SCIENCE CHINA
Life Sciences

July 2010 Vol.53 No.7: 766–775
doi: 10.1007/s11427-010-4022-4

Changes in soil organic carbon of terrestrial ecosystems in China: A mini-review

HUANG Yao[*], SUN WenJuan, ZHANG Wen & YU YongQiang

State Key Laboratory of Atmospheric Boundary Layer Physics and Atmospheric Chemistry (LAPC), Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing 100029, China

Received February 9, 2010; accepted March 10, 2010

The present study provides an overview of existing literature on changes in soil organic carbon (SOC) of various terrestrial ecosystems in China. Datasets from the literature suggest that SOC stocks in forest, grassland, shrubland and cropland increased between the early 1980s and the early 2000s, amounting to (71±19) Tg·a^{-1}. Conversion of marshland to cropland in the Sanjiang Plain of northeast China resulted in SOC loss of (6±2) Tg·a^{-1} during the same period. Nevertheless, large uncertainties exist in these estimates, especially for the SOC changes in the forest, shrubland and grassland. To reduce uncertainty, we suggest that future research should focus on: (i) identifying land use changes throughout China with high spatiotemporal resolution, and measuring the SOC loss and sequestration due to land use change; (ii) estimating the changes in SOC of shrubland and non-forest trees (i.e., cash, shelter and landscape trees); (iii) quantifying the impacts of grassland management on the SOC pool; (iv) evaluating carbon changes in deep soil layers; (v) projecting SOC sequestration potential; and (vi) developing carbon budget models for better estimating the changes in SOC of terrestrial ecosystems in China.

change, China, soil organic carbon, terrestrial ecosystem, uncertainty

Citation: Huang Y, Sun W J, Zhang W, *et al*. Changes in soil organic carbon of terrestrial ecosystems in China: A mini-review. Sci China Life Sci, 2010, 53: 766–775, doi: 10.1007/s11427-010-4022-4

As a consequence of human activity, the atmospheric carbon dioxide (CO_2) concentration has increased from a pre-industrial value of 280 to 385 ppmv in 2008 [1]. The fourth assessment report of the Intergovernmental Panel on Climate Change (IPCC) pointed out that most of the observed increase in global average temperatures since the mid-20th century is very likely due to the observed increase in anthropogenic greenhouse gas concentrations [2]. Moreover, model projections based on various SRES (Special Report on Emissions Scenarios) suggest that the global average temperature would likely increase by 1.1°C to 6.4°C by the end of the 21st century [2]. The rise in atmospheric CO_2 concentration is mainly attributed to an increase in global consumption of fossil fuels, although terrestrial ecosystems do play an important role in mitigating atmospheric CO_2 via plant photosynthesis. Over the period 2000–2005, global CO_2 emissions from fossil fuel consumption and cement production averaged 7.2 Pg C·a^{-1} (1 Pg=10^{12} kg), and the global terrestrial carbon sink averaged 0.9 Pg C·a^{-1} [2], offsetting 12.5% of the CO_2 emission.

World soils hold 1500 Pg [3] of organic carbon in the terrestrial systems; twice that in the atmosphere, and 2–4 times that in the terrestrial biomass [4,5]. The soil organic carbon (SOC) stocks in China were estimated to be 70–90 Pg in the early 1980s [6–9]. Changes in SOC stocks affect the atmospheric CO_2 concentration [10,11]. Any practices that increase the photosynthetic input of carbon (C) into the soils or slow the release of soil C, will increase the amount of stored carbon, thereby sequestering C from the atmosphere. Since the industrial revolution, global land use

---

[*]Corresponding author (email: huangy@mail.iap.ac.cn)

change and agricultural cultivation have induced C losses of (136±55) Pg [12]. According to Lal [13], the global potential for soil carbon sequestration could reach 0.4–1.2 Pg C·a^{-1}, offsetting 5%–15% of fossil fuel CO_2 emissions.

Climate change, induced by increasing atmospheric CO_2 and other greenhouse gases, has affected human well-being, and sustainable social and economic development. To mitigate the increase of atmospheric CO_2, the improvement of SOC sequestration has been gaining international interest [14]. Over the last decade, Chinese scientists have made great efforts to evaluate SOC changes in various terrestrial ecosystems. This paper provides an overview of existing literature on SOC changes in forest, grassland, shrubland, cropland and wetland in China. We attempt to clarify the changes in SOC over the last three decades, evaluate uncertainties in the estimated SOC change, and address future research needs.

1 Changes in SOC

1.1 Forest

China has a large area of plantation forests, and the forest area ranks fifth in the world. According to the 6th national forest inventory (completed during 1999–2003) [15], the forest area was 174.9 Mha and the forest coverage was 18.2% of China, which was 59.6 Mha and 6.2% higher, respectively, than those in the 2nd national forest inventory (completed during 1977–1981).

Changes in forest SOC estimated by various researchers, are widely divergent (Table 1). Based on a multiple regression equation of SOC that depends on a normalized difference vegetation index (NDVI) and climatic factors (temperature and precipitation), Piao *et al*. [16] estimated an increased rate of (4.0±4.1) Tg C·a^{-1} (1 Tg=10^9 kg) between 1982 and 1999. By adopting the rate of SOC sequestration in European forests, Xie *et al*. [9] estimated that forest soils in China have sequestered carbon over the last two decades by an annual amount of 11.7 Tg C·a^{-1}. Simulations using a biogeochemical model (InTEC) suggest that forest SOC increased at a rate of 7.84 Tg C·a^{-1} during 1950–1987, but declined sharply at a rate of 61.54 Tg C·a^{-1} during 1988–2001 [17]. Chen *et al*. [18] estimated that Chinese forest soils lost 6.0 Tg C·a^{-1} based on a model simulation. As for SOC density, the estimated SOC change by Xie *et al*. [9] agrees with that by Piao *et al*. [16] over a similar period (Table 1).

Forest types in China show great diversity and are distributed across a vast area spanning wide ranges of temperate, subtropical and tropical climates. The major types of forest from the north to the south of China are coniferous, conifer-broadleaf mixed, evergreen-broadleaf, monsoon and rain forests. Although Shao *et al*. [19] calibrated the InTEC model using the measurements of forest SOC at two sites (Liping County, Guizhou Province in southwest China and Changbai Mountain in northeast China), such a limited calibration could not allow for upscaling the model to all the forests across China. Estimates using the InTEC model (Table 1) may remain uncertain due to insufficient calibration and validation. The model simulations by Chen *et al*. [18] did not take into account reforestation and afforestation in China, also resulting in an improper estimate. However, disregarding the model's limitations, the changes in SOC density of Chinese forest was calculated to be (36±33) kg·a^{-1} when taking both estimates by Xie *et al*. [9] and Piao *et al*. [16] into account. Using the forest area of 130 Mha (mean of 1980–2000) [16], the SOC sequestration rate in China was estimated to be (4.7±4.3) Tg C·a^{-1}, which is mainly attributed to reforestation and afforestation [20,21].

