dissolved organic matter from manures can move deep down the soil profile with excessive irrigation (Brye et al., 2001). Micro-organisms may also make some contribution to SOC in the soil profile. These factors may account for the significant difference in SOC between the two production systems at 20–60 cm depth ($P < 0.05$). The higher concentrations of TN and NO_3-N in the greenhouse system (Figs. 1b and 2a) may also have resulted from excessive N fertilizer and manure applications (Zhu and Chen, 2002; He et al., 2007). NO_3-N as a percentage of TN was 6.0–10.0% at 0–100 cm depth in the greenhouse system and 1.2–8.1% in the conventional system. Excessive NO_3^- leaching in the highly irrigated greenhouse system may have resulted in heavy pollution of the groundwater (Li et al., 2007), with the irrigation rate reaching 1800 mm per year in the greenhouse system (He et al., 2007).

Discrimination against the heavier C isotope can result in less negative values in C_4 plants (e.g. maize) than in C_3 plants (e.g. vegetables) and a similar effect may have occurred during the decomposition of the applied manures. Excessive manure application in the greenhouses may have been mainly responsible for the difference in $\delta^{13}C$ in the surface soil but little change was found below 10 cm depth in both production systems (Fig. 1d). The difference at 10–40 cm depth might be related to root distribution and maize/wheat rotation because the root distribution of vegetables is much more restricted than that of maize or wheat (Zotarelli et al., 2009; Nakamoto, 2000). $\delta^{13}C$ at 40–100 cm may reflect the soil background because the $\delta^{13}C$ values in the two production systems were almost equivalent (Fig. 1d). Mineral N fertilizers are originally derived from atmospheric N_2 and their $\delta^{15}N$ is close to 0‰. In contrast, composts become enriched in ^{15}N by a series of biological and chemical processes (Kerley and Jarvis, 1996). Watzka et al. (2006) found that the $\delta^{15}N$ of various organic fertilizers and composts varied within the range 6.0–14.3‰. We also measured the $\delta^{15}N$ of different fertilizers and manures and obtained values of: $(NH_2)_2CO$ 0.2%, NH_4HCO_3 2.4%, $(NH_4)_2HPO_4$ 0.6‰, cattle manure 7.9‰, pig manure 11.9‰ and chicken manure 16.8‰. Thus, the $\delta^{15}N$ of surface soils in the conventional system with chemical fertilizer was less dominant than that in the greenhouses with large manure inputs (Fig. 1e). The variation in $\delta^{15}N$ below 20 cm soil depth may be related to the accumulation of NO_3-N (Fig. 2a) in the profile after long-term excessive fertilizer N application.

The SOC/TN ratio reflects the stability of soil organic matter and relative decomposition stage and the age of the humus (Vejre et al., 2003; Russell et al., 2005). As Fig. 1f shows, at 0–20 cm depth the regenerative rate of SOM in the greenhouse system is faster than in the conventional system because the fresh SOM formed from manures is less stable than the native SOM (Springob and Kirchmann, 2003). Below 20 cm depth the SOC/TN ratio was lower in the greenhouse soil than in the cereal areas (Fig. 1c), due mainly to N-rich organic material deposition (e.g. POM-C & POM-N in Table 3), the accumulation of excessive NO_3-N (Fig. 2a) and the massive irrigation, with NO_3^- facilitating soil H_2O hydrolysis for the charge balance with further decline in soil carbonate (Table 2) as a result of soil acidification (Table 1) (Barak et al., 1997; Malhi et al., 1998; Ju et al., 2007).

The contents of SOC and TN were no more than 110 t C ha^{-1} and 15 t N ha^{-1} at 0–100 cm depth in the soil profile in the two studies systems, respectively (Table 2). There could be considerable potential for C and N sequestration in the two systems in the study area if protective management practices were adopted (Batjes, 2002). The main component of soil total C (TC) is soil inorganic C (IC) at the Yingli site and SOC at the Tianliu site (Table 2). IC content in the greenhouse system at the four sites was lower than in the conventional system, and this may be attributed to decreasing soil pH in the greenhouse system as shown in Table 1. Soil acidification was likely the result of the nitrification of excessive applied N and NO_3^- leaching under the unrestricted irrigation regime (Ju et al., 2007).

