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Perspectives on studies on soil carbon stocks and the carbon sequestration potential of China

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Soil carbon stocks and sequestration have been given a lot of attention recently in the study of terrestrial ecosystems and global climate change. This review focuses on the progress made on the estimation of the soil carbon stocks of China, and the characterization of carbon dynamics of croplands with regard to climate change, and addresses issues on the mineralization of soil organic carbon in relation to greenhouse gas emissions. By integrating existing research data, China's total soil organic carbon (SOC) stock is estimated to be 90 Pg and its inorganic carbon (SIC) stock as 60 Pg, with SOC sequestration rates in the range of 20–25 Tg/a for the last two decades. An estimation of the biophysical potential of SOC sequestration has been generally agreed as being 2 Pg over the long term, of which only 1/3 could be attainable using contemporary agricultural technologies in all of China's croplands. Thus, it is critical to enhance SOC sequestration and mitigate climate change to improve agricultural and land use management in China. There have been many instances where SOC accumulation may not induce an increased amount of decomposition under a warming scenario but instead favor improved cropland productivity and ecosystem functioning. Furthermore, unchanged or even decreased net global warming potential (GWP) from croplands with enhanced SOC has been reported by a number of case studies using life cycle analysis. Future studies on soil carbon stocks and the sequestration potential of China are expected to focus on: (1) Carbon stocks and the sequestration capacity of the earths' surface systems at scales ranging from the plot to the watershed and (2) multiple interface processes and the synergies between carbon sequestration and ecosystem productivity and ecosystem functioning at scales from the molecular level to agro-ecosystems. Soil carbon science in China faces new challenges and opportunities to undertake integrated research applicable to many areas.

soil carbon stock, carbon sequestration, SOC stability, greenhouse gas emission, soil carbon science

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Global warming and the associated abrupt changes in the global climate system, which are considered very likely to be due to ever increasing anthropogenic greenhouse gases emissions, have been well documented in IPCC AR_4 released in 2007. Enhancing terrestrial C sinks and decreasing greenhouse gas (GHGs) emissions have been recognized as priorities for increasing global sustainability (http://unfccc.int/press/items/2794 php.2008) [1,2]. Worldwide soils store organic carbon, as much as 1550 Pg plus an inorganic carbon stock of over 1000 Pg [3], up to one meter depth, playing a key role in global carbon cycling and climate change.

China's GHGs emissions have been accelerating because of an ever increasing demand for energy consumption, coupled with rapid industrialization and urbanization as well as soil degradation by overgrazing in grasslands and by over intensification in croplands. Thus, there are national and

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international concerns about environmental issues and the ability of the country to enhance carbon sequestration and mitigation of GHGs in terrestrial ecosystems.

The many types of terrestrial ecosystems existing in large areas of China have a significant role to play in terms of carbon stock changes and GHGs released because of land use and land cover changes. The topsoil organic carbon stocks have been estimated as being 5.9 Pg in forests covering 1.42 Mha, 1.15 Pg in grasslands covering 3.31 Mha [4] and 5 Pg in croplands of over 1.30 Mha plus 0.9 Pg in a wetland area of 0.4 Mha [5]. However, the changes in total carbon stock under agricultural development for the last decades and the sequestration capacity of the croplands in future have been in a great debt since the early 21st century. This review addresses soil organic carbon dynamics, sequestration capacity as well as its impact on land use related GHGs emissions, and discusses the key issues for future soil carbon studies.

1 Progress in carbon stock counting of China' s soils

Basic counting of the national and global soil carbon stocks has been complete since the early 1990s in European and North American countries. Estimation of China's soil carbon stocks has been one of the key research areas in soil and ecosystem C cycling studies since the mid 1990s, when national carbon stocks and their dynamics received a lot of attention. An initial report, by an ecologist, on China's soil carbon stocks put them as high as 185 Pg using a normalized soil depth of 1 m [6]. Later, a value for soil carbon stocks as low as 50 Pg (to soil depth of 1 m) was reported [7] which was based on the complete set of archived data from the work of China's Soil Species, retrieved from the 2nd National Soil Survey conducted during 1979–1985 [8]. Since 2000, there has been a large number of accounting studies on China's soil carbon stocks, using either soil survey or the biome biomass survey data based on vegetation and soil cover maps at various scales. Using a soil map at a scale of 1∶1000000, it has been estimated that the total soil carbon stocks are between 92 [9] and 100 Pg [10] respectively based on the SOC data archive of the 1st and 2nd National soil surveys. However, using a modified carbon density accounting methodology with an improved estimation of soil bulk density from SOC data, a total soil carbon stock of 70.3 Pg has been reported [11]. Also a new soil sampling expedition investigating 810 profiles across the Tibetan area, where soil sampling during the 2nd national soil survey was very limited, was undertaken and a correlation analysis of bulk density and soil organic carbon storage changes with soil depth was performed [12]. Including this data, the estimates could be refined to 69.1 Pg for the whole of China. At the same time an estimation of 88.3 Pg for a normalized soil to 1-m-deep depth by documenting 2456 soil profiles and 8714 soil diagnostic horizons from the soil information system of China was made [13]. Based on this Soil Information System, a new estimate for the total soil SOC stock in China of 89.1 Pg was obtained [14,15]. It was at a national panel meeting of the Xiangshan Science Conference [16] that the soil scientists agreed with a general estimation of total SOC stock in the range of 70–90 Pg with a default stock value of 90 Pg.

