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Soil organic carbon dynamics under long-term fertilizations in arable land of northern China

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Abstract

Soil organic carbon (SOC) data were collected from six long-term experiment sites in the upland of northern China. Various fertilization (e.g. inorganic fertilizations and combined inorganic-manure applications) and cropping (e.g. mono- and double-cropping) practices have been applied at these sites. Our analyses indicate that long-term applications of inorganic nitrogen-phosphorus (NP) and nitrogen-phosphorus-potassium (NPK) result in a significant increase in SOC at the sites with the double-cropping systems. The applications of inorganic NP and/or NPK combined with manure lead to a significantly increasing trend in SOC content at all the sites. However, the application of NPK with crop residue incorporation can only increase SOC content in the warm-temperate areas with the double-cropping systems. Regression analyses suggest that soil carbon sequestration responds linearly to carbon input at all the sites. Conversion rates of carbon input to SOC decrease significantly with an increase of annual accumulative temperature or precipitation, showing lower rates (6.8%–7.7%) in the warm-temperate areas than in the mid-temperate areas (15.8%–31.0%).

1 Introduction

Soil organic carbon (SOC) is an important index of soil fertility because of its relationship to crop productivity (Vinther et al., 2004; Rahman and Parkinson, 2007). For instance, declining SOC levels often leads to decreased crop productivity (Lal, 2006; Dominy et al., 2002). Thus, maintaining SOC level is essential for long-term sustainable agriculture. The concept of sustainable agricultural production emphasizes the importance of SOC management for food security and environment protection (Lal, 2005; Buyanovsky and Wagner, 1998). Because of the potential of agro-ecosystems to absorb a large amount of atmospheric carbon dioxide (CO_2) through carbon sequestration in the form of SOC, SOC management is recognized as a “win-win strategy”(Smith et al., 1999; Lal, 2002b), and has been put forward as one of the mitigating options for climate change (Lal, 2002a; Post et al., 2004). Particularly, the potential of soil carbon sequestration as SOC in China may offset more than 10% of the annual fossil fuel emissions in China (Lal, 2004).

There are a number of studies showing that SOC levels are influenced by agriculture practices, such as fertilization, tillage, rotation and etc. (Zimmer et al., 2005; Al-Kaisi and Grote, 2007; Al-Kaisi et al., 2005; Slattery and Surapaneni, 2002; Miglierina et al., 2000). In general, SOC level increases under practices of balanced fertilization, organic amendments, conservative tillage (i.e. no-till), and fallow (Cai and Qin, 2006; Su et al., 2006; Matus et al., 2008; Liu et al., 2005; Morari et al., 2006; Kahle et al., 2007; Purakayastha et al., 2008; Sainju et al., 2007). All these practices result in high crop yields, thus lead to increased crop residue return into soil, which promotes SOC accumulation. It is recently documented that soil fertility and carbon sequestration in croplands have been improved due to the extensive applications of balanced fertilization over the past 20 years in China, especially with additional organic materials and/or incorporation of crop residue (Huang and Sun, 2006; Huang et al., 2007; Zhang et al., 2008).

While carbon input may be one of the means to increase SOC content in agro-ecosystems, the relationship between SOC and carbon input is complicated. On the one hand, many studies have demonstrated that SOC level shows a linear increase in response to carbon input (Kong et al., 2005; Kundu et al., 2007; Campbell et al., 2007; Kundu et al., 2001). On the other hand, some studies (Six et al., 2002; Gulde et al., 2008; Fontaine et al., 2004; Gill, 2002) indicate that the SOC content does not increase much even after a large amount of organic material is incorporated into the soil, suggesting that these soils may be carbon-saturated. The complex relationship between SOC and carbon input may be related to climate conditions and soil properties. For example, the application of inorganic fertilizer can increase SOC level in the subtropical areas (Purakayastha et al., 2008; Zhang et al., 2008), but cannot increase SOC in the arid temperate area (Su et al., 2006). Clearly, more studies are needed to better understand the relationship between the carbon input and SOC level.

It is estimated that there are 111–170 Pg SOC stored in arable soils in the world, which counts for about 10% of the global terrestrial SOC pool in top one meter soil (Schlesinger, 1999; Paustian et al., 1997). There are approximately 80–90 Pg SOC in the surface soil in China (Wu et al., 2003; Li et al., 2007; Xie et al., 2007). It has been reported that about 2 Pg of SOC, 40% of the SOC stock in the arable top soil, has been lost from agricultural cultivation due to the rapid economic growth and the changes in farming practices in China (Song et al., 2005). Thus, there have been concerns on the SOC losses, not only for the sustainability of agricultural production, but also for soil carbon sequestration (Lal, 2004). Here, we investigate SOC dynamics under long-term fertilizations at several sites in the arable land of northern China. The objectives of this study are to (i) assess the long-term impacts of fertilization practices on SOC variations in mono-cropping and double-cropping systems; and (ii) examine the relationship between soil carbon sequestration and carbon input under various climate and soils conditions.

2 Materials and methods

2.1 Site descriptions

There are six long-term experiment sites with mid-temperate to warm-temperate climate conditions in arable land of the northern China (Fig. 1). Table 1 presents soil classifications by the FAO (FAO-UNESCO, 1988) and Chinese systems, and basic site descriptions. Soils at the Changping (CP), Zhengzhou (ZZ), and Xuzhou (XZ) sites, with the same soil parents (i.e. loess), had been used for agriculture for a long time before the experiments. For the UC and ZY sites in the arid and semi-arid areas, soils were cultivated with irrigation for a few years before the experiments. Annual mean temperature varies from 4.5°C at the Gongzhuling (GZL) site in the northeast to 14.5°C at the XZ site in the central China. Annual precipitation is generally low, ranging from 127 mm at the Zhangye (ZY) site to 832 mm at the XZ site. However, annual evaporation is much higher relative to precipitation, varying from 1400 mm to 2570 mm. The highest evaporation is found at the Urumqi (UC) site whereas the highest annual precipitation is at the XZ site. In general, 50%–70% of the annual precipitation occurs in the non-growing season. Thus, irrigation is usually applied during the growing season, especially at the two dry sites (i.e. UC and ZY).