1.2 Grassland

Natural grassland in China is approximately 400 Mha, accounting for 41.7% of the nation [15]. The majority of grassland is distributed in the western and northern regions, with northern grassland accounting for approximately 78% of the total grassland in China [22]. Although grassland in China plays an important role in carbon cycling, few studies have been dedicated to estimating the changes in grassland SOC on a national scale. Based on a multiple regression equation of SOC that is driven by NDVI and climatic factors, Piao *et al*. [16] estimated that the rate of increase of SOC in Chinese grassland (331 Mha) was (6.0±1.0) Tg C·a^{-1} between 1982 and 1999. However, no significant

Table 1 Estimated changes in SOC of Chinese forests

Period	Acreage /Mha	Soil depth /cm	Changes in SOC		Method	Reference
			C storage /Tg·a^{-1}	C density /kg·ha^{-1}·a^{-1}		
1980s–2000s	249	NA*	11.72	47	Rate of SOC change × Forest area	[9]
1982–1999	130	NA	4.0±4.1	31±32	Statistic model	[16]
1950–1987	167	0–30	7.84	47	Biogeochemical model (InTEC)	[17]
1988–2001	167	0–30	−61.54	−368	Biogeochemical model (InTEC)	[17]
1982–2002	130	NA	−6.00	−46	Biogeochemical model (FORCCHN)	[18]

* Not available.

changes in SOC of northern grassland and Qinghai-Tibetan alpine grassland (total 196 Mha) were found over the same period by Yang *et al.* [23,24] who analyzed a large number of field measurements. This is inconsistent with Piao *et al.* [16]. Using carbon sink ratios for Europe where the soil carbon sink accounts for 30% of the total carbon sink [25] and for the United States where the soil carbon sink is about two-thirds of the vegetation carbon sink [26], we estimated the soil carbon sink to range from 3 to 4.7 Tg C·a^{-1} in Chinese grasslands when a vegetation carbon sink of 7 Tg C·a^{-1} (mean of 1981–2000) [21] was adopted. Merging these two values and the estimate by Piao *et al.* [16], the rate of increase in SOC stocks in Chinese grasslands was estimated to be (4.9±1.6) Tg C·a^{-1}, but uncertainties still exist in this estimate.

1.3 Cropland

China is a typical agricultural country, with arable land of 130 Mha and an annual harvest area of 150 Mha. Compared with natural ecosystems, SOC in cropland shows great sensitivity to human activities such as tillage, fertilization and irrigation. With the adoption of recommended management practices, the global potential of C sequestration was estimated to be 0.4–0.9 Pg C·a^{-1} in agricultural soils [13,27].

By a synthetical analysis of datasets extracted from 132 publications, Huang and Sun [28] reported that the concentration of SOC increased in 53%–59%, decreased in 30%–31% and stabilized in 4%–6% of the national croplands. As a whole, the cultivated layer (0–20 cm) of cropland soils in China sequestered 15–20 Tg C·a^{-1} between 1980 and 2000 [28]. A further investigation showed that the average rate of SOC sequestration in the topsoil to ~30 cm depth ranged from 16.6–27.8 Tg C·a^{-1} over the same period [29]. Recent estimates of SOC sequestration in Chinese cropland made by Xie *et al.* [9], Lu *et al.* [30], Yu *et al.* [31] and Pan *et al.* [32] are similar to estimates by Huang and Sun [28]. By running a biogeophysical model Agro-C [34] that has been widely validated in China, Huang *et al.* [33] estimated that the annual rate of increase of SOC in Chinese croplands was 14.5–20.3 Tg C·a^{-1} from 1980 to 2000.

Combining the estimates from various studies (Table 2), the increase in SOC density was estimated to be (167±33) kg·ha^{-1}·a^{-1} over the last two decades. Accordingly, the average rate of SOC sequestration in Chinese cropland that covers an area of over 130 Mha was (21.7±4.3) Tg C·a^{-1} during this period. This is substantially attributed to the improvements in crop production [35], residue incorporation, manure amendment and extension of zero and reduced tillage practices [28,30].

1.4 Shrubland and wetland

Shrubland is a widely distributed biome type in China, covering about 200 Mha [16,21]. However, few studies have dealt with the changes in vegetation and soil carbon. By employing a multiple regression equation of SOC that is driven by NDVI, temperature and precipitation, Piao *et al.* [16] reported that the increase in SOC of shrubland (215 Mha) in China averaged (39.4±9.0) Tg C·a^{-1} during 1982–1999, which is higher than that of forest (Table 1), grassland and cropland (Table 2). By examining the regression equation [16], it appears that NDVI contributes greatly to the increased SOC. However, this statistical equation is only able to interpret 33% of the observed SOC variation. Estimates using this type of regression equation do not provide a high level of confidence.

Wetland in China is about 65.9 Mha excluding rivers and ponds, of which natural wetland is ~25.9 Mha. Marshland is the largest natural wetland in China, covering an area of ~12 Mha [36]. The Sanjiang Plain, located in northeast China, was formerly the largest marshland complex with a total area of 5.35 Mha in the early 1950s. An estimated ~3 million ha of marshland in this region was converted to cropland over the period 1950–2000 [36–38]. According to Huang *et al.* [38] and Liu *et al.* [39], marshland conversion resulted in a loss of 218–240 Tg SOC during this period. The annual carbon loss was estimated to be (6.2±1.8) Tg·a^{-1}

Table 2 Changes in SOC of Chinese croplands

Period	Area /Mha	Soil depth /cm	Changes in SOC		Method	Reference
			C storage /Tg·a^{-1}	C density /kg·ha^{-1}·a^{-1}		
1980–2000	118	20	15.6–20.1	132–170	Meta-analysis	[28]
1980s–2000s	156	~20	23.6	151	Meta-analysis	[9]
1980–2000	130	30	16.6–27.8	128–214	Meta-analysis	[29]
2000s	118	NA*	16.5	140	Statistical model	[30]
1985–2006	130	20	22.2–27.6	171–212	Meta-analysis	[32]
1980–2000	98	30	14.5–20.3	148–207	Biogeophysical model (Agro-C)	[33]

* Not available.

between 1980 and 2000 [38].

2 Uncertainties

2.1 Land use change

Land use/cover change is one of the key driving forces of carbon cycling in terrestrial ecosystems. Conversion of one land use to another might lead to a change in SOC storage. As far as the impact of land use change on the terrestrial carbon budget is concerned, conversions among forest, grassland and cropland have been given special attention [51–53].

Using forest inventory data for the periods of 1989–1993 and 1999–2003, Fang *et al.* [21] estimated that the forest (20% canopy coverage) area in China increased by 11 Mha between the two periods. By contrast, Liu *et al.* [53] who used Landsat™ images in 1990 and 2000 reported that the forest and grassland areas decreased by 1.0 Mha and 3.35 Mha, respectively, and the cropland area increased by 4.05 Mha between 1990 and 2000. The conversion of forest and grassland to cropland resulted in a SOC loss of 74.9 Tg and 87.4 Tg, respectively, during this period [53]. The average loss of SOC is thus 7.5 Tg·a^{-1} and 8.7 Tg·a^{-1}, respectively, which is even higher than the estimated SOC sequestration in forests by Piao *et al.* [16] (Table 1).