To this point, there had been a lot of uncertainty in the carbon stock estimations for China, although the values obtained from different means were similar. The greatest difference in the stock estimations may have resulted from the differences in data coverage, spatial resolution of the soil map, the attributes and the inconsistency of the SOC changes when up-scaling. Data coverage and accounting methodology have seemed to be key factors in the uncertainty of the estimates since 2003 due to the type of soils [7] and ecosystems [6] present with the (weighted) mean values being mainly used in the early stages of the carbon stock accounting studies. The number of soil profiles for SOC storage estimation would have been critical in the accounting process. The studies conducted after 2003 have used soil SOC data of over 2000 profiles plus data from diagnostic horizons and attributes from the Soil Information System [13,14]. Likewise, the data for soil area could be another important factor that impacts on the final estimation of the value of the carbon stocks for soils in China. While the data from the second soil survey reports were used in the early studies, an area value of soil cover for a soil type retrieved from the maps has been used since 2007. An area of 8.80 Mkm^2 was used for all of China's soil cover in the study [12] but a value of 9.28 Mkm^2 was used elsewhere [14], causing a large difference in the SOC stocks of 20 Pg between the two studies. In addition, data availability for soil bulk density and the soil depth could have also influenced the carbon stock estimation. In fact, the soil depth would be less than 1 m in many mountainous areas especially in southwest China and in the Tibetan Plateau [12], while a default depth to 1 m has been used in most estimation studies. Nevertheless, the difference in SOC storage estimations between 70 and 96 tC/hm^2 is apparently smaller than the difference in the total SOC stock estimations between 50 and 185 Pg.

There has been less data available for soil inorganic carbon (SIC) (than for SOC) for China. A first estimation of 60 Pg was given when accounting for the mean SIC storage from over 2500 soil profiles from the second soil survey [7, 17]. In a later report, it was shown as 55.3 Pg using similar soil survey data [18]. More recently, soil resource survey data with normalizing the soil depth to 1 m enabled an estimate SIC stock as being 77.9 Pg [13], which was much greater than in previous studies (Table 1). Nevertheless, the SIC stock size for all of China soils seems to be smaller than for SOC, even though large uncertainties still exist.

Carbon stored as SIC in soils may have long lasting se questration effect for atmospheric CO_2, as it has a much longer residence time than SOC. There may have been carbon

Table 1 Estimates of China's SIC pool (Pg)

C Stock estimate	Accounting methodology	Reference
60.0	Depth-weighted means, soil profiles from China's Soil Species, Vols. 1–6	[7,17]
55.3	Statistics for 34411 profiles in the 2nd National Soil Survey Archive	[18]
77.9	Data for 2456 profiles and 8714 diagnostic horizons from the Soil Information System of China	[13]

transfer from organic carbon decomposition or microbial respiration to SIC in soils under arid and semiarid conditions or in limestone soils: i.e. SOC→CO_2 (evolved) CO_2 → (dissolved)→$Ca(HCO_3)_2$(in solution)→$CaCO_3$ (precipitated). Thus, SOC-C may be transformed or transferred to SIC which finally precipitates in the subsoil, increasing the soil secondary SIC content with increases in dissolved bicarbonate [19]. Recently, efforts have been made to characterize the transformation of SOC to SIC in soils from West China. While soil thin section observations were used to describe the transformed SIC features in soils (and to qualitatively deduce the SIC from soil biological process [20]), differentiating the secondary transferred SIC from primary carbonates could be also allowed using ratio of $^{87}Sr/^{86}Sr$ in loess profiles of Luochuan, Shanxi, China [21]. However, the sequestration of photosynthesized atmospheric CO_2 through SOC-SIC transfer could also be documented by their relative distribution in soil profiles. While looking at the impacts of land use on SOC changes in temperate grasslands from Inner Mongolia [22], it has been found that calcic subhorizons (with new SIC accumulation) were formed under the topsoil because of the degradation of SOC in a cultivated steppe previously dominated by Stipa baicalensis. Meanwhile, grazing in grasslands could have induced a decrease in SIC content in the topsoil through a SOC decline in topsoil, but a relative increase in subsoil SIC was observed. In an 18-year long experiment with irrigated desert soils from Gansu, China [23], there was a negative correlation of SIC with SOC in the 50 cm depth where the SOC-SIC transfer was markedly affected by moisture fluctuations with irrigation. Also, they showed that the combined fertilization of inorganic and organic fertilizers decreased SIC while increased SOC in the plowed topsoil. Likewise, a 20-year-long experiment with fertilization treatments in North China Great Plain demonstrated that SOC contents significantly increased and SIC decreased under well designed applications of N and P fertilizers [24]. Nevertheless, the mechanisms and processes of SOC-SIC transfer for soil and land surface systems have not yet been well understood.