2.2 Cropping practices

The long-term experiment has a mono-cropping system at the GZL, UC, and ZY sites, and a double-cropping system at the CP, ZZ, and XZ sites (Table 1). The main crops are corn (*Zea mays* L.) and wheat (*Triticum Aestivium* L.). The double cropping systems have a rotation of summer corn (seeded in late April or early May) and winter wheat (seeded in October). The mono-cropping systems have a continues corn cropping at the GZL site, but a rotation of corn-wheat-wheat (i.e. corn cropping for one year and wheat cropping for next two years) at the ZY and UC sites. Corn is seeded during late April to early May for the mono-cropping system. Wheat is seeded in March at the ZY site. For the UC site, spring wheat is seeded in mid-April and winter wheat in late September in the same year. Prior to the experiment, the field has been under the same rotation for 2–3 years at each site.

Wheat are harvested by cutting straws close to the ground. Corn stovers are also cut to ground after the grain harvest. Thus, only roots and litters are left in the soil. All above-ground biomass of wheat and corn are removed from the fields. Crop grains and residues are air-dried, threshed, oven-dried at 70°C to a uniform moisture level, and then weighted separately.

2.3 Fertilization treatments

There are five common treatments at all the six sites: non-fertilization (CK), inorganic nitrogen (N), inorganic nitrogen and phosphorus combination (NP), inorganic nitrogen, phosphorus and potassium combination (NPK), inorganic NPK combined with livestock or farmyard manure (NPKM) (Table 2). For the GZL, UC, CP, and ZZ sites, there are additional two fertilization treatments: higher application rates of NPKM (hNPKM), and inorganic NPK combined with crop residue incorporation (NPKS). There is an additional treatment at the ZY and XZ sites: inorganic NP combinated with manure (NPM). There are four replicates for each treatment at the XZ and three for the ZY site whereas there are no replicates at the other four sites.

The inorganic nitrogen, phosphorus and potassium fertilizers are urea, calcium superphosphate, and potassium chloride, respectively. At the GZL and UC sites, the application rates of total nitrogen (i.e. inorganic plus organic) are the same (i.e. nitrogen balanced) for the N, NP, NPK, and NPKM treatments (Table 3). For the CP, ZY and XZ sites, application rates of inorganic nitrogen for all the treatments so that the NPKM treatment receives extra input of organic nitrogen (nitrogen unbalanced). For the NPKM treatment at the nitrogen balanced sites, 30% of total nitrogen is inorganic, and the rest organic (Table 4). The application rates of inorganic and organic fertilizers for the hNPKM treatment are 1.5 times of those for the NPKM treatments at the GZL, CP, and ZZ sites. For the UC site, the rates of inorganic (organic) fertilizers are two-third (2 times) of those for the NPKM. The annual application rate of nitrogen is 195–242 kg ha^{-1} for the mono-cropping systems and 300–353 kg ha^{-1} for the double-cropping systems (Table 3).

Application rates of phosphorus and potassium vary according to soil properties at each site. Phosphorus fertilizer application rate is 30% of nitrogen fertilizer application rate at the UC site, and 20% for the other sites. Application rate of potassium fertilizer is 20% of nitrogen fertilizer at the CP and UC sites, 40% for the GZL, ZZ and ZY sites, and 60% at the XZ site. Inorganic fertilizers of phosphorus and potassium are applied before seeding. A part of inorganic nitrogen fertilizer is applied as a base fertilizer before seeding, and the rest for topdressing at the jointing stage (Table 3). The source of organic manure includes farmyard manure and pury manure from household livestock such as horse, goat, and cattles (Table 4). At the ZY and CP sites, farmyard manure is mixed with soil and/or crop residue. Manure is applied before seeding once a year. For the double cropping system, manure is applied before wheat seeding.

2.4 Soil sample analyses

Experiment plots, ranging from 33.3 m^2 to 468 m^2, are isolated by 100-cm-cement baffle plates (Table 2). Soil samples are collected from the top 20 cm each year after harvest (i.e. during September-October). 5–10 (20–40) cores in 5-cm-diam are randomly sampled for each plot with (without) replicates. The soil samples of these cores are mixed thoroughly, and air dried for seven days. Air-dried soil is sieved through 2.00-mm screens to determine pH (1:1 w/v water) and other soil properties. Representative sub-samples are crashed to 0.25 mm for measurements of SOC, total nitrogen (TN), total phosphorus (TP), and total potassium (TK).

Soil organic carbon content is determined by vitriol acid-potassium dichromate oxidation (Walkley and Black, 1934). Total nitrogen is determined by the method described by Black (1965), TP by method of Murphy and Riley (1962), and TK by Kundsen et al. (1982). Available nitrogen is measured following the method of Lu (2000). Available phosphorus (Olsen-P) is determined by the Olsen-P method (Olsen et al., 1954), and available potassium by Shi (1976). Three replicates are carried out for each analysis.

Table 5 presents the initial soil properties of all the six sites. Soil pH has a range of 7.2–8.7. The initial SOC content is considerably higher at the GZL, UC, and ZY sites with the mono-cropping systems than the other three sites with the double-cropping systems. The initial total and available soil nutrients and clay content at the GZL site are the highest, suggesting that soil fertility at this site is relatively higher than other sites. While the C/N ratio is around 10 for most sites, the ZY site has a value of 13.4, suggesting that soil organic matter may be difficult to decompose at this site.

2.5 Estimations of carbon input and soil carbon sequestration rate

Carbon input into top soil includes root residues and addition of organic manure or crop residue incorporation. The annual rate of organic carbon input by roots is estimated as 30% of the above-ground carbon biomass (Chander et al., 1997; Kuzyahov and Domenski, 2000).

For the ZY and XZ sites where only grain yield data are available, above-ground biomass are estimated using a grain to straw ratio of 1:1.1 for wheat and 1:1.2 for corn (NCATS, 1994). Organic carbon contents in wheat and corn are estimated according to NCATS (1994). For the NPKS treatment, organic carbon contents in corn and wheat straw returned are taken as 12.4 and 27.8 $\mathrm{g\,kg^{-1}}$ (at fresh base), respectively. For all the treatments, organic carbon contents in corn and wheat roots are taken as 39.9 $\mathrm{g\,kg^{-1}}$ and 44.4 $\mathrm{g\,kg^{-1}}$ (at oven-dried base), respectively.

Soil carbon sequestration rate (C_{rate}, $\mathrm{t\,ha^{-1}\,yr^{-1}}$) is calculated from the regression slope of SOC content vs. fertilization period, a ($\mathrm{g\,kg^{-1}\,yr^{-1}}$):

$$C_{\mathrm{rate}}=a \times BD \times d, \tag{1}$$

where BD ($\mathrm{g\,cm^{-3}}$) is the initial value of the soil bulk density, and d the soil depth (0.2 m).