A large number of studies have indicated an improvement in vegetation and soil C accumulation when conversion of cropland to forest, afforestation and reforestation are implemented [54–59]. Zhou *et al.* [60] reported that old-growth forests (stand age greater than 400 years) in southern China can still accumulate carbon in soils at 610 kg $\text{C·ha}^{-1}\text{·a}^{-1}$. A meta-analysis of large datasets by Post and Kwon suggested that conversion of cropland to woodland could accumulate C at an average rate of 33.8 g $\text{C·m}^{-2}\text{·a}^{-1}$, lasting 50–100 years [61], while conversion of grassland to pine forest led to SOC loss [62]. Duan *et al.* [63] reported that SOC in a *Cryptomeria fortunei* plantation in Sichuan Province increased with stand age (Figure 1A), but Wang *et al.* [64] found that conversion of cropland to woodland in Jilin Province reduced SOC during the initial years of the plantation (Figure 1B). Similar results have been reported by Paul *et al.* [65], Huang *et al.* [66] and Bai *et al.* [67].

The afforestation area of cash, shelter and landscape trees in China increased significantly in the last three decades. Taking the shelter trees as an example, the area of plantation increased by 53 Mha from 1978 to 2007 [68]. During the period of 2003–2007, the plantations of shelter trees accounted for 73% of the national afforestation (Figure 2). Although the afforestation of cash, shelter and landscape trees in China may have increased C accumulation in soils [69–71], the rates of SOC accumulation are far from understood.

2.2 Grassland management

Over the last three decades, overgrazing and irrational reclamation of grassland have become increasingly serious issues in China. Overgrazing has been recognized as a principal factor in the degradation of Chinese grassland [22]. According to the 2006 Report on the State Environment in China, 204 counties in 266 semi-pastoral and semi-agricultural regions were overgrazed. On average, the livestock density in natural grassland was ~34% higher than that for normal grazing [15]. The degradation rate of grassland was estimated to be 1.3 Mha·a^{-1} in the late 1980s and 2.0 Mha·a^{-1} in the early 2000s. As a result, about 90% of the natural grassland in China has degraded to some degree [20]. In the major pastoral region of north China, degraded grassland accounted for 39.7% of the total available grassland in the mid-1980s. This value increased to 50.2% in the mid-1990s when the pastures with light, moderate and heavy grazing accounted for 57.3%, 30.5% and 12.2% of the total degraded grassland [72], respectively. To prevent grassland from further degradation, the Chinese government has implemented a comprehensive program. For example, the enclosed area of grassland was 52.5 Mha, and the areas where grazing was forbidden and rest-rotation grazing management was performed amounted to 86.6 Mha until 2006 [20].

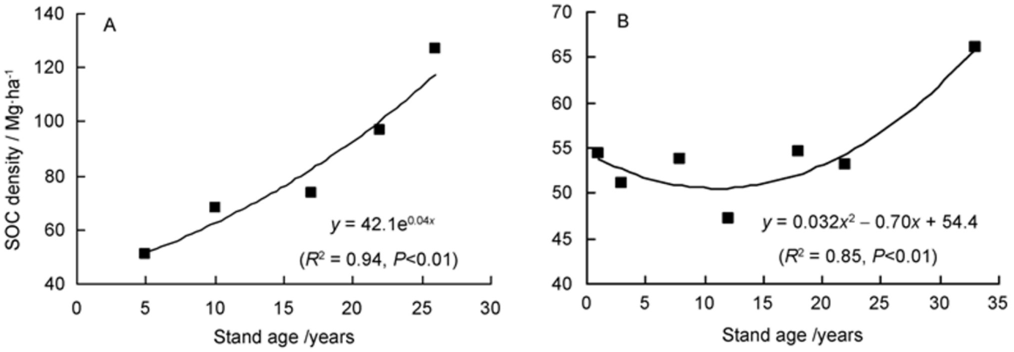

Figure 1 Changes in woodland SOC with different stand age. (A) *Cryptomeria fortunei* at Pengzhou County, Sichuan Province. Data source: Duan *et al.* [63]; (B) *Larix olgensis* at Dunhua, Jilin Province. Data source: Wang *et al.* [64].

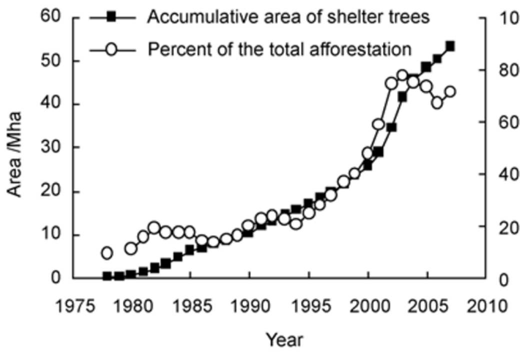

Figure 2 Plantation area of shelter trees and its percentage of the total afforestation area in China, 1978–2007. Data source: National Bureau of Statistics of China [68].

Grassland degradation induces a loss of SOC [73,74]. Analysis of paired datasets extracted from the literature [75–78], showed that SOC stocks in the lightly, moderately and severely degraded pastures were (27±8)%, (49±4)% and (55±3)%, respectively, lower than that in non-degraded pasture (Figure 3A). The SOC also declined significantly with increasing grazing intensity [79–82]. SOC stocks in the lightly, moderately and heavily grazed pastures were (30±12)%, (35±14)% and (50±15)%, respectively, lower than that in non-grazing pasture (Figure 3B). In degraded grasslands, enclosures not only promoted plant growth but also improved SOC accumulation [83–89]. The SOC was found to increase by 28% after 20 years of enclosure, and by 1.6 and 4.5 times after 14–23 and 40–50 years of vegetation restoration, respectively, when compared with that in the initial 0–4 years (Figure 3C).

A meta-analysis by Shi *et al.* [92] indicated that SOC in the light-, moderate-, heavy- and over-grazed grasslands changed at the rates of –0.54 (range of 0.04 – –1.94), –0.49 (range of –0.42 – –3), –1.52 (range of –0.52 – –3.75) and –2.34 (range of –0.85 – –5.62) $\mathrm{Mg \cdot ha^{-1} \cdot a^{-1}}$, respectively. Enclosure and grazing forbidden areas were found to promote SOC accumulation at the rates of 0.48 (0.28–2.23) and 0.19 (0.04–0.68) $\mathrm{Mg \cdot ha^{-1} \cdot a^{-1}}$, respectively [92]. Shi *et al.* [92] reported that the losses of SOC in the grassland with various grazing intensities exceeded the SOC increase in enclosure and grazing forbidden grassland. Although there is substantive evidence that human activities have significantly affected SOC stocks in China's grasslands over the last three decades, the quantities of human-induced SOC changes have not been determined on a national scale.

2.3 Organic carbon change in deep soil layers

The estimates of SOC change have generally focused on surface soil layers (Tables 1 and 2), but changes in organic carbon may occur in deep soil layers. Boddey *et al.* [93] analyzed the paired datasets of long-term field experiments conducted in different regions of Brazil, and found that there were significant accumulations of SOC in zero-till soils, when studying the soil profile down to 100 cm depth. On average SOC accumulation to 100 cm depth was 59% greater than that to a depth of 30 cm [93]. However, other studies suggested that an increase in SOC occurred only in the upper soil layers when no-tillage was practiced [94,95].