2 Soil carbon stock dynamics with land use change

2.1 Historical changes in soil carbon stocks of China

Studies on the historical changes in soil carbon stocks have demonstrated an important impact of anthropogenic activities on global climate change [25,26]. Estimations of global or regional historical carbon stock changes have been developed by using biome dynamics and spatial-temporal scaling [27]. It has been well accepted that reductions in soil SOC stock due to historical land use amounted to 5% of the global total [28]. The total loss of world soil SOC stocks was estimated to be 55 Pg [29]. However, the historical loss of soil carbon stocks of China has received a great concern. It has been estimated that there has been a total loss of 3.5 Pg, including about 2 Pg from desertification [30]. Based on a review of soil SOC data from the agricultural literature published before 1960, it has been shown that there have been SOC losses across wide ranges of ecosystems of China [31]. Furthermore, it has been suggested that soil SOC storage has been continuously reducing since the 1950s, amounting to 70 Tg since the 1970s [32], when using the DNDC model. These reports have internationally acknowledged, however, they have not been verified and validated with re-sampling. A statistical analysis of SOC storage for cultivated soil compared with natural soils from the archived second soil survey data allowed an estimation of a total loss of SOC stock at 7–8 Pg to 1 m depth, because of historical cultivation of the native soils [11], and the loss was found mainly in the North and other arid and semiarid regions of China. Nevertheless, it has been argued that there have been some areas and soil-land use associations where significant changes are minimal or even increases in SOC storage have occurred, especially in irrigated areas. In a previous study by our group, data for cultivated and uncultivated soils were statistically analyzed and compared in terms of region and soil-land use associations. The cultivation induced topsoil SOC storage loss was estimated as being 14.8±15.1 t/ha, giving a total stock loss at 2 Pg [33], among which over 60% was from Northeast China, Northwest China and Southwest China. Such large losses from these eco-tones and climate change sensitive regions could be validated by using some case studies from vulnerable limestone terrains [34] and where severe water erosion occurred [35]. In addition, cultivation of wetlands could be a significant source of SOC stock loss for China as a recent report of 1.5 Pg total loss was estimated [5]. Therefore, the significant loss of SOC under intensified cultivation and increased inorganic fertilizer inputs could account for, at least partly, the low level of SOC in croplands but also indicate a significant role for CO_2 losses to the atmosphere from China's historical land use/land cover changes.

2.2 Recent carbon stock dynamics and sequestration

(i) SOC stock changes with changes in wetland areas. Data from Wetlands International showed wetlands covered 6% of the globe (http://www.wetlands.org/articlemenu.aspx?id=ae774022-0c1a-4293-a107-a73225128e75). The total SOC stock of wetlands was therefore estimated to be 550 Pg, which corresponds to one third of the global soil total and almost one half of the total for the atmosphere and vegetation (http://unfccc.int/files/meetings/cop13/application/pdf/cmp_guid_cdm.pdf). This great loss could be attributed to the cultivation of wetlands mainly in the past. Total reclaimed wetlands in China since the 1950s was estimated to be 1.3 Mha [36], while large areas of wetlands in Sanjiang Plain have been cultivated in the past 3 decades [37]. However, SOC losses may differ between wetland types and with land use intensity. The peat wetlands from Nuoergai in the Tibetan area and Sanjiang Marsh Plain underwent large SOC losses at 80% to 90% of the original, which could be coincident with a sharp conversion of carbon sinks to carbon sources [38]. Overall, SOC loss from wetland cultivation from the Sanjiang Plain could amount to as high as 215 Tg because of excessive cultivation [39]. However, the reduction in SOC storage was found to be 30% lower in wetlands along the middle and lower reaches of the Yangtze River valley. In addition, the cultivation of rice paddies caused a smaller reduction in SOC storage compared with that of dry croplands as shown in the case studies on the Sanjiang Plain of Northeastern China [40,41]. Our recent study has shown an overall SOC stock loss of 1.5 Pg for the last 5 decades because of wetland cultivation in China, which could be close to the total CO_2 emissions from the energy consumption of our country in 2006 [42]. Thus conservation of wetlands may be a key issue for the mitigation of GHGs emissions under land use/land cover change.