2.6 Statistical analyses

Soil organic carbon and above-ground carbon biomass under various fertilization practices during the third five-year (i.e. from the 11th to 15th year of fertilization) are analyzed using the ANOVA method in SPSS 11.5. Simple analyses of linear regression are performed to characterize the change trends in SOC under various fertilizations, and the relationships between soil carbon sequestration rate and annual carbon input.

3 Results

3.1 Above-ground carbon biomass and carbon input

Figure 2 shows annual changes in the above-ground assimilated carbon biomass under various fertilizations. Clearly, the CK treatment has the lowest carbon biomass

(~4 t C ha^{-1}) with a decline trend at all the sites. Most of the fertilization treatments show a pronounced increase (>50%) in carbon biomass during the 15–23 years of experiment. The exception is that the N treatment has variable effects on the carbon biomass, showing little changes at the CP and ZZ sites, small increases at the UC and ZY sites and moderate increases at the GZL and XZ sites. Overall, the NPKM and/or hNPKM treatments lead to the highest carbon biomass during the studied periods. There are large inter-annual fluctuations with extremely low carbon biomass (~4 t C ha^{-1}) for some years at the ZY site that has a desert soil with the highest initial C/N ratio (Table 5). Interestingly, the XZ site has the highest carbon biomass (~12 t C ha^{-1}) during the initial few years of fertilizations despite of the lowest initial SOC and total N contents. While fertilizations result in more than 100% increase in carbon biomass at the XZ site, there is a clear decline in carbon biomass during the last ten years.

There have been studies indicating that nitrogen fertilizer application can increase grain yields and biomass (Aulakh and Aulakh, 2005; He et al., 2006). Here, we compare the averaged annual production of above-ground carbon biomass during the third five-year period (i.e. from the 11th to 15th years of fertilization in Fig. 2). Table 6 indicates that the N treatment shows significant effect on carbon biomass during the third five-year period at the GZL and XZ sites. All other fertilization treatments significantly increase carbon biomass except on the grey desert soil (e.g. the UC site) where only the hNPKM treatment results in a significant increase. In general, biomass in the double-cropping systems are approximately two times of those in the mono-cropping systems except at the GZL site where soil has the highest values of initial SOC, total and available N, P and K. There are no significant differences in the carbon biomass among the NPK, NPKM, hNPKM and NPKS treatments except at the XZ site, indicating that the application of manure has no significant effect on the above-ground carbon biomass at most of the sites. A recent study demonstrates that application of manure tends to increase grain yields during late years in the corn and corn-wheat cropping systems, but initial years in the rice cropping systems (Zhang et al., 2009). Nevertheless, the application of manure with balanced fertilization shows promise in sustaining carbon biomass (Fig. 2).

Figure 3 presents the annual total carbon input, including carbon from roots, manure and/or crop residue, averaged over the whole studied periods. Results show that the N treatment significantly increase annual carbon input except for the CP site. The annual rates of carbon input for the NP and NPK treatments are significantly higher than those of the N treatments. There is not significant difference in carbon input between the NP and NPK treatments except for the XZ site. Obviously, with the additional carbon from manure and/or crop residue, the annual carbon inputs of the combined treatments (i.e. NPM, NPKM, hNPKM, & NPKS) are much higher than that of the inorganic treatments (e.g. N, NP, & NPK) (Fig. 3). Among the mono-cropping systems, the annual rates of carbon input under the NPKM treatment are 6.4 and 4.6 t ka^{-1} at the GZL and UC sites, respectively, which are nearly 2–3 times of that at the ZY site (Table 4). For the double cropping systems, the annual rate of carbon input for the NPKM treatment ranges from 5.9 to 9.7 t ka^{-1}. For the GZL, UC, CP, and ZZ sites, the annual rate of carbon input under the NPKM treatment is significantly lower than that of the hNPKM treatment, but higher than that of the NPKS treatment.

3.2 Soil organic carbon and carbon sequestration

Soil organic carbon level remains low for the CK and the inorganic fertilization treatments (e.g. N, NP, and NPK) with a decline trend (Fig. 4) except for the CP site that has the lowest initial C/N ratio (8.9). As expected, SOC content is relatively high under the manure applications (e.g. the NPM, NPKM, hNPKM treatments), showing an increasing trend. Particularly, the XZ site, with the highest carbon biomass (~12 t C ha^{-1}), shows a pronounced increase under the NPM and NKPKM treatments over the entire experiment period. At the end of the studied periods, SOC is nearly two times of the initial values under the NPKM and hNPKM treatments except for the ZY and CP sites.

Table 7 illustrates that under the CK and N treatments, the SOC level declines significantly at the ZY site but increase significantly at the CP site. The former has the highest initial soil C/N ratio, while the latter has the lowest initial soil C/N ratio. Among the mono-cropping systems, the NPK treatment has various effects on SOC. The GZL site, with the highest carbon biomass (Table 6), maintains the initial SOC level whereas the UC site shows a significant decline in SOC. For all the double-cropping systems, SOC shows a significantly increasing trend under the NPK treatment. The manure treatments (i.e. NPM, NPKM, hNPKM) increase SOC significantly at all the sites. The increasing rate of SOC for the NPKM at the GZL and UC sites (0.36–0.41 g kg^{-1} yr^{-1}) are much higher than that of the ZY sites (0.1 g kg^{-1} yr^{-1}) that has the lowest annual carbon input. The annual change rate varies from 0.16 to 0.24 g kg^{-1} yr^{-1} in the double cropping systems. For the NPKS treatment, SOC content shows little change in the mono-cropping systems, but a significantly increasing trend in the double-cropping systems.

Further analyses indicate that, during the third five-year period, the N application has no effect on SOC except for the ZZ and XZ sites (Table 8). The NP and NPK treatments cannot increase SOC content at the GZL and UC sites with the mono-cropping systems. However, these two treatments show significant effects on SOC at the three sites with the double-cropping systems. Similar results are reported for the subtropical area with the same cropping system (Zhang et al., 2008). As expected, manure applications (e.g. the NPM, NPKM, hNPKM treatments) show significant effects on SOC at all the sites, which is coincident to the findings from other long-term experiments (Bhattacharyya et al., 2007; Majumder et al., 2008). Among the mono-cropping systems, the NPKM treatment results in an increase of SOC content by 40% and 78% at the GZL and UC, respectively, which are about 2 and 3.5 times of that at the ZY site. For the double-cropping systems, the NPM, NPKM and hNPKM treatments increase SOC content by 18%–123%. Under the NPKS treatment, the SOC content shows little increase at the sites with the mono-cropping systems, but a significant increase at the sites with the double-cropping systems.