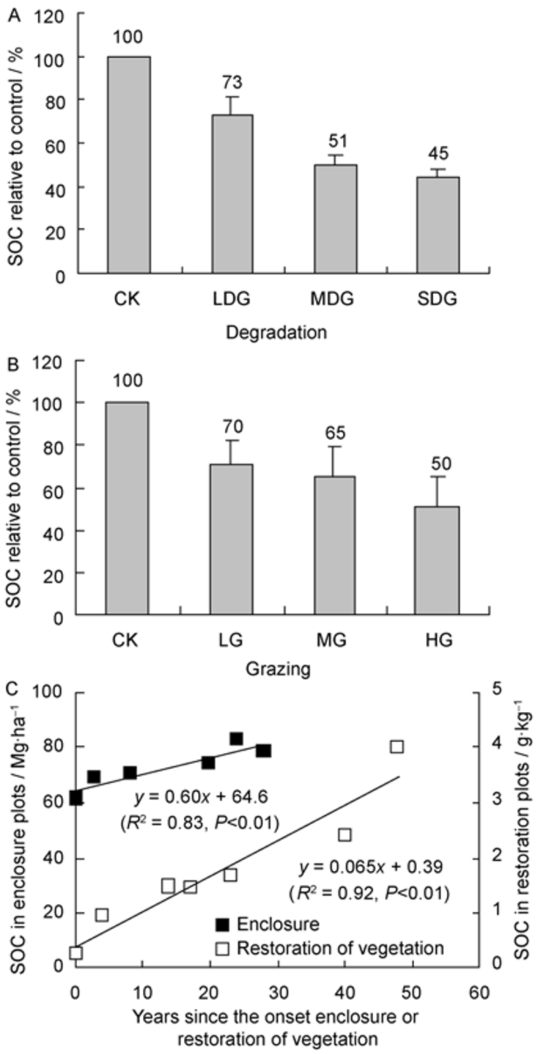

Figure 3 Impact of degradation, grazing and grassland management on SOC. (A) SOC in grassland with different degrees of degradation. LDG, MDG and SDG represent the lightly, moderately and severely degraded grassland, respectively. CK is the non-degraded grassland. Data sources: Qiu *et al.* [75], Liu *et al.* [76], Zhou *et al.* [77] and Wang *et al.* [78]. (B) Impact of grazing intensity on SOC. LG, MG and HG refer to the light, moderate and heavy grazing grassland, respectively. CK is the non-grazing grassland. Data sources: Pei *et al.* [79], Dong *et al.* [81] and Qiu *et al.* [82]. (C) Impact of grassland enclosure and vegetation restoration on SOC. Data sources: Wu *et al.*[90] and Jia *et al.* [91].

Due to limitations in human and financial resources, less attention has been directed to the accumulation and decomposition of carbon in deep soil layers. Analysis of limited data from the literature [64,96–100] suggests that the accumulation of organic carbon may occur in deep soil layers when agricultural management is optimized and cropland is converted to woodland or grassland (Figure 4). Optimizing fertilization (i.e. optimal combination of NPK, synthetic fertilizer plus manure) increased SOC by ~12% (Figure 4A) in the soil layers as deep as 40–100 cm. The SOC accumulation to 100 cm depth was 55% greater than that to a depth of 30 cm when cropland was reverted back into woodland (Figure 4B). Similarly, the increase in SOC to 60 cm depth was 11% higher than that to a depth of 30 cm when measured 12 years after cropland was reverted back into grassland (Figure 4C). Thus, there is reason to presume that the SOC accumulation in China may have been underestimated.

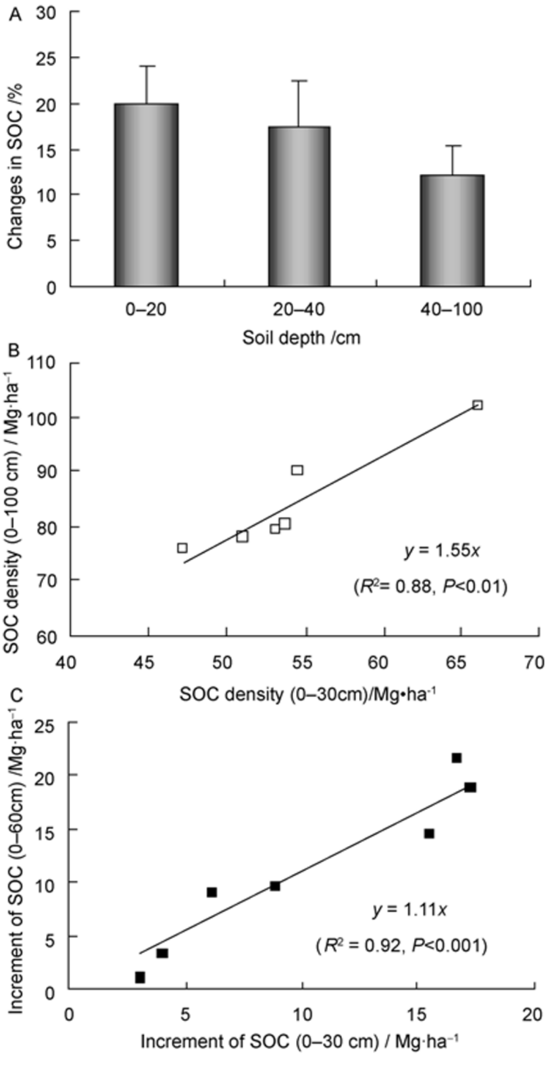

Figure 4 Influence of managements on the SOC change in different soil layers. (A) Fertilization impact on changes in SOC (5 experimental sites with 17 treatments). To make comparisons, changes in SOC were expressed as a percentage. For instance, the SOC change in the plots received chemical fertilizer and organic manure was calculated relative to the plots receiving chemical fertilizer only by $(SOC_{\mathrm{CF+OM}} - SOC_{\mathrm{CF}})/SOC_{\mathrm{CF}} \times 100\%$, where $\mathrm{SOC}_{\mathrm{CF+OM}}$ and $\mathrm{SOC}_{\mathrm{CF}}$ represent SOC content or density in the plots receiving chemical fertilizer and organic manure, and chemical fertilizer only, respectively. Data sources: Gu *et al*. [96], Fan *et al*. [97] and Shi *et al*. [98]. (B) Relationship of SOC density to 100 cm with that to 30 cm after 3–33 years of reverting cropland to woodland (*Larix olgensis*). Data source: Wang *et al*. [64]. (C) Relationship of SOC increment to 60 cm with that to 30 cm after 12 years of reverting cropland to grassland with different management practices. The SOC increment is calculated by SOC relative to mowing treatment. Data source: Franzluebbers and Stuednemann [99].