(ii) SOC stock dynamics with agricultural development. It has been well understood that the topsoil is the most sensitive to climate change and human interference. Global topsoil covers a total SOC stock of 684 Pg [43] at depth of 0–30 cm, giving a mean topsoil SOC storage of 47.8 t/ha for non-ice sheet covered land surfaces. It has been shown that the mean topsoil SOC storage was 70.8 t/ha for native soils and 53.0 t/ha for cultivated soils of Europe [44]. An estimation in a previous work [33] showed a mean topsoil SOC storage of 50±47 t/ha for native soils and 35±32 t/ha for cultivated soils. Meanwhile, topsoil SOC storage was higher (46.9±25.7 t/ha) for rice paddies than for dry croplands (35.9±32.8 t/ha) [45] with an overall mean storage of 38.4±31.2 t/ha for croplands. An analysis of 966 monitored cropland sites showed that SOC sequestration was subject to land use and management practices [46]. In this study, garden soils had a much higher SOC storage than rice paddies and dry croplands with an annual accumulation rate of 2.88±3.4% relative to the original and the SOC sequestration rate for crop carbon input was found to be higher in rice paddies than in dry croplands, by 170%. A statistical analysis of cropland quality from the Ministry of Agriculture, showed that the SOC storage has changed with land use for the last two decades in a county from Jiangsu Province, China and that converting rice paddies to garden soils, dry croplands, nursery and forest lands has caused a general SOC decline in the short term but the rice paddies have been found to have continuous SOC accumulation [47]. However, in a case study in a similar area, maize cultivation in a rice paddy had induced a large loss of topsoil SOC at 30% of the original in the rice paddy over 3–5 years, which was shown by ^{13}C isotope abundance changes [48]. This could be attributable to enhanced SOC decomposition under plowing for maize production and the loss of biophysical protection of SOC in the paddy. Land ownership and management system changes may also have impacted on cropland SOC dynamics. Land fragmentation, as affected by household ownership seems to prevail for a long time in China [49], and has already been shown to exert adverse effects on land quality, resource efficiency and profitability of agriculture [50,51]. Their potential impact on SOC had again received much attention for the globe other than China [52]. A pilot study of soil quality and household farming was conducted in a rural area of Jiangxi Province where the local people had been traditionally living on their land [53]. In this case, the topsoil SOC varied widely from 1.7 to 25.2 g kg^{-1}, depending on the size of total cropland area and the land tenure status. The amount of SOC in plots of <0.1 hm^2 was significantly lower by 20% than in those >0.1 hm^2 and the owned croplands had a higher SOC level by almost 100% on average than those leased or contracted out. Therefore, improving land tenure and land management systems may play a key role in enhancing SOC sequestration in China's croplands.

(iii) Overall changes in cropland SOC stock of China. The SOC stocks of croplands, among the other terrestrial ecosystem carbon pools, has been considered to be prone to human interference especially as technology has improved, though the global soil stores a huge stock of carbon being 1500 Pg of SOC and over 1000 Pg of SIC [54]. Accordingly, SOC stock and its sequestration capacity has been accepted as a key parameter for evaluating the mitigation potential for a certain region. Active studies on SOC dynamics has focused on the size of carbon sequestration potential, the dynamics and the land use effects, the accounting methodology associated with the databases, model development and improvement of monitoring systems and data collection. There have been a large numerous studies on the adverse impacts of Chinese intensified agriculture on natural resources and the environment including desertification, extension of arid areas, secondarily salinized soils, N overuse and water quality deterioration as well as historical SOC loss. However, an increase in overall SOC storage in agricultural soils has been well documented at county level from Jiangsu [55], at village level from Jiangxi [56] and at regional level from the North China Plain and Northeastern black soil region [57].