Figure 5 reveals soil carbon sequestration rate under various fertilization treatments. The manure application treatments (e.g. NPM, NPKM, hNPKM) result in significant carbon sequestration at all the sites, varying from 0.23 to 1.46 t C ha^{-1} yr^{-1}. There is about 0.22 and 0.14 t ha^{-1} yr^{-1} C lost under the NPK treatment at the UC site during the studied period. However, there is about 0.08–0.25 ha^{-1} yr^{-1} C sequestered in soils under the NPK treatment at the ZZ, XZ, and CP sites.

There are significantly positive, linear correlations between soil carbon sequestration rate and annual carbon input at all the sites (Fig. 6). Conversion rate of carbon input to SOC can be expressed as the slope of carbon sequestration rate vs. carbon input. The conversion rates at the GZL, UC, and ZY sites (i.e. the mono-cropping systems in the mild-temperate areas) are 2–4 times of those at the CP, ZZ, and XZ sites (i.e. the double cropping systems in the warm-temperate areas). For example, the warm-temperate areas (the CP, ZZ, and XZ sites) have a conversion rate of 6.8%–7.7%. In the mid-temperate areas, the conversion rate is 15.8% at the GZL site under semi-humid climate, and 26.7% and 30.1% at the UC and ZY sites with arid and semi-arid climate, respectively.

4 Discussion

Fertilization has been an essential practice to maintain and/or increase food production in the world agriculture. There have been various fertilizer applications, including single or combined inorganic fertilizations with or without addition of organic materials. Here, we discuss how different fertilization practices affect SOC dynamics under various climate and soil conditions.

4.1 Effects of long-term inorganic fertilization on SOC

There is a decline trend in SOC under the inorganic nitrogen fertilization at most sites, indicating that such practice is not good for SOC management. With a mono-cropping system, the combined applications of inorganic fertilizers (e.g. NP and NPK) can only maintain SOC level at the high soil fertility site (the GZL site), though these practices can significantly increase annual carbon input (Fig. 3). However, there is an increasing trend in SOC under the NP and NPK treatments in the double-cropping systems (i.e. the CP, ZZ, and XZ sites), suggesting that combined inorganic fertilization can sequester carbon under intensive cropping system (Cai and Qin, 2006; Fan et al., 2005; Zhang et al., 2008). There is not a significant difference in SOC between the NP treatment and the NPK treatment for all the sites, indicating that application of K fertilizer has no effect on soil carbon sequestration. The balanced inorganic fertilization (i.e. the NPK treatment) cannot prevent the decline in SOC in the arid and semi-arid areas (the ZY and UC sites), which may be partly attributed to the accelerated mineralization of SOC in the arid and semi-arid area with high evaporation (Zhao et al., 2008). A similar decline trend in SOC was also observed in the semi-arid Brazil (Lessa et al., 1996).

4.2 Effects of long-term organic fertilization on SOC

The additional applications of manure (e.g. the NPM, NPKM, and hNPKM treatments) provide extra organic carbon input into soil, leading to an increasing trend in SOC (Fan et al., 2008; Ferreras et al., 2006; Galantini and Rosell, 2006; Kaiser et al., 2007). Our results indicate that manure is necessary to maintain SOC level and to sequester carbon in soils, especially in the arid and semi-arid areas. It has been reported that manure application is not only helpful for soil fertility and crop yields, but also benefits the soil microbes thus enhance their activities (Ganry et al., 2001). Therefore, the combinated inorganic-organic fertilizations (e.g. the NPKM, hNPKM treatments) are sustainable practices not only for soil fertility, but also for carbon sequestration in soils, which is widely documented all over the world (Cuvardic et al., 2004; Galantini and Rosell, 2006; Shen et al., 2007; Mando et al., 2005).

The NPKS treatment shows no effect on SOC at the GZL and UC sites with mono-cropping system whereas the NPKS treatment results in an increases of SOC in the double-cropping systems (Table 8). Crop residue incorporated into soil may be difficult to be decomposed in mid-temperate zone because of the relative low temperature (Powlson et al., 2008). However, it seems that crop residue incorporation could be recommendable in the areas with double-cropping systems. While the carbon input is lower in the NPKM treatment than in the NPKS treatment at the UC site, the SOC content is significantly higher in the NPKM treatment than in the NPKS treatment, indicating that carbon input from manure is apt to be sequestered in soil in the semi-arid area. There are similar results from long-term experiments in the northern China (Fan et al., 2008).

4.3 Soil carbon sequestration

Response of SOC to carbon input has been controversial (e.g. Campbell et al., 2007; Purakayastha et al., 2008). Our study indicates that applications of combinated inorganic fertilizers (i.e. the NP and NPK fertilization) with or without manure can sequester carbon in soils at most of the sites. The soil carbon sequestration rates vary from 0.08 to 0.98 $\mathrm{t\,ha^{-1}\,yr^{-1}}$ in northern China under the NP, NPK and NPKM treatments, which are comparable to those from other studies (Akselsson et al., 2005; Causarano et al., 2008; Kundu et al., 2007; Hien et al., 2006; Kroodsma and Field, 2006). For the high application rate of manure (i.e. twice of the conventional application rate), soil carbon sequestration rate is slightly higher at the UC site than that in agricultural soils (0.2–1.0 $\mathrm{t\,ha^{-1}\,yr^{-1}}$) (Hutchinson et al., 2007), but much lower than those in pasture and forest ecosystems (Akala and Lal, 2001; Huntington, 1995). Our results confirm that crop residue incorporation can be a recommendation practice to sequester carbon in soil with intensive cropping systems (Zhang et al., 2008), and/or in the mid-temperate areas (Powlson et al., 2008).

There are studies showing that carbon input does not increase SOC content, suggesting that these soils may be close to carbon saturation (Six et al., 2002; Gulde et al., 2008; Fontaine et al., 2004; Gill, 2002). Our results show that soil carbon sequestration response linearly to carbon input at most the sites, indicating that these soils are not carbon-saturated. There is evidence of linear correlation between the soil carbon sequestration and carbon input in other long- and/or short-term experiments (Rasmussen and Parton, 1994; Kundu et al., 2007; Kundu et al., 2001; Campbell et al., 2007; Kong et al., 2005).