2.4 Approaches to the estimation of SOC change

Changes in SOC are usually estimated by using the measurements of SOC over a significant period [101]. The measurement-based approach needs a much higher density of monitoring sites to ensure that they are representative of the actual range of environmental and management conditions. Theoretically speaking, more sites in a given area lead to better representation, but this is difficult to put into practice. In general, the precision of measurement could be improved with an increased number of monitoring sites. The monitoring sites would exponentially increase for an improvement in the precision [102]. To reduce uncertainties in the estimates of SOC change, measurements should be made at a sufficient number of sites, allowing for upscaling of these site-specific measurements to a finite area [24,103]. Unfortunately, the measurements of SOC in woodland and shrubland in the 2000s are rather deficient in China, which inevitably introduces errors into measurement-based estimates.

There is an effective approach to evaluating the impact of land-use conversion or management measures on terrestrial carbon balance, which is based on the analysis of a large number of literature datasets [28–32,59,92]. Laganière *et al.* [59] extracted 189 paired datasets from publications. These datasets included the SOC accumulation in 120 monitoring sites distributed globally where the cropland and grassland were converted to woodland. A meta-analysis of these datasets suggested that key factors controlling SOC restoration were the land use before conversion, tree species, climate, and soil clay fraction [59].

Model estimation of terrestrial carbon budgets is becoming increasingly popular on regional and global scales, but the validity of the models, utility of model input parameters, and upscaling processes may restrict the accuracy of the estimates [33,104,105]. Piao *et al.* [16] developed regression models to estimate the changes in SOC. These models took temperature, precipitation and biomass production into account, but explained only 23%–53% of the variation in the observed values for SOC storage. Upscaling of these models to a national scale will no doubt yield low reliability of the estimates.

Using a biogeochemical model DNDC and 1990 conditions, Li *et al.* [106] estimated that China's croplands lost 95 Tg $\mathrm{C{\cdot}a^{-1}}$, being equivalent to 1.6% of their SOC (0–30 cm), and that U.S. cropland lost 7 Tg $\mathrm{C{\cdot}a^{-1}}$. By contrast, the U.S. Environmental Protection Agency estimated that agricultural soils in U.S. sequestered 15.7 Tg $\mathrm{C{\cdot}a^{-1}}$ in 1990 [107]. Examining the estimates of DNDC, we concluded that the amount of carbon input in China's croplands may have been underestimated. Based on 2112 measurements at 300 agrometeorological stations across China, Zhang and Zhu [108] reported that the ratio of aboveground residue to crop yield, ranged from 1.30 to 2.99 for the majority of crops, while the ratio derived from the DNDC simulation was 0.94–0.97.

The low ratio of aboveground residue to crop yield could have resulted in an underestimation of the residue production, which consequently led to a reduction of residue carbon input in the DNDC simulation. Moreover, the ratio of root to shoot ranged from 0.07 to 0.11 for the majority of crops in China [109], while the derived ratio from DNDC simulation was 0.057–0.060. The estimated loss of SOC using DNDC [107] may be largely attributed to an underestimation of organic carbon input in the model simulation.

3 Conclusions and perspectives

There have been significant changes in SOC stocks in terrestrial ecosystems in China over the last three decades. The average rate of SOC sequestration from the early 1980s to early 2000s was 4.7±4.3 $\mathrm{Tg\cdot a^{-1}}$ in woodland (124–143 Mha), 4.9±1.6 $\mathrm{Tg\cdot a^{-1}}$ in grassland (331 Mha), (39.4±9.0) $\mathrm{Tg\cdot a^{-1}}$ in shrubland (200 Mha) and (21.7±4.3) $\mathrm{Tg\cdot a^{-1}}$ in cropland (130 Mha), giving a total of (71±19) $\mathrm{Tg\cdot a^{-1}}$. Conversion of marshland to cropland in the Sanjiang Plain of northeast China resulted in SOC losses of (6±2) $\mathrm{Tg\cdot a^{-1}}$ during the same period. Nevertheless, large uncertainties exist in these estimates. These uncertainties come primarily from the identification of land use change, the impacts of cropland and grassland management on SOC, and the estimation of organic carbon change in deep soil layers. When terrestrial carbon models were used to estimate the changes in SOC, validity of the models, utility of the model input parameters, and upscaling processes restricted the accuracy of the estimates.

To objectively estimate the changes in SOC stocks of Chinese terrestrial ecosystems and reduce uncertainties in the estimates, future research should focus on the following aspects:

(i) Land use change and its impact on SOC. Conversions among woodland, grassland and cropland lead to changes in SOC with temporal continuity [53,59,61–65]. Landsat data have been used to identify land use change with high temporal resolution, which makes it possible to estimate SOC change with temporal continuity [53].

(ii) Impact of grassland management on the SOC pool. Overgrazing has been recognized as a principal factor in the degradation of Chinese grassland. To prevent grassland from further degradation, the Chinese government has taken a series of measures, including enclosure of grassland, rest-rotation and forbidding grazing management [15]. The impacts of grassland degradation and restoration on the SOC pool should be quantitatively evaluated on a national scale.

(iii) Estimation of SOC changes in shrubland and non-forest woodland. Shrubland in China is widely distributed and restores quickly, suggesting an important potential carbon sink [21]. However, such a carbon sink is far from being understood [21]. The planted area of cash trees, shelter trees and landscape trees has increased significantly over the last three decades [68], which may have promoted carbon accumulation not only in vegetation, but also in the soil. Taking into account SOC accumulation in these areas, the SOC sequestration in Chinese woodland should be higher than the current estimates, but this needs to be clarified.

(iv) Measurement and evaluation of changes in SOC in deep soil layers. There is evidence that the conversion of one land-use type to another, and changing field management, alters the carbon balance in deep soil layers. Insufficient measurements of SOC down to significant soil depths make it extremely difficult, or even impossible, to fully take into account SOC changes on a national scale. Hence, more effort should be made in the measurement, and the evaluation, of changes in SOC in deep soil layers.

(v) Evaluation of soil C sequestration potential. According to the National Plan for Ecological and Environmental Protection, the Forestry Action Plan on Climate Change, and the National Plan for Food Production and Development (2006–2020), the Chinese government has been implementing the Grain-to-Green program (i.e. reversion of cropland to woodland or grassland), making considerable efforts in controlling soil erosion and desertification, constructing man-made pastures, improving grassland, increaseing crop residue retention, and extending conservation tillage in agriculture. All of these will no doubt promote SOC sequestration. Evaluation of SOC sequestration potential is of great importance for a mitigation policy developed from the best available knowledge on the terrestrial carbon balance in China.

(vi) Model development and application. Model estimations of terrestrial carbon budgets are becoming increasingly significant on regional and global scales [52]. Models not only help to quantify the spatiotemporal changes in terrestrial carbon balance in the past and at the present, but are able to evaluate carbon sequestration potential and project future changes. In recent years, several terrestrial ecosystem models have been developed in China. The validity and utility of these models need to be further improved, especially when extrapolating them to a wider domain [33]. Moreover, the uncertainties of existing model estimates should be quantified.