The above mentioned SOC storage increase has been validated with long term agro-ecosystem experiments and modeling. While increases in topsoil SOC storage have been well established using long-term experimental data, enhanced SOC accumulation under improved fertilization has been documented with a 13-year long experiment in un-irrigated croplands with combined organic and inorganic fertilizer inputs in Jiangxi, China [58]. Also, similar effects have been observed with a 15-year-long experiment in a rice paddy from Hunan, China [59], with a long term fertilizer experiment in Wujiang, Tai Lake region, China [60], with a 16-year long experiment of different tillage experiment [61] in a rice soil of purple soil in Chongqing, Southwest China as well as a 16-year long experiment from the Central Huang-Huai-Hai Plain, China [24,62]. Consequently, an overall SOC increase has been well documented as summarized in Table 2 though the exact SOC sequestration capacity varied with data size and counting methods [63,64]. A statistical analysis of the data from 26 sites of long term agro-ecosystem experiments over China showed that the annual gain of topsoil SOC had been between 0.05–0.29 g/kg using a balanced, compound chemical fertilizer and a combination of inorganic and organic fertilization, thus an overall annual SOC increase could amount to at least 0.2–1.6 Pg over the last 20 years for all of China's croplands [65]. A meta analysis of SOC data from 200 publications, covering 60 thousand single measurements over the period 1993–2005, showed that in China's croplands, 53%–60% of the observations had an increase in SOC while 30%–35% had a decrease and the others remained unchanged [66]. These authors gave a semi-quantitative assessment of SOC stock increases as being 0.3–0.4 Pg for the period of 1985–2005. More recently, an analysis of the SOC data from soil monitoring surveys available from 146 publications estimated a SOC sequestration rate in China's croplands over the years 1980–2000 at 21.9 Tg/a giving a total of 0.44 Pg [67]. Another study used a set of 1099 single SOC measurements from the soil monitoring system, retrieved from literature published up to 2006 and analyzed the annual rate of SOC increase by means of a meta analysis [68]. They estimated an annual overall SOC increase in the topsoil at 0.06±0.20 g/kg for un-irrigated croplands and 0.11±0.24 g/kg for rice paddies respectively. Accordingly, a total yearly SOC stock increase of China was estimated as 25.5 Tg over the period of 1985–2006, though there was a wide variation of SOC increase across regions. These authors concluded that the topsoil (0–20 cm) for China's croplands had sequestered as much as 0.58 ± 0.38–0.65 ± 0.53 Pg C during the past 2 decades, which may be a significant contribution to offsetting the nation's GHGs emissions from energy consumption. In summary, these studies have shown carbon sequestration rates in the range of 20–25 Tg/a. Reasonably, the SOC sequestration in croplands in China could be accounted for mostly by the increasing the amount of straw or residue being returned and these increased crop inputs were affected by fertilizer application as well as enhanced humification with increased N status.

Table 2 Topsoil SOC sequestration rates from China's croplands (Taken from the literature)

Sequestration rates (Tg/a)	Observation period	Reference
23.6	1996–2006	[63]
7.9	1990–2000	[64]
21.9	1980–2000	[67]
15–20	1993–2006	[66]
24.9	1985–2006	[65]
24.1–27.1	1980–2006	[68]

(iv) Soil organic carbon sequestration capacity and technical barriers in croplands. As estimated by the FAO, the SOC sequestration capacity of global croplands may be as high as 20 Pg, with an expected mean annual sequestration rate of 0.9±0.3 Pg in the first 25 years [3]. One study [30] proposed an overall carbon sequestration capacity of 11 Pg until 2050 including 105–198 Tg/a for SOC and 7–138 Tg/a for SIC. Recently, other workers estimated the total sequestration capacity as being 2–2.5 Pg carbon up to 2050 [65]. However, the sequestration potential of 500 Tg by reclamation of low yielding croplands was assessed [69] without a defined time span.

There may be various approaches to reaching an acceptable estimation of the topsoil SOC sequestration rate of China's croplands both in terms of biophysical or technologically attainability. First, an estimation of the sequestration rate may be assessed by determining the recovery of SOC losses from cultivation. Assuming the area of all the croplands would not be changed greatly, a potential amount of sequestration would be then as high as 2 Pg in the long run, which was similar to the estimated total loss in another study [33]. This could be regarded as a theoretical or biophysical potential. Another approach for sequestration potential estimation may be by synthesizing the SOC sequestration rates with the initial SOC level, where the gap between the attainable level and the present level could be considered as the sequestration potential [70]. Using the data in Figure 1 from the literature [71], it was estimated that rice paddies and dry croplands of China could sequester 0.8±0.2 Pg and 1.2±0.5 Pg respectively assuming the land area remained unchanged in the long run. Alternatively, the sequestration potential of croplands should be considered the capacity to store all the input C, which is the case in the practice of conservation tillage with full straw return, already known as the best means for enhancing SOC sequestration in croplands [72]. Thus the gap between the attainable SOC saturation level under the best scenario of conservation tillage with straw return and the present SOC level [68], would be the calculated sequestration potential. By