4.2. Soil active C and N pools

POM can respond sensitively to management practices (Mrabet et al., 2001) and can enhance soil aggregation by different binding agents such as fungal hyphae, fine roots, bacterial cells and polysaccharides (Jastrow and Miller, 1997). The increase in C and N concentrations of POM (Table 3) in the greenhouse system can be attributed to excessive manure and fertilizer applications. Compared to the conventional system, $\delta^{13}C$ and $\delta^{15}N$ of POM at 0–20 cm depth indicate that the contribution of manure to POM-N was significantly greater ($P < 0.05$) than that to POM-C in the greenhouse system. Mendham et al. (2004) reported that a higher quality POM could lead to a decline in net N mineralization rate; POM-C as a percentage of SOC and POM-N as a percentage of TN were significantly higher in the greenhouse soils ($P < 0.05$). According to Marriott and Wander (2006a,b), this would indicate that manure application facilitated an increase in POM concentration and that soil aggregation would increase. However, in the greenhouse system in Shouguang county soil carbonate collapse (Table 2) indicates that the original soil structure was undergoing deterioration.

The POM-C/POM-N ratio can reflect the original C/N ratio of organic materials incorporated into the soil and their degree of decomposition (Gregorich et al., 1996; Christensen, 2001). The POM-C/POM-N ratio in the greenhouse system (13–15) was reduced compared to the conventional counterparts (16–19) and the ratio of POM-$\delta^{13}C$ to POM-$\delta^{15}N$ was significantly different in the two systems ($P < 0.05$; Table 3). These results reflect the significant alteration of the original organic materials of POM after over one decade of excessive N-rich and low C:N manure amendment in the greenhouses. Cereal (both wheat and maize) residues have high C/N ratios which are reflected in the higher POM-C/POM-N ratio in the conventional system.

Soil microbial biomass accounts for 1–5% of the SOC and TN pools (Perelo et al., 2006) and our results are in agreement with this (Table 4). At different soil depths the higher proportion of SMBC to SOC and SMBN to TN in the conventional system indicate that there were more complex microbial communities for substrate-use efficiency with inputs of exogenous materials (Moore et al., 2000). In general, manures markedly increase soil microbial biomass (Masto et al., 2006) but the higher SOC and TN content with the lower concentrations of SMBC and SMBN in the greenhouse system (Fig. 1a and b, Table 4) indicate that the capacity of nutrient cycling in the greenhouse system decreased.

The ratio of SMBC/SMBN can partly reflect soil microbial community structure and status. Paul and Clark (1989) reported that the C/N ratios for bacteria ranged from 3 to 5 and those for fungi from 4 to 15. In our study the SMBC/SMBN values were in the range 5.7–7.1. SMBC/SMBN ratio can be impacted by soil quality properties such as pH, texture, structure, microbial diversity, SMBC/SOC and SMBN/TN (Moore et al., 2000; Bastida et al., 2008) and also by root density, root depth and root exudates (Moore et al., 2000). These factors may contribute to the lower SMBC/SMBN ratio in the greenhouse system in comparison with the conventional system, as shown in Tables 1 and 4.

DOM (DOC and DON) plays an important role in soil biogeochemical processes (Kalbitz et al., 2000; Kalbitz and Geyer, 2002; Park et al., 2002). Lower DOM values in our study (Table 5) compared to those in grassland soils reported by Ghani et al. (2007) may have resulted from differences in climate, disturbance through tillage, and fertilizer applications. The higher DOC the in greenhouse system and significant difference in DOC/SOC ($P < 0.05$) below 10 cm soil layer in both production systems (Table 5) may have been due to excessive manure applications (Borken et al., 2004) and the acidification of the soil (Table 1) Thus low soil pH can intensify the leaching of bridging cations (e.g. Ca^{2+}, Mg^{2+}) and further enhance the solubilization of organic matter (Zech et al., 1994). DON release would have been affected by the inorganic N pool (Kalbitz and Geyer, 2002) and so the combined effects of NO_3^- leaching and root capture may have contributed to the occurrence of the maximum DON at 10–20 cm depth in the soil profiles.