The conversion rates of carbon input to SOC vary from 15.8% to 31.0% in the mid-temperate areas with the mono-cropping systems, which are comparable to those (14%–21%) from previous studies of similar climate areas (Rasmussen and Collins., 1991; Kundu et al., 2001; Kundu et al., 2007). For the warm-temperate areas with the double cropping systems, the conversion rate has a range of 6.8%–7.7%, which is very close to that (7.6%) in Kong et al. (2005).

The conversion rate of carbon input to SOC is largely related to environmental conditions such as climate, microbiology, cropping system, soil physical and chemical properties (e.g. the initial SOC level, soil texture etc.). It is well known that soil physical and chemical properties have important influence on soil microbial activities, which regulates the SOC dynamics (Stark et al., 2007). However, our analyses with limited data show no significant relationship between the conversion rate and the initial soil properties, but significantly negative relationships between the conversion rates and climate conditions. The conversion rate declines significantly with the increases in annual accumulative (>10°C) temperatures and precipitation (Fig. 7). This conclusion is robust whatever the percentage (e.g. 10%, 30% or 40%) is used to estimate annual organic carbon input by roots. It is believed that low temperature, too dry or too wet climate conditions are apt to sequester carbon in soil (Kutsch and Kappen, 1997; Hyvonen et al., 2007; Ding et al., 2007; Davidson and Janssens, 2006), while high soil moisture can accelerate SOC decomposition under the same level of carbon input (Roldan et al., 2005).

It is also well know that soil properties have important enfluence on soil microbial properties, which drives the SOC dynamics (Stark et al., 2007). Soils rich in clay may have more potential to sequester cabon than those rich in sandy and silt in the similar climate zone, due to the physical protection of mineral on SOC (Matus et al., 2008). Our results indicate that soil high in clay in mid-temperate has higher convertion rate than that in the warm temperate area with low clay content though there is no significant relationship between the conversion rate and soil clay content.

5 Conclusions

We have studied SOC dynamics and its response to carbon input under various long-term fertilizations in the northern China. Our study indicates that long-term applications of inorganic fertilizaters (i.e. NP and NPK) shows decline trends in SOC in the arid and semi-arid areas with the mono-cropping systems. As expected, manure applications (e.g. the NPM, NPKM, hNPKM treatments) show significant effects on SOC at all the studied sites. Our study also shows that SOC response linearly to carbon input in arable land under mid-temperate and warm-temperate climates. There are about 15.8%–31.0% of annual carbon input that are converted into SOC during the studied periodes in the mid-temperate areas with the mono-cropping systems. However, the conversion rate is much lower (6.8%–7.7%) in the warm-temperate areas with the double cropping systems. While manure applications are necessary to maintain SOC level and sequester carbon in the mid-temperate areas with the mono-cropping systems, applications of manure, balanced inorganic fertilizations (NPK) and crop residue incorporation (NPKS) are sound practices to increase SOC and sequester more carbon in agricultural soils in the warm-temperate areas.

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Table 1. Basic description of the long-term experiment sites.

Sites[a]	Climate[b]	Soil classification		Altitude (m)	AMT[c] (°C)	Annual P[d] (mm)	Annual E[e] (mm)	Cropping system[f]
		In China	In FAO (FAO/Unesco, 1988)					
GZL	MT-SH	Black soil	Luvic Phaeozems	220	4.5	525	1400	MC-CCC
UC	MT-SA	Grey desert soil	Haplic Calcisol	600	7.7	310	2570	MC-CWW
ZY	MT-A	Irrigated desert soil	Anthrosol	1511	7.0	127	2345	MC-CWW
CP	WT-SH	Brown fluvo-aquic soil	Haplic Luvisol	20	11	600	2301	DC-CW
ZZ	WT-SH	Fluvo-aquic soil	Calcaric Cambisol	59	14.3	632	1450	DC-CW
XZ	WT-SH	Yellow fluvo-aquic soil	Calcaric Cambisol	20	14.5	832	2200	DC-CW

[a] GZL: Gongzhuling; UC: Urumqi; ZY: Zhangye; CP: Changping; ZZ: Zhengzhou; XZ: Xuzhou.

[b] MT-SH: Mild-temperate, semi-humid; MT-A: Mild-temperate, arid; MT-SA: Mild-temperate, semi-arid; WT-SH: Warm-temperate, semi-humid.

[c] AMT: annual mean temperature.

[d] P: precipitation.

[e] E: evaporation.

[f] MC-CCC: Mono-cropping, corn-corn-corn; MC-CWW: Mono-cropping, corn-wheat-wheat; DC-CW: Double-cropping, corn-wheat.

Table 2. Experiment design at the long-term experiment sites.

Sites	GZL	UC	ZY	CP	ZZ	XZ
Plot size (m^2)	400	468	33.3	200	400	33.3
CK	+	+	+	+	+	+
N	+	+	+	+	+	+
NP	+	+	+	+	+	+
NPK	+	+	+	+	+	+
NPM	−	−	+	−	−	+
NPKM	+	+	+	+	+	+
hNPKM	+	+	−	+	+	−
NPKS	+	+	−	+	+	−

+: the treatment is included;
−: the treatment is not included.

Table 3. Annual application rates (kg ha^{-1}) of inorganic nitrogen for various treatments.

Sites	Periods	Crops	N/NP/NPK	NPM/NPKM	hNPKM	NPKS
GZL[a]	1990-2005	Corn	165	50	74	165
UC[b]	1990–1994	Corn/wheat	99	30	60	89
	1995–2005	Corn/wheat	242	85	152	217
ZY[c]	1982–1990	Corn	240	240	–	–
		Wheat	120	120	–	–
	1991–2002	Corn	300	300	–	–
		Wheat	150	150	–	–
	2000	Corn	450	450	–	–
	2003	Corn	360	360	–	–
CP[b]	1990–2005	Corn	150	150	225	150
		Wheat	150	150	225	150
ZZ[b]	1990–2005	Corn	188	188	282	188
		Wheat	165	49.5	74.2	49.5
XZ[d]	1981–2001	Corn	150	150	–	–
		Wheat	150	150	–	–

[a] Phosphorus and potassium fertilizers, and one-third of nitrogen (N) fertilizer are applied as base fertilizers before seeding, two-third of nitrogen fertilizer as topdressing at the jointing stage.

[b] Phosphorus and potassium fertilizers and 60% of N fertilizer, are applied as base fertilizer before seeding, 40% of N fertilizer as topdressing at the jointing stage; Cotton was planted in 1999.

[c] Phosphorus and potassium fertilizers, and 50% of N fertilizer are applied as base fertilizer before wheat seeding, and the other 50% of N fertilizer as topdressing at three-leaf stage. For corn, 30%, 30%, and 40% of the N fertilizer are applied before seeding, at the jointing/elongation and 10- to 12-leaf (pretasseling) stages, respectively.