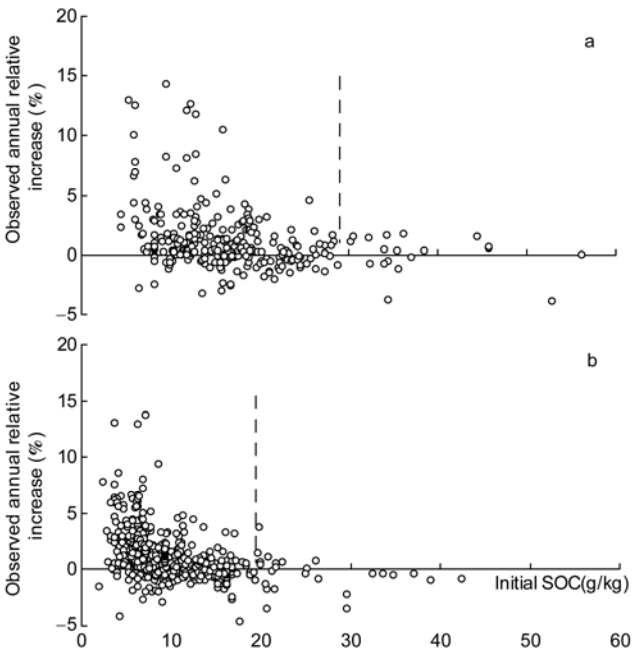

Figure 1 Changes in relative annual increments of SOC with the initial SOC contents in soil monitoring (a, paddy soil; b, dryland) [71].

employing data from long experiments using conservation tillage, and assuming effective sequestration duration of 10 years, it was estimated that China's rice paddies and unirrigated croplands could sequester 0.91 and 1.01 Pg SOC respectively, theoretically, under conservation tillage with all residues returned. By this means, a similar value of 2 Pg was obtained for topsoil SOC sequestration rates in the long term for all China's croplands unless the area of cropland was unchanged. All these estimations seemed similar to the estimate by Lal [30] which reported the cropland's potential of 2 Pg among the total of 11 Pg for the whole China's ecosystems.

Soil organic carbon sequestration in croplands may have a significant role in the mitigation of all GHGs emissions from China. The calculated SOC sequestration potential possesses a proportion of 20% to the ecosystem total of China (11 Pg). The predicted SOC stock increase during the last 25 years may have offset 40% of the total CO_2 emissions from the energy consumption sector in 2006. The predicted SOC sequestration for the period of 1985–2006 was almost a contribution at 20% of the GHGs mitigation target calculated on baseline of 1994. However, SOC sequestration in the USA and EU countries may be comparable to only 5%–7% of their reduction targets over the same time period [73,74]. A previous study predicted a topsoil SOC sequestration in the Jiangsu croplands of 24 Tg over 1985–2004, which was equal to 20% of the total CO_2 emissions of the province in 1994 [75]. Seemingly, all our estimated soil SOC sequestration values seemed to agree with the IPCC AR4 report, that is, carbon sequestration in agricultural soils may contribute to offsetting a proportion of the reductions target for global GHGs emissions [76]. Meanwhile, the studies with long term experiments under well managed practices have proven positive effect of SOC accumulation on reduction in overall GHG emissions [77, 78], on decreasing net carbon flux [79,80], and on improving soil fauna health [81], microbial community and diversity [82,83], weed diversity and its control [84], PAHs degradation in soil [85] as well as crop productivity [86,87]. Thus SOC sequestration in croplands, particularly in rice paddies, would offer double win options for crop productivity and mitigation of greenhouse gas emission in agriculture, ensuring food security for China [88]. Therefore, the roles of SOC sequestration in enhancing crop productivity and reducing GHG emissions should be given a greater emphasis in China's attempts to mitigate the impact of agriculture on climate change [89].

The estimated carbon sequestration capacity of 2 Pg for all of China's croplands is controlled by many biophysical processes in these agro-ecosystems, exploiting this potential capacity may depend on the scope and effectiveness of sequestration-promoting technologies, such as the rational use of biochar. While the biophysical potential will be impaired by technical barriers, the technical potential will be considered as the maximum capacity for soil carbon sequestration realizable under acceptable technologies [90]. For example, the management practice of conservation tillage with residue return and the combined use of fertilizer may have considerable effects on SOC sequestration in croplands, yet the potential contribution of these practices to the CO_2 emission mitigation depends on the extent of these techniques in croplands across all of China. Furthermore, the predicted SOC sequestration of all China's croplands as revealed by synthesizing soil monitoring data was seen as 0.6 Pg over the last 25 years [68], being only one third of the total biophysical potential of 2 Pg. As shown in a recent study, conservation tillage with residue return was the most effective SOC sequestration practice for Chinese croplands [71]. However, this technology was only extended on 2 Mha of land, that is, less than 2% of all China's croplands in 2007 [90]. It is anticipated that extension of this practice will increase to a proportion of 10% to the total croplands by 2015. In the past few years, a well designed N fertilizer scheme which resulted in increasing SOC storage [91], was applied to 60%–70% of the total croplands of China. Thus, to overcome technological barriers and to extend coverage of optimal agro-management practices would be a priority for realizing the technical SOC sequestration potential in the near future. In addition, land management systems for croplands tend to have an impact on their technological potential. For example, a recent study has shown that significantly higher, by up to one third, SOC sequestration rates in croplands with a bigger plot size and non-leased croplands than those in smaller and sub-contracted or leasing arrangements [53]. Evidently, improving the land tenure system and developing scaled cropland management would be one of the major approaches to working towards enhancing SOC sequestration in China's croplands.