The DOC/DON ratio is important in predicting gross N mineralization (Kalbitz et al., 2000) and Ghani et al. (2007) reported DOC/DON ratios ranging from 5 to 6 in most soils. In the present study the ratio ranged from 2.5 to 6.0 (Table 5) due to the exogenous substrate amendment. However, this may still have contributed to the differences in DOC/DON between soil depths in both production systems because N fertilization would have increased DON concentrations while leaving DOC concentrations unchanged (Neff et al., 2000).

5. Conclusions

Shifting from the conventional cereal production system to highly intensive greenhouse vegetables has resulted in higher accumulated NO_3-N, higher TN, and lower SOC/TN ratios and total C stocks due to a dramatic decline in carbonates in the soil caused by intensive ammonium fertilization and massive irrigation, which involved high nitrification rates and a large release of protons as well as nitrate leaching. There were no significant differences between the two production systems in the isotopic signatures of SOC and TN ($P > 0.05$) but the SOC in surface soil contained much more newly formed C sources (POM-C) and the $\delta^{15}N$ of POM-N responded sensitively to the effects of the exogenous substrates ($P < 0.05$). Soil quality may deteriorate with low SOC/TN ratios and very low SMBC/SOC and SMBN/TN ratios ($P < 0.05$) in the greenhouse system. In addition, large accumulation of NO_3-N poses a considerable threat to the quality of groundwater and may even be harmful to local residents. In conclusion, the potential conservation of soil C and N stocks will be greater on the North China Plain if the negative effects of excessive N applications and massive irrigation can be avoided in intensive greenhouse vegetable production systems.

Acknowledgments

This work was supported by the National Natural Science Foundation of China (NSFC Grant no. 40771098), the 973 project (2009CB118606), the Sino-German Cooperative Project (DFG International Research Training Groups, GK1070), the '863' Project (2008AA06Z315), and the Innovative Group Grant of NSFC (no. 30821003).

References

Barak, P., Jobe, B.O., Krueger, A.R., Peterson, L.A., Laird, D.A., 1997. Effects of long-term soil acidification due to nitrogen fertilizer inputs in Wisconsin. Plant Soil 197, 61–69.

Bastida, F., Zsolnay, A., Hernández, T., García, C., 2008. Past, present and future of soil quality indices: a biological perspective. Geoderma 147, 159–171.

Batjes, N.H., 2002. Carbon and nitrogen stocks in the soils of Central and Eastern Europe. Soil Use Manage. 18, 324–329.

Bongiovanni, M.D., Lobartini, J.C., 2006. Particulate organic matter, carbohydrate, humic acid contents in soil macro- and microaggregates as affected by cultivation. Geoderma 136, 660–665.

Borken, W., Xu, Y.J., Beese, F., 2004. Leaching of dissolved organic carbon and carbon dioxide emission after compost application to six nutrient-depleted forest soils. J. Environ. Qual. 33, 89–98.

Bronson, K.F., Zobeck, T.M., Chua, T.T., Acosta-Martinez, V., van Pelt, R.S., Booker, J.D., 2004. Carbon and nitrogen pools of southern high plains cropland and grassland soils. Soil Sci. Soc. Am. J. 68, 1695–1704.

Brookes, P.C., Landman, A., Pruden, G., Jenkinson, D.S., 1985. Chloroform fumigation and the release of soil nitrogen: a rapid direct extraction method to measure microbial biomass nitrogen in soil. Soil Biol. Biochem. 17, 837–842.

Brye, K.R., Norman, J.M., Bundy, L.G., Gower, S.T., 2001. Nitrogen and carbon leaching in agroecosystems and their role in denitrification. J. Environ. Qual. 30, 58–70.