This work was jointly supported by the A3 Foresight Program (*Grant No. 30721140306*), *National Science Foundation of China, the Knowledge Innovation Program* (*Grant No. KZCX2-YW-Q1-15*), *Chinese Academy of Sciences, and the National High-Tech Research and Development Program of China* (*Grant No. 2009AA12Z1462*).

1 World Meteorological Organization. The State of Greenhouse Gases in the Atmosphere Using Global Observations through 2008. WMO Greenhouse Gas Bulletin, Switzerland, 2009

2 IPCC. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press, 2007

3 Batjes N H. Total carbon and nitrogen in the soils of the world. Eur J

Soil Sci, 1996, 47: 151–163

4 Lal R. World soils and the greenhouse effect. Global Change News Lett, 1999, 37: 4–5

5 Watson R T, Noble I R. Carbon and the science-policy nexus: the Kyoto challenge. In: Steffen W, Jager J, Carson D, *et al*. eds. Challenges of a Changing Earth. Proceedings of the global change open science conference. Berlin: Springer, 2001. 57–64

6 Wu H B, Guo Z T, Peng C H. Distribution and storage of soil organic carbon in China. Global Biogeochem Cy, 2003, 17: 1048–1058

7 Yu D S, Shi X Z, Wang H J, *et al*. National scale of soil organic carbon storage in China based on Chinese Soil Taxonomy. Pedosphere, 2007a, 17: 11–18

8 Yu D S, Shi X Z, Wang H J, *et al*. Regional patterns of soil organic carbon stocks in China. J Environ Manage, 2007b, 85: 680–689

9 Xie Z B, Zhu J G, Liu G, *et al*. Soil organic carbon stocks in China and changes from 1980s to 2000s. Glob Change Biol, 2007, 13: 1989–2007

10 Cox P M, Betts R A, Jones C D, *et al*. Acceleration of global warming due to carbon-cycle feedbacks in a coupled climate model. Nature, 2000, 408: 184–187

11 Davidson E A, Janssens I A. Temperature sensitivity of soil carbon decomposition and feedbacks to climate change. Nature, 2006, 440: 165–173

12 Lal R. Soil carbon sequestration to mitigate climate change. Geoderma, 2004, 123: 1–22

13 Lal R. Soil carbon sequestration impacts on global climate change and food security. Science, 2004, 304: 1623–1627

14 Food and Agriculture Organization of the United Nations. Soil carbon sequestration for improved land management. Rome, 2001, 17–43

15 State Environmental Protection Administration. 2006 Report on the State Environment in China (in Chinese). Beijing: 2007. 82–89

16 Piao S L, Fang J Y, Ciais P, *et al*. The carbon balance of terrestrial ecosystems in China. Nature, 2009, 458: 1009–1013

17 Wang S, Chen J M, Ju W M, *et al*. Carbon sinks and sources in China's forests during 1901—2001. J Environ Manage, 2007, 85: 524–537

18 Chen P Q, Wang X K, Wang L M, *et al*. Carbon Budgets of Terrestrial Ecosystems and Countermeasures to Achieve Carbon Sink in China (in Chinese). Beijing: Science Press, 2008. 116–117

19 Shao Y, Pan J, Yang L, *et al*. Validation of soil organic carbon density using the InTEC model. J Environ Manage, 2007, 85: 696–701

20 State Environmental Protection Administration. 2008 Report on the State Environment in China (in Chinese). Beijing: 2009. 54–56

21 Fang J Y, Guo Z D, Piao S L, *et al*. Terrestrial vegetation carbon sinks in China, 1981—2000. Sci China Ser D-Earth Sci, 2007, 50: 1341–1350

22 Chen Z Z, Wang S P. Typical Grasslands Ecosystem of China (in Chinese). Beijing: Science Press, 2000. 1–5

23 Yang Y H, Fang J Y, Smith P, *et al*. Changes in topsoil carbon stock in the Tibetan grasslands between the 1980s and 2004. Glob Change Biol, 2009, 15: 2723–2729

24 Yang Y H, Fang J Y, Ma W H, *et al*. Soil carbon stock and its changes in northern China's grasslands from 1980s to 2000s. Glob Change Biol, 2010, doi: 10.1111/j.1365-2486.2009.02123.x

25 Janssens I A, Freibauer A, Ciais P, *et al*. Europe's terrestrial biosphere absorbs 7 to 12% of European anthropogenic CO_2 emission. Science, 2003, 300: 1538–1542

26 Pacala S W, Hurtt G C, Baker D, *et al*. Consistent land- and atmosphere-based US carbon sink estimates. Science, 2001, 292: 2316–2320

27 Metting F B, Smith J L, Amthor J S, *et al*. Science needs and new technology for increasing soil carbon sequestration. Clim Change, 2001, 51: 11–34

28 Huang Y, Sun W J. Changes in topsoil organic carbon of croplands in mainland China over the last two decades. Chin Sci Bull, 2006, 51: 1785−1803

29 Sun W J, Huang Y, Zhang W, *et al*. Carbon sequestration and its potential in agricultural soils of China. Glob Biogeochem Cy, 2010, 24, GB3001, doi:10.1029/2009GB003484

30 Lu F, Wang X, Han B, *et al*. Soil carbon sequestrations by nitrogen fertilizer application, straw return and no-tillage in China's cropland. Glob Change Biol, 2009, 15: 281–305

31 Yu Y, Guo Z, Wu H, *et al*. Spatial changes in soil organic carbon density and storage of cultivated soils in China from 1980 to 2000. Glob Biogeochem Cy, 2009, 23, GB2021, doi:10.1029/2008GB003428

32 Pan G X, Xu X W, Smith P, *et al*. An increase in topsoil SOC stock of China's croplands between 1985 and 2006 revealed by soil monitoring. Agr Ecosyst Environ, 2010, 136: 133–138

33 Huang Y, Zhou G S, Wu J S, *et al*. Modelling Carbon Budgets of Terrestrial Ecosystems in China (in Chinese). Beijing: Science Press, 2008. 143–211

34 Huang Y, Yu Y Q, Zhang W, *et al*. Agro-C: A biogeophysical model for simulating the carbon budget of agroecosystems. Agr Forest Meteorol, 2009, 149: 106–129

35 Huang Y, Zhang W, Sun W J, *et al*. Net primary production of Chinese croplands from 1950 to 1999. Ecol Appl, 2007, 17: 692–701

36 China Wetland Resources Development and Environmental Protection Research Group. Reviewing the history of developing land resources in Sanjiang plain (in Chinese). Territory Nat Res Stud, 1998, 1: 15–19

37 Liu X T. Wetland resources and its sustainable use in Songnen-Sanjiang Plain (in Chinese with English abstract). Scientia Geographica Sinica, 17: 451–460

38 Huang Y, Sun W J, Zhang W, *et al*. Marshland conversion to cropland in northeast China from 1950 to 2000 reduced the greenhouse effect. Glob Change Biol, 2010, 16: 680–695

39 Liu Z G, Zhang K M. Wetland soils carbon stock in the Sanjiang Plain (in Chinese with English abstract). J Tsinghua Univ (Sci Technol), 45: 788–791.