3 Stability of soil carbon pools in response to global change

3.1 Stabilization of newly sequestered carbon in relation to GHG emissions from croplands

Stabilization of newly sequestered SOC refers to the susceptibility of decomposition to environmental changes, which may, in turn, affect the emission of GHGs from croplands. There have been several studies on SOC decomposition and GHG emission as affected by N deposition and soil acidification [92], and global warming [93,94]. In croplands, however, the stability of SOC and newly sequestered carbon could be subject to the farm management practices used, including tillage and irrigation/drainage. The distribution of carbon pools in the soil with differing levels of availability, and their response and feedback to climate change has been poorly understood [94]. There have, however, been contradictory findings with regard to chemical recalcitrance, biological decomposition potential and feedbacks to the warming potential of SOC accumulation in soils [95]. Soil organic carbon decomposition and microbial metabolic utilization of organic substrates from croplands tends to be controlled by the chemical structure and recalcitrance of the carbon rather than enzyme activities [96]. Yet, it has been argued that the decomposition of indigenous SOC could not be affected by the soil microbial community and its activity [97]. Similarly, it has been found that there was no difference in the decomposition susceptibility and temperature dependence between old and new carbon pools [98]. However, as shown in a study of decomposition of SOC from croplands under maize cultivation for different time frames, microbial attack on old SOC pools was more sensitive to warming stress than young carbon pools [99]. In contrast, in a long term field soil core incubation study, microbial growth and utilization of residue-input carbon was significantly enhanced under warming in a straw-amended soil [100]. Thus, it was commented that microbial activity would be a key factor in determining the carbon balance of agroecosystems. One of our previous studies, with a long term agro-ecosystem experiment from Wujiang, China, showed that both SOM recalcitrance [101] and microbial activity [84,85] were impacted when chemical fertilizer was applied only compared with the use of combined organic/ inorganic fertilizers. Such difference in microbial activity between different fertilization treatments has been also well demonstrated in a long-term experiment from Jiangxi [102]. Another incubation study on SOC decomposition using laboratory incubations under aerobic and anaerobic conditions respectively was allowed to draw changes in chemical stabilization with different long term fertilization treatments from a rice paddy soil under long term fertilization from Jiangxi, China [103]. While a much lower decomposition rate was measured under anaerobic conditions, the temperature sensitivity was not related to the availability of the SOC under aerobic conditions but to the microbial quotient under anaerobic conditions. This finding suggests that the controls on SOC decomposition could vary either with SOC recalcitrance or with microbial activity, which could be dependent of the rate limiting factor. Nevertheless, there has not yet been a generally accepted understanding that newly sequestered SOC could exert a priming effect on microbial growth and thus enhance SOC decomposition, thereby inducing an increase in GHG emissions from croplands. However, these contradictory findings were associated with whether or not the study was conducted using a bulk or rhizosphere soil incubation [104–106], and whether in long term field experiments or short term incubation [106,107].

3.2 Soil organic carbon sequestration and GHG emissions from croplands

Generally, soil heterotrophic respiration increases with increasing SOC, thus resulting in increased CO_2 emissions. This seemed apparent when very high soil respiration and overall CO_2 fluxes from peat lands rich in SOC were measured under drainage or cultivation [40,108]. The mineralization potential of SOC from wetlands from the lower reaches of the Yangtze valley was observed to be several folds greater than from rice paddies converted from the wetlands. Such a response has been considered the main reason why soil respiration sharply increased after drainage [109] and the topsoil SOC stock quickly declined within the first decade after reclamation and cultivation [110,111].