Choi, W.J., Ro, H.M., Lee, S.M., 2003. Natural ^{15}N abundances of inorganic nitrogen in soil treated with fertilizer and compost under changing soil moisture regimes. Soil Biol. Biochem. 35, 1289–1298.

Christensen, B.T., 2001. Physical fractionation of soil and structural and functional complexity in organic matter turnover. Eur. J. Soil Sci. 52, 345–353.

Clapp, C.E., Allmaras, R.R., Layese, M.F., Linden, D.R., Dowdy, R.H., 2000. Soil organic carbon and ^{13}C abundance as related to tillage, crop residue, and nitrogen fertilization under continuous corn management in Minnesota. Soil Till. Res. 55, 127–142.

Cookson, W.R., Osman, M., Marschner, P., Abaye, D.A., Clark, I., Murphy, D.V., Stockdale, E.A., Watson, C.A., 2007. Controls on soil nitrogen cycling and microbial community composition across land use and incubation temperature. Soil Biol. Biochem. 39, 744–756.

Davidson, E.A., Trumbore, S.E., Amundson, R., 2000. Biogeochemistry: soil warming and organic carbon content. Nature 408, 789–790.

Ghani, A., Dexter, M., Carran, R.A., Theobald, P.W., 2007. Dissolved organic nitrogen and carbon in pastoral soils: the New Zealand experience. Eur. J. Soil Sci. 58, 832–843.

Gregorich, E.G., Monreal, C.M., Schnitzer, M., Schulten, H.R., 1996. Transformation of plant residues into soil organic matter: chemical characterization of plant tissue, isolated soil fractions, and whole soils. Soil Sci. 161, 680–693.

Halvorson, A.D., Reule, C.A., Follett, R.F., 1999. Nitrogen fertilization effects on soil carbon and nitrogen in a dryland cropping system. Soil Sci. Soc. Am. J. 63, 912–917.

Halvorson, A.D., Wienhold, B.J., Black, A.L., 2002. Tillage, nitrogen, and cropping system effects on soil carbon sequestration. Soil Sci. Soc. Am. J. 66, 906–912.

He, F.F., Chen, Q., Jiang, R.F., Chen, X.P., Zhang, F.S., 2007. Yield and nitrogen balance of greenhouse tomato (*Lycopersicum esculentum* Mill.) with conventional and site-specific nitrogen management in northern China. Nutr. Cycl. Agroecosyst. 77, 1–14.

Hu, S., Chapin, F.S., Firestone, M.K., Field, C.B., Chiariello, N.R., 2001. Nitrogen limitation of microbial decomposition in a grassland under elevated CO_2. Nature 409, 188–191.

Huang, Y., Sun, W.J., 2005. Changes in topsoil organic carbon of croplands in mainland China over the last two decades. Chinese Sci. Bull. 51, 1785–1803.

Janzen, H.H., Campbell, C.A., Izaurralde, R.C., Ellert, B.H., Juma, N., McGill, W.B., Zentner, R.P., 1998. Management effects on soil C storage on the Canadian prairies. Soil Till. Res. 47, 181–195.

Jastrow, J.D., Miller, R.M., 1997. Soil aggregate stabilization and carbon sequestration: feedbacks trough organomineral associations. In: Lal, R., Kimble, J., Follett, R., Stewart, B. (Eds.), Soil Processes and the Carbon Cycle. CRC Press, Boca Raton, FL, pp. 207–223.

Jenkinson, D.S., 1988. Determination of microbial biomass carbon and nitrogen in soil. In: Wilson, J.R. (Ed.), Advances in Nitrogen Cycling in Agricultural Ecosystems. CAB International, Wallingford, UK, pp. 368–386.

Ju, X.T., Kou, C.L., Christie, P., Dou, Z.X., Zhang, F.S., 2007. Changes in the soil environment from excessive application of fertilizers and manures to two contrasting intensive cropping systems on the North China Plain. Environ. Pollut. 145, 497–506.

Kalbitz, K., Geyer, S., 2002. Different effects of peat degradation on dissolved organic carbon and nitrogen. Org. Geochem. 33, 319–326.