40 Bolin B, Sukumar R. Global Perspective. In: Watson R T, Noble I R, Bolin B, *et al*, eds. Land Use, Land Use Change, and Forestry. Cambridge: Cambridge University Press, 2000. 23–51

41 Foley J A, DeFries R, Asner G P, *et al*. Global consequences of land use. Science, 2005, 309: 570–574

42 Wang X D, Li M H, Liu S Z, *et al*. Fractal characteristics of soils under different land-use patterns in the arid and semiarid regions of the Tibetan Plateau, China. Geoderma, 2006, 134: 56– 61

43 Li X G, Li F M, Bhupinderpal-Singh, *et al*. Soil management changes organic carbon pools in alpine pastureland soils. Soil Till Res, 2007, 93: 186–196

44 Gao J F, Pan G X, Jiang X S, *et al*. Land-use induced changes in topsoil organic carbon stock of paddy fields using MODIS and TM/ETM analysis: A case study of Wujiang County, China. J Environ Sci, 2008, 20: 852–858

45 Hu Y L, Zeng D H, Fan Z P, *et al*. Changes in ecosystem carbon stocks following grassland afforestation of semiarid sandy soil in the southeastern Keerqin Sandy Lands, China. J Arid Environ, 2008, 72: 2193–2200

46 Yang Y S, Xie J S, Sheng H, *et al*. The impact of land use/cover change on storage and quality of soil organic carbon in midsubtropical mountainous area of southern China. J Geogr Sci, 2009, 19: 49–57

47 Chen G Q, Huang D Y, Su Y R, *et al*. Effects of soil organic matter in hilly red soils from mid-subtropics region under various utilization patterns (in Chinese). J Agro-Environ Sci, 2005, 24: 256–260

48 Yang Y S, Chen G, Wang Y X, *et al*. Carbon storage and allocation in *Castanopsis kawakamii* and *Cunninghamia lanceolata* plantations in subtropical China (in Chinese). Scientia Silvae Sinicae, 2006, 42: 43–47

49 Zhang L Q, Zhang M K. Changes of organic C, N and P pools in red soil in transformation between agricultural land and forestry land (in Chinese). J Zhejiang Forest College, 2006, 23: 75–79

50 Zhou T, Shi P J. Indirect impacts of land use change on soil organic carbon change in China (in Chinese). Adv Earth Sci, 2006, 21: 138–143

51 Penman J, Gytarsky M, Hiraishi T, *et al*. Good Practice Guidance for Land Use, Land-Use Change and Forestry. Institute for Global

Environmental Strategies (IGES), 2003. http://www.ipcc-nggip.iges.or.jp

52 Denman K L, Brasseur G, Chidthaisong A, *et al.* Couplings between Changes in the Climate System and Biogeochemistry. In: Solomon S, Qin D, Manning M, *et al*, eds. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press, 2007

53 Liu J Y, Wang S Q, Chen J M, *et al.* Storages of soil organic carbon and nitrogen and land use changes in China: 1990~2000 (in Chinese). Acta Geograph Sinica, 2004, 59: 483–496

54 Fang J Y, Chen A P, Peng C H, *et al.* Changes in forest biomass carbon storage in China between 1949 and 1998. Science, 2001, 292: 2320–2322

55 Potter C, Klooster S, Hiatt S, *et al.* Satellite-derived estimates of potential carbon sequestration through afforestation of agricultural lands in the United States. Clim Change, 2007, 80: 323–336

56 Xie J S, Yang Y S, Chen G S, *et al.* Effect of vegetation restoration on water stability and organic carbon distribution in aggregates of degrade red soil in subtropics in China (in Chinese). Acta Ecolo Sinica, 2008, 28: 702–709

57 Zhang G B, Tian D L, Fang X, *et al.* Distribution characteristics of soil organic carbon in Huitong as affected by different afforestation models for conversion of cropland to forestland (in Chinese). J Central South U Forest Tech, 2008, 28: 8–12

58 Huang C D, Zhang J, Yang W Q, *et al.* Soil organic carbon density in plantations of hilly region in the western Sichuan (in Chinese). J Zhejiang Forest Sic Tech, 2009, 29: 5–8

59 Laganière J, Angers D A, Parè D. Carbon accumulation in agricultural soils after afforestation: a meta-analysis. Glob Change Biol, 2010, 16: 439–453

60 Zhou G Y, Liu S G, Li Z A, *et al.* Old-growth forests can accumulate carbon in soils. Science, 2006, 314: 1417

61 Post W M, Kwon K C. Soil carbon sequestration and land-use change: processes and potential. Glob Change Biol, 2000, 6: 317–328

62 Berthrong S T, Jobbágy E G, Jackson R B. A global meta-analysis of soil exchangeable cations, pH, carbon, and nitrogen with afforestation. Ecol Appl, 2009, 19: 2228–2241

63 Duan W X, Zhu B, Liu R, *et al.* Carbon dynamics in *Cryptomeria fortunei* plantations (in Chinese). J Beijing Forest Univ, 2007, 29: 55–59

64 Wang C M, Liu Y H, Shao B, *et al.* Quantifying the soil carbon changes following the afforestation of former arable land (in Chinese). J Beijing Forest Univ, 2007, 29: 112–119

65 Paul K I, Polglase P J, Nyakuengama J G, *et al.* Change in soil carbon following afforestation. Forest Ecol Manage, 2002, 168: 241–257

66 Huang C D, Zhang J, Deng Y L, *et al.* Carbon storage and allocation patterns of young forests converted by farmland (in Chinese). J Soil Water Conserv, 2007, 21: 130–133

67 Bai X S, Hu Y L, Zeng D H, *et al.* Effects of farmland afforestation on ecosystem carbon stock and its distribution pattern in semi-arid region of northwest China (in Chinese). Chin J Ecol, 2008, 27: 1647–1652

68 National Bureau of Statistics of China. The past 60-year (1949-2009) in China (in Chinese). Beijing: China Statistics Press, 2009

69 Li Z C, Xu D Y, Fu M Y, *et al.* Effects of land-use change on vertical distribution and storage of soil organic carbon in north subtropical areas (in Chinese). For Res, 2007, 20: 744–749

70 Zhang X L, Li J J, Shi F C. Organic carbon and nitrogen contents and microbial biomass in soil under rapid-growth poplar plantation (in Chinese). J Ecol Rural Environ, 2008, 24: 32–35

71 Wan M, Tian D L, Fan W. Spatial and temporal distribution characteristics of soil organic carbon in the agro-forestry systems of eastern Henan plain (in Chinese). J Central South Univ For Tech, 2009, 29: 1–5

72 Du Q L. Strategy for Sustainable Development of Grassland Production in China (in Chinese). Beijing: China Agriculture Press, 2006

73 Wu R, Tiessen H. Effect of land use on soil degradation in alpine grassland soil, China. Soil Sci Soc Am J, 2002, 66: 1648–1655

74 Zou C, Wang K, Wang T, *et al.* Overgrazing and soil carbon dynamics in eastern Inner Mongolia of China. Ecol Res, 2007, 22: 135–142

75 Qiu D. The study on vegetation succession law of degraded grassland of “Black Soil Type” on southern Qinghai province (in Chinese). Chin Agric Sci Bull, 2005, 21: 284–293