[d] Phosphorus and potassium fertilizers, and 50% of N fertilizer are applied as base fertilizers before wheat seeding, and the other 50% of N fertilizer as topdressing at the jointing stage.

Table 4. Annual application rates of organic carbon (C, t ha^{-1}) under the relevant fertilizations at the long-term experiment sites.

Sites	Period	Crops	Manure sources			NPM	NPKM	hNPKM	NPKS
			Source [a]	Organic C (g kg^{-1})[b]	C/N ratio				
GZL	1990–2005	corn	HM	36.0	20	–	3.86	5.79	0.93
UC	1990–2005	Corn/wheat	GM	33.6	17	–	2.82	5.64	1.47
ZY	1982–1990	Corn/wheat	FYM-soil	13.5	11	0.55	0.55	–	–
	1991–2001	Corn/wheat	FYM- soil	13.5	11	0.68	0.68	–	–
	2002–2003	Corn/wheat	FYM- soil	13.5	11	0.55	0.55	–	–
CP	1990–2005	Corn	–	–	–	–	0	0	0
		Wheat	FYM-S	17.4	20	–	3.15	4.72	1.00
ZZ	1990–2005	Corn	–	–	–	–	0	0	0
		wheat	HM	36.0	20	–	4.89	7.33	1.32
XZ [c]	1981–1984	Corn	HM	36.0	20	4.80	4.80	–	–
		Wheat	HM	36.0	20	4.80	4.80	–	–
	1985–2001	Corn	CM	36.8	23	2.40	2.40	–	–
		Wheat	CM	36.8	23	2.40	2.40	–	–

[a] HM: horse manure; GM: goat manure; CM: cow manure; FYM-soil: farmyard manure with soil as base material; FYM-S: farmyard manure with crop residue as base material.

[b] Organic C content in various sources of manure are estimated following NCATS (1994).

[c] Each plot was separated into two subplots for breeding experiments for wheat and corn from 1998 to 2001.

Table 5. Initial soil properties at the long-term experiment sites.

Sites	GZL	UC	ZY	CP	ZZ	XZ
SOC ($g\,kg^{-1}$)	13.0	8.8	11.5	7.1	6.7	6.5
Total N ($g\,kg^{-1}$)	1.42	0.91	0.86	0.80	0.67	0.66
C/N ratio	9.2	10.4	13.4	8.9	10.0	9.8
Total P ($g\,kg^{-1}$)	1.53	0.67	0.82	1.60	0.64	0.74
Total K ($g\,kg^{-1}$)	24.6	23.0	nd	17.3	16.9	22.7
Available N ($mg\,kg^{-1}$)	131.5	55.2	28.1	49.7	51.3	nd
Olsen-P ($mg\,kg^{-1}$)	23.3	3.4	21.7	12.0	6.5	12.0
Available K ($mg\,kg^{-1}$)	160	288	99	88	74	63
pH	7.2	8.1	nd	8.7	8.3	8.2
Clay (<0.002 mm) (%)	32.1	20.9	nd	10.2	13.4	6.0
Bulk density ($g\,cm^{-3}$)	1.19	1.25	1.20	1.58	1.24	1.25

nd: no data.

Table 6. Above-ground carbon biomass ($\mathrm{t\,ha^{-1}}$) averaged for the third five-year (i.e. from the 11th to 15th years) of fertilization at the long-term experiment sites.

Sites	GZL	UC	ZY	CP	ZZ	XZ
CK	2.86 a	2.17 a	1.73 a	3.24 a	4.73 a	4.12 a
N	6.88 b	3.96 ab	2.96 ab	3.48 a	4.62 a	5.89 b
NP	7.90 b	5.58 ab	5.32 bc	7.84 b	10.45 b	9.34 c
NPK	8.40 b	5.77 ab	5.85 c	9.68 c	11.32 bc	11.02 d
NPM	–	–	6.10 c	–	–	12.17 e
NPKM	9.04 b	5.96 ab	6.35 c	10.83 c	10.86 bc	12.59 e
hNPKM	9.58 b	6.56 b	–	11.18 c	11.74 c	–
NPKS	9.24 b	5.72 ab	–	9.81 c	11.56 bc	–

Values followed by the same letter in one column indicates that there is no significant difference (p=0.05).

Table 7. Slopes of surface (0–20 cm) SOC vs. fertilization time under various fertilizations at the long-term experiment sites.

Sites	GZL	UC	ZY	CP	ZZ	XZ
CK	0.006	−0.090**	−0.125**	0.094**	−0.049**	−0.026
N	−0.026	−0.050	−0.121**	0.070**	−0.003	0.014
NP	0.019	−0.006	−0.039	0.129***	0.03	0.045**
NPK	0.070	−0.089*	−0.060	0.078*	0.063*	0.033**
NPM	–	–	0.10**	–	–	0.22***
NPKM	0.41***	0.36***	0.10**	0.17***	0.16***	0.24***
hNPKM	0.403**	0.59***	–	0.26***	0.24***	–
NPKS	0.043	-0.014	–	0.15***	0.09**	–

Significant correlations are marked with one ($p<0.05$), two ($p<0.01$), and three ($p<0.001$) asterisks.

Table 8. Surface SOC (g kg^{-1}) averaged for the third five-year of fertilization

Sites	GZL	UC	ZY	CP	ZZ	XZ
CK	12.8 a	7.7 a	9.8 ab	8.2 a	6.1 a	5.3 a
N	12.6 a	8.6 a	9.5 a	8.3 a	6.6 b	6.5b
NP	13.2 a	8.9 a	11.2 c	9.0 bc	7.3 c	6.7 bc
NPK	14.1 a	8.4 a	11.0 bc	8.4 ab	7.4 c	7.1 c
NPM	–	–	12.6 d	–	–	11.8 d
NPKM	17.9 b	13.7 b	12.0 cd	9.7 d	9.1 e	11.7 d
hNPKM	19.2 b	16.8 c	–	10.5 e	9.9 f	–
NPKS	13.5 a	8.7 a	–	9.3 cd	8.4 d	–

Values followed by the same letter in one column indicates that there is no significant difference (p=0.05).