Kalbitz, K., Solinger, S., Park, J.H., Michalzik, B., Matzner, E., 2000. Controls on the dynamics of dissolved organic matter in soils: a review. Soil Sci. 165, 277–304.

Kerley, S.J., Jarvis, S.C., 1996. Preliminary studies of the impact of excreted N on cycling and uptake of N in pasture systems using natural abundance stable isotopic discrimination. Plant Soil 178, 287–294.

Knorr, W., Prentice, I.C., House, J.I., Holland, E.A., 2005. Long-term sensitivity of soil carbon turnover to warming. Nature 433, 298–301.

Körner, C., Arnone, J.A., 1992. Responses to elevated carbon dioxide in artificial tropical ecosystems. Science 257, 1672–1675.

Lal, R., Kimble, J., Stewart, B.A., 1995. World Soils as a Source or Sink for Radio-Active Gases. In: Soil Management and Greenhouse Effect. Lewis Publishers, London, pp. 1–7.

Lehmann, J., Cravo, M.D., Zech, W., 2001. Organic matter stabilization in a Xanthic Ferralsol of the central Amazon as affected by single trees: chemical characterization of density, aggregate, and particle size fractions. Geoderma 99, 147–168.

Li, X.X., Hu, C.S., Delgado, J.A., Zhang, Y.M., Ouyang, Z.Y., 2007. Increased nitrogen use efficiencies as a key mitigation alternative to reduce nitrate leaching in north China Plain. Agric. Water Manage. 89, 137–147.

Loeppert, R.H., Suarez, D.L., 1996. Carbonate and gypsum. In: Sparks, D.J. (Ed.), Methods of Soil Analysis. Part 3. Chemical Methods. Soil Science Society of America, American Society of Agronomy, Madison, WI, USA, pp. 437–474.

Lynch, D.H., Voroney, R.P., Warman, P.R., 2006. Use of ^{13}C and ^{15}N natural abundance techniques to characterize carbon and nitrogen dynamics in composting and in compost-amended soils. Soil Biol. Biochem. 38, 103–114.

Malhi, S.S., Nyborg, M., Harapiak, J.T., 1998. Effects of long-term N fertilizer-induced acidification and liming on micronutrients in soil and in bromegrass hay. Soil Till. Res. 48, 91–101.

Mariotti, A., Peterschmitt, E., 1994. Forest savanna ecotone dynamics in India as revealed by carbon isotope ratios of soil organic matter. Oecologia 97, 475–480.

Marriott, E.E., Wander, M., 2006a. Qualitative and quantitative differences in particulate organic matter fractions in organic and conventional farming systems. Soil Biol. Biochem. 38, 1527–1536.

Marriott, E.E., Wander, M.M., 2006b. Total and labile soil organic matter in organic and conventional farming systems. Soil Sci. Soc. Am. J. 70, 950–959.

McCarty, G.W., Meisinger, J.J., 1997. Effects of N fertilizer treatments on biologically active N pools in soils under plow and no tillage. Biol. Fertil. Soils 24, 406–412.

Masto, R.E., Chhonkar, P.K., Singh, D., Patra, A.K., 2006. Changes in soil biological and biochemical characteristics in a long-term field trial on a sub-tropical inceptisol. Soil Biol. Biochem. 38, 1577–1582.

Mendham, D.S., Heagney, E.C., Corbeels, M., O'Connell, A.M., Grove, T.S., McMurtrie, R.E., 2004. Soil particulate organic matter effects on nitrogen availability after afforestation with *Eucalyptus globulus*. Soil Biol. Biochem. 36, 1067–1074.

Mrabet, R., Saber, N., El-Brahli, A., Lahlou, S., Bessam, F., 2001. Total, particulate organic matter and structural stability of a Calcixeroll soil under different wheat rotations and tillage systems in a semiarid area of Morocco. Soil Till. Res. 57, 225–235.

Moore, J.M., Susanne, K., Tabatabai, M.A., 2000. Soil microbial biomass carbon and nitrogen as affected by cropping systems. Biol. Fertil. Soils 31, 200–210.