76 Liu B, Wu N, Luo P, *et al.* Characteristics of soil nutrient distribution in high-altitude meadow ecosystems with different management and degradation scenarios (in Chinese). Chin J Eco-Agric, 2007, 15: 45–48

77 Zhou W H, Feng R Z, Man Y R. Characteristics of soil in different degraded pasture in the headwaters of the Yellow Rivers (in Chinese). Grassland Turf, 2008, 4: 24–28

78 Wang C T, Long R J, Wang Q L, *et al.* Changes in soil organic carbon and microbial biomass carbon at different degradation successional stages of alpine meadows in the headwater region of Three Rivers in China (in Chinese). Chin J Appl Environ Biol, 2008, 14: 225–230

79 Pei H K. Effect of different grazing intensity on soil nutrient and texture (in Chinese). J Qinghai Univ, 2004, 22: 29–31

80 Wang Q L, Cao G M, Wang C T. The impact of grazing on the activities of soil enzymes and soil environmental factors in alpine *Kobresia pygmaea* meadow (in Chinese). Plant Nutr Fert Sci. 2007, 13: 856–864

81 Dong Q M, Zhao X Q, Ma Y S, *et al.* Effect of grazing intensity on soil organic matter and organic carbon in alpine-cold artificial grassland (in Chinese). Chin Qinghai J Anim Vet Sci, 2007, 37: 6–8

82 Qiu Y, Gan Y M, Wang Q, *et al.* Preliminary study on classified index system of grazing alpine meadow in northwest Sichuan (in Chinese). Hubei Agric Sci, 2007, 46: 723–726

83 Qu W L, Pei S F, Zhou Z G, *et al.* Influences of overgrazing and exclosure on Carbon of soils and characteristics of vegetation in desert steppe, Inner Mongolia, north China (in Chinese). J Gansu Forest Sci Tech, 2004, 29: 4–6

84 Xue B, Hu X L, Liu J, *et al.* Influence of enclosure on soil fertility and vegetation character in the degenerative meadow (in Chinese). J Inner Mongolia Forest Sci Tech, 2008, 34: 18–21

85 Jia H T, Jiang P A, Zhao C Y, *et al.* The influence of enclosing life on carbon distribution of grassland ecosystem (in Chinese). Agric Res Arid Areas, 2009, 27: 33–36

86 Su Y Z, Li Y L, Cui J Y, *et al.* Influences of continuous grazing and livestock exclusion on soil properties in a degraded sandy grassland, Inner Mongolia, northern China. Catena, 2005, 59: 267–278

87 Cui X, Wang Y, Niu H, *et al.* Effect of long-term grazing on soil organic carbon content in semiarid steppes in Inner Mongolia. Ecol Res, 2005, 20: 519–527

88 Pei S, Fu H, Wan C. Changes in soil properties and vegetation following exclosure and grazing in degraded Alxa desert steppe of Inner Mongolia, China. Agric Ecosyst Environ, 2008, 124: 33–39

89 He N P, Yu Q, Wu L, *et al.* Carbon and nitrogen store and storage potential as affected by land-use in a *Leymus chinensis* grassland of northern China. Soil Biol Biochem, 2008, 40: 2952–2959

90 Wu L, He N, Wang Y, *et al.* Storage and dynamics of carbon and nitrogen in soil after grazing exclusion in *Leymus chinensis* grasslands of northern China. J Environ Qual, 2008, 37: 663–668

91 Jia X H, Li X R, Li Y S. Soil organic carbon and nitrogen dynamics during the re-vegetation process in the arid desert region (in Chinese). J Plant Ecol. 2007, 31: 66–74

92 Shi F, Li Y E, Gao Q Z, *et al.* Effects of managements on soil organic carbon of grassland in China (in Chinese). Pratacultural Sci, 2009, 26(3): 9–15

93 Boddey R M, Jantalia C P, Conceic P C, *et al.* Carbon accumulation at depth in Ferralsols under zero-till subtropical agriculture. Glob Change Biol, 2010, 16: 784 –795

94 Baker J M, Ochsner T E, Venterea R T, *et al.* Tillage and carbon sequestration – What do we really know? Agric Ecosyst Environ, 2007, 118: 1–4

95 Blanco-Canqui H, Lal R. No-Tillage and soil-profile carbon sequestration: An on-farm assessment. Soil Sci Soc Am J, 2008, 72: 693–701

96 Gu Q Z, Yang X Y, Sun B H, *et al.* Effects of long-term fertilization

and irrigation on soil nutrient distribution in profile of Loess soil (in Chinese). Chin Agric Sci Bull, 2004, 20: 139– 142

97 Fan J, Hao M D, Dang T H. Effect of long-term fertilization on nutrient distribution in profiles of black loessial soil (in Chinese). Plant Nutr Fert Sci, 2001, 7: 249–254

98 Shi J P, Zhang F D, Lin B. Effects of long-term located fertilization on contents of soil humus (in Chinese). Soil Fert, 2002, 1: 15–19

99 Franzluebbers A J, Stuedemann J A. Soil-profile organic carbon and total nitrogen during 12 years of pasture management in the Southern Piedmont USA. Agric Ecosyst Environ, 2009, 129: 28–36

100 Pan G X, Wu L S, Li L Q, *et al*. Organic carbon stratification and size distribution of three typical paddy soils from Taihu Lake region, China. J Environ Sci, 2008, 20: 456–463

101 IPCC. 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Prepared by the National Greenhouse Gas Inventories Programme. IGES, Japan, 2006

102 Zhang X Q, Chen X G, Wu S H. Methodological issues related to measuring and monitoring carbon stock changes induced by land use change and forestry activities (in Chinese). Acta Ecologica Sinica, 2004, 24: 2068–2073

103 Holmes K W, Chadwick O A, Kyriakidis P C, *et al*. Large-area spatially explicit estimates of tropical soil carbon stocks and response to land-cover change. Global Biogeochem Cy, 2006, 20, GB3004, doi: 10.1029/2005GB002507

104 Knorr W, Heimann M. Uncertainties in global terrestrial biosphere modeling, Part I: a comprehensive sensitivity analysis with a new photosynthesis and energy balance scheme. Global Biogeochem Cy, 2001a, 15: 207–225

105 Knorr W, Heimann M. Uncertainties in global terrestrial biosphere modeling, Part II: global constraints for a process-based vegetation model. Global Biogeochem Cy, 2001b, 15: 227–246

106 Li C S, Zhang Y H, Frolking S, *et al*. Modeling soil organic carbon change in croplands of China. Ecol Appl, 2003, 13: 327–336

107 U.S. Environmental Protection Agency. Inventory of U.S. greenhouse gas emissions and sinks: 1990~2006. Washington, DC, USA, 2008.

108 Zhang F C, Zhu Z H. Harvest index for various crops in China (in Chinese). Chin Agric Sic, 23: 83–87

109 Liu X H, Gao W S, Zhu W S. Mechanism and Techniques in Straw Application (in Chinese). Beijing: China Agriculture Press, 2001. 1–215