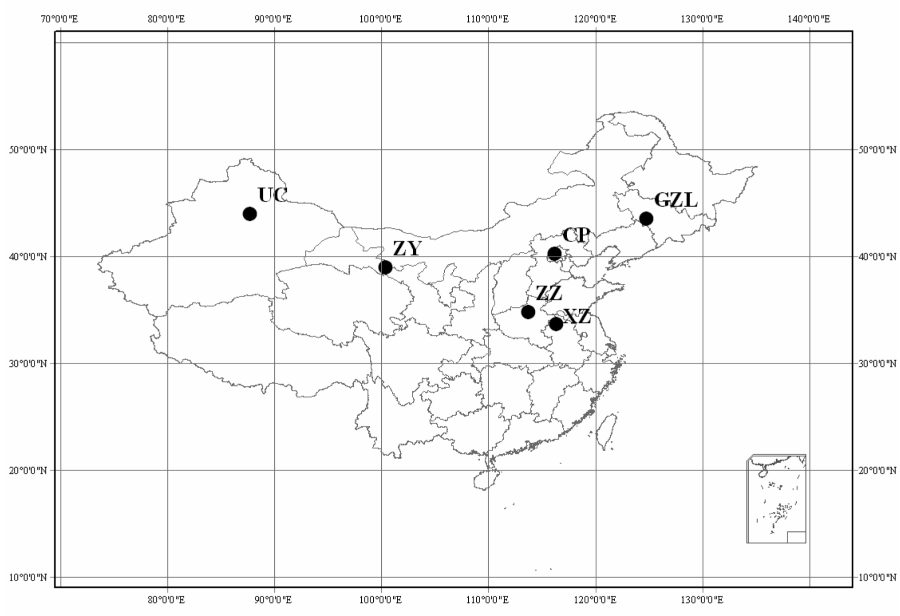

Fig. 1. Map of the long-term experiment sites. GZL: Gongzhuling; UC: Urumqi, ZY: Zhangye; CP: Changping; XZ: Xuzhou; ZZ: Zhengzhou.

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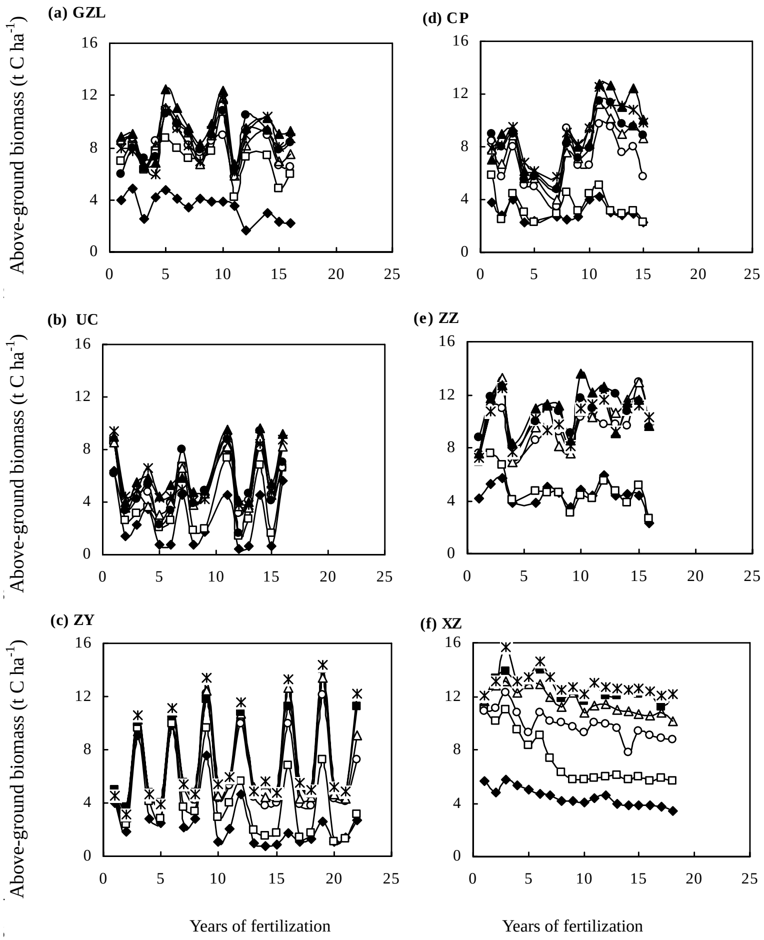

Fig. 2. Annual total above-ground carbon biomass under long-term fertilizations. ♦CK, □N, ○NP, △NPK, ■NPM, ✻NPKM, ▲hNPKM, ●NPKS.

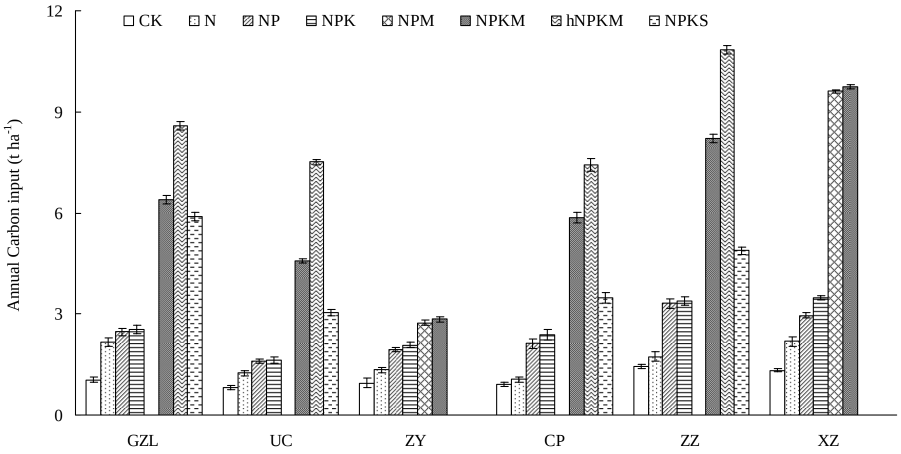

Fig. 3. Averaged annual carbon input (±S.E.) under various fertilizations during the studied periods.