Nakamoto, T., 2000. The distribution of wheat and maize root as influenced by biopores in a subsoil of Kanto Loam type. Plant Prod. Sci. 3, 140–144.

Neff, J.C., Hobbie, S.E., Vitousek, P.M., 2000. Nutrient and mineralogical control on dissolved organic C, N and P fluxes and stoichiometry in Hawaiian soils. Biogeochemistry 51, 283–302.

Park, J.H., Kalbitz, K., Matzner, E., 2002. Resource control on the production of dissolved organic carbon and nitrogen in a deciduous forest floor. Soil Biol. Biochem. 34, 813–822.

Paul, E.A., Clark, F.E., 1989. Soil Microbiology and Biochemistry. Academic Press, San Diego, Calif, pp. 1–265.

Perelo, L.W., Jimenez, M., Munch, J.C., 2006. Microbial immobilisation and turnover of ^{15}N labelled substrates in two arable soils under field and laboratory conditions. Soil Biol. Biochem. 38, 912–922.

Perelo, L.W., Munch, J.C., 2005. Microbial immobilisation and turnover of ^{13}C labelled substrates in two arable soils under field and laboratory conditions. Soil Biol. Biochem. 37, 2263–2272.

Russell, A.E., Laird, D.A., Parkin, T.B., Mallarino, A.P., 2005. Impact of nitrogen fertilization and cropping system on carbon sequestration in Midwestern Mollisols. Soil Sci. Soc. Am. J. 69, 413–422.

Schlesinger, W.H., Lichter, J., 2001. Limited carbon storage in soil and litter of experimental forest plots under increased atmospheric CO_2. Nature 411, 466–469.

Sinsabaugh, R.L., Zak, D.R., Gallo, M., Lauber, C., Amonette, R., 2004. Nitrogen deposition and dissolved organic carbon production in northern temperate forests. Soil Biol. Biochem. 36, 1509–1515.

Springob, G., Kirchmann, H., 2003. Bulk soil C to N ratio as a simple measure of net N mineralization from stabilized soil organic matter in sandy arable soils. Soil Biol. Biochem. 35, 629–632.

Vejre, H., Callesen, I., Vesterdal, L., Raulund-Rasmussen, K., 2003. Carbon and nitrogen in Danish forest soils: contents and distribution determined by soil order. Soil Sci. Soc. Am. J. 67, 335–343.

Wander, M., 2004. Soil organic matter fractions and their relevance to soil function. In: Magdoff, F.R., Weil, R.R. (Eds.), Soil Organic Matter in Sustainable Agriculture. CRC, Boca Raton, pp. 67–102.

Watzka, M., Buchgraber, K., Wanek, W., 2006. Natural ^{15}N abundance of plants and soils under different management practices in a montane grassland. Soil Biol. Biochem. 38, 1564–1576.

Wu, J., Joergensen, R.G., Pommerening, B., Chaussod, R., Brookes, P.C., 1990. Measurement of soil microbial biomass C by fumigation-extraction: an automated procedure. Soil Biol. Biochem. 22, 1167–1169.

Zech, W., Guggenberger, G., Schulten, H.-R., 1994. Budgets and chemistry of dissolved organic carbon in forest soils: effects of anthropogenic soil acidification. Sci. Total Environ. 152, 49–62.

Zhu, Z.L., Chen, D.L., 2002. Nitrogen fertilizer use in China: contributions to food production, impacts on the environment and best management strategies. Nutr. Cycl. Agroecosyst. 63, 117–127.

Zogg, G.P., Zak, D.R., Pregitzer, K.S., Burton, A.J., 2000. Microbial immobilization and the retention of anthropogenic nitrate in a northern hardwood forest. Ecology 81, 1858–1866.

Zotarelli, L., Scholberg, J.M., Dukes, M.D., Muñoz-Carpena, R., Icerman, J., 2009. Tomato yield, biomass accumulation, root distribution and irrigation water use efficiency on a sandy soil, as affected by nitrogen rate and irrigation scheduling. Agric. Water Manage. 96, 23–34.