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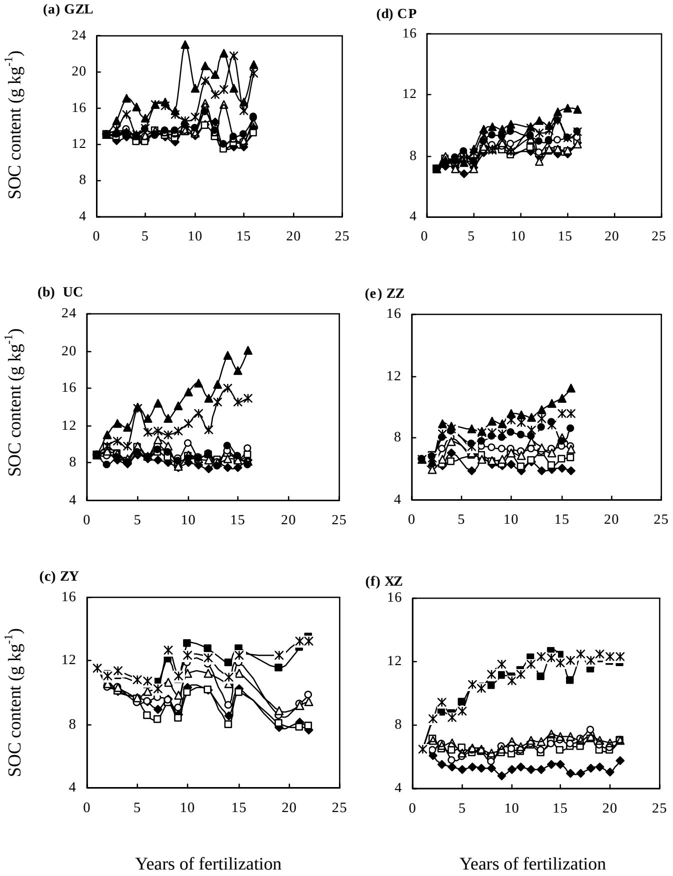

Fig. 4. Soil organic carbon content under long-term fertilizations. ◆CK, ☐N, ○NP, △NPK, ■NPM, ∗NPKM, ▲hNPKM, ●NPKS.

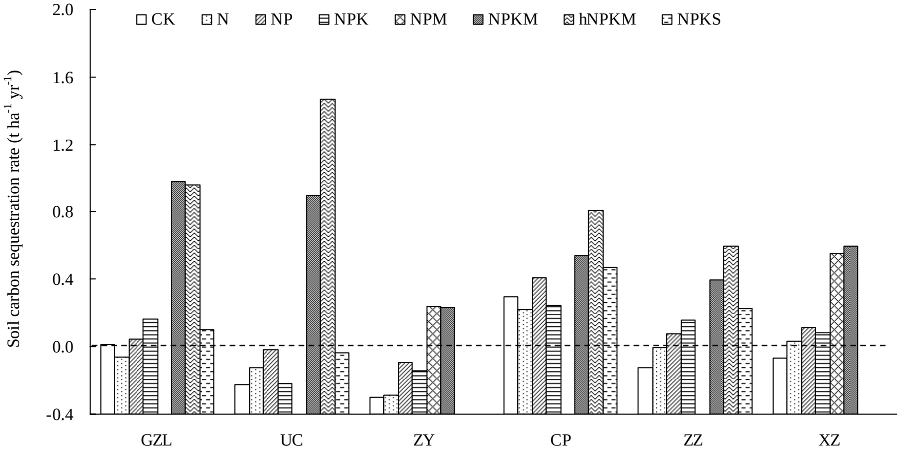

Fig. 5. Soil carbon sequestration rate averaged over the entire period of fertilizations.

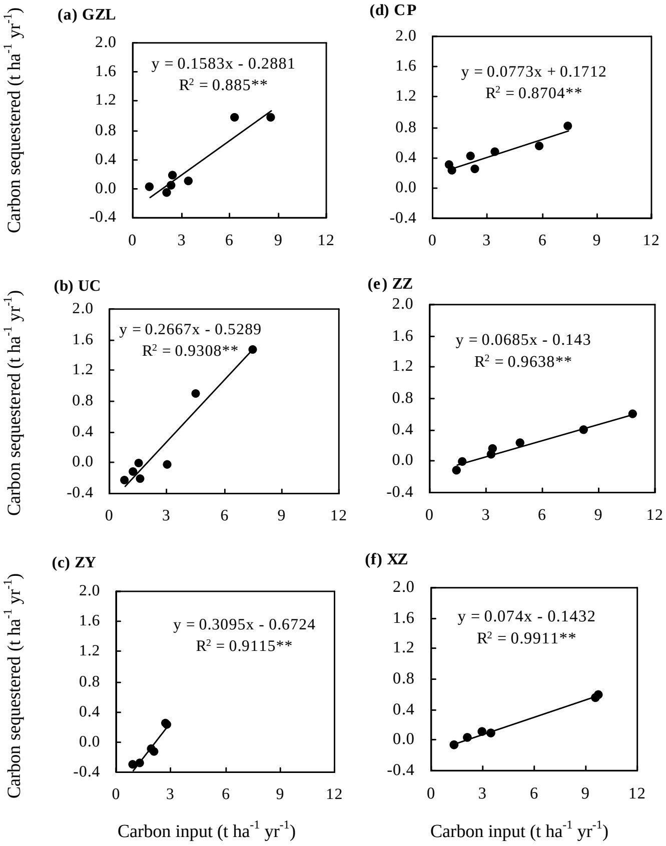

Fig. 6. Correlations between carbon sequestrated and carbon input. Significant correlations are marked with two ($p<0.01$) asterisks.

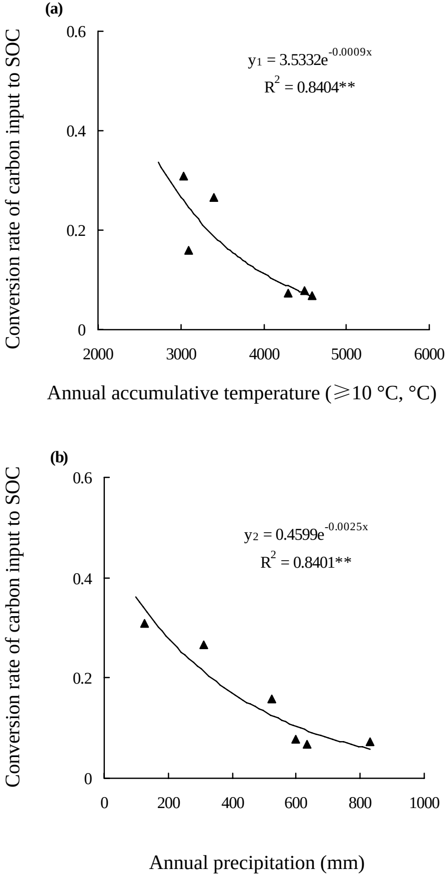

Fig. 7. Correlations between the conversion rates of carbon input to SOC and **(a)** annual accumulative temperature (°C) and **(b)** annual precipitation. Significant correlations are marked with two ($p<0.01$) asterisks.