A number of laboratory incubation studies have shown that SOC decomposition and aerobic respiration in rice paddies with different pedogenic origins tended to be lower than in corresponding forest or grassland soils [93]. While the N level was generally accepted as a key factor controlling soil microbial respiration [93,112], the correlation of soil respiration with SOC content in rice soils which are not N limiting were generally poor. Instead, soil respiratory activity and respired CO_2 flux was often shown to be lower in plots rich in SOC under a well designed fertilizer scheme when compared with relatively SOC-poor plots under long term agro-ecosystem experiments [77,103,104]. Decreases in soil respiratory activity with increased SOC have been observed in dry croplands under organic fertilization than those under non organic amendments [62,113]. Similarly, a reduction in the microbial metabolic quotient and mineralization intensity of SOC was also evidenced in a long-term field experiment under combined organic/inorganic fertilization over only chemical fertilization [77,78]. An integrated field study using a number of long-term experiments from rice paddies of South China has demonstrated an increasing dominance of the fungal over the bacterial community with increasing SOC accumulation under good agro-management, which in turn supports a decrease in soil respiratory activity [114]. A new insight into SOC sequestration and GHG emission was that total global warming potential calculated from all the GHGs fluxes in a plot continuously receiving compound fertilizers seemed smaller than one receiving chemical fertilizer only [115].

Over the past few years, assessment of the net C balance using life cycle analysis further supports the idea that the C sink effect would be profound in SOC-accumulated soils receiving fertilizer. In some cases, the net C sink was 1.5–3 folds greater under a combined organic/inorganic fertilizer regime than under chemical fertilization only, in rice paddies from Jiangxi and Jiangsu, China [116,117]. Another similar study indicated that there was a higher net C sink (by 1.1–1.7 folds) under organic amendments compared to under chemical fertilization only [118]. These studies have also shown evidence of a higher rice yield and hence economical income in SOC accumulated soils as compared with SOC-poor soils across several sites. Therefore, SOC accumulation under a well designed combined organic/inorganic fertilizer regime may be adopted as a major countermeasure to enhance the effects on both crop productivity and the mitigation of soil GHG losses in agriculture.

Some studies have argued that a priming effect of SOC accumulation in rice paddies, and in turn, new labile carbon pools would be a potential source for increased CO_2 fluxes, as was the case when a ^{14}C labeled maize residue incubation was undertaken [119]. Comparatively, the priming effect in rice paddies was certainly much weaker than in dry croplands. Recently, it has been hypothesized that the stabilization of newly sequestered SOC may have involved soil ecological stabilization (in addition to chemical recalcitrance-stabilization) and microbial stabilization, which may not be simply accounted for by a linkage of SOC-substrate-microbial activity. It should be also taken into account that SOC sequestration enhances crop productivity and thus enhance N efficiency, which in turn, helps to reduce the amount of N required for a certain yield [87]. It is our point of view that SOC sequestration may be useful for reducing total GWP by enhancing carbon efficiency for a single unit of production.

4 Conclusions and perspectives

Identifying carbon pool dynamics and C sequestration potential using carbon counting methodology have been “hot spots” in China’s research on land use/land cover and global climate change. With the methodology of carbon pool counting consistently updated, more or less consistent estimates of both total SOC stock and sequestration potential of China’s soils have been reported hitherto. There has, however, been some discrepancy in estimation of topsoil carbon pool changes with historical land use, which could considered due to the incompatibility of topsoil data available with the management authorities. In particular, a default topsoil depth of 0–20 cm has been adopted in a national geochemical survey performed by the National Geo-survey Bureau for cropland quality monitoring. However, the default depth of 0–30 cm was widely accepted internationally. Such a problem impairs data comparison and integration of national or international datasets. In addition, SOC in deep soils is being given more attention as it has a high stability and a slow response to global warming. As there is very limited data on deep soil SOC stocks, there are likely to be more research opportunities in this field, for the future C study in China.

The existing SIC pool for arid and semiarid regions will play an increasing role in the carbon budget and carbon balance in terrestrial ecosystems. As a carbon form with the lowest turnover rates in land surfaces, studies on the transfer and immobilization of SOC to SIC will determine its potential role in future carbon capture and carbon storage projects and deserve priority in future research work.

Furthermore, regional or watershed carbon dynamics and its impact on land use/land cover changes (in response to global environmental changes) would be an ever increasing multi disciplinary area of geo-bioscience. The definition of the “critical zone” (the heterogeneous, near surface environment in which complex interactions involving rock, soil, water, air, and living organisms regulate the natural habitat and determine the availability of life-sustaining resources) [120] may offer a theoretical framework for such an integrated study, which deals with the pedogenic, geochemical and biological aspects of carbon sequestration plus C mobilization, transportation and deposition within a watershed or a large geographical region. But the net C sink effect will be determined by the capacity of the whole system rather than by a single soil or single piece of cropland. These studies may be organized by integrating projects on biology and ecology and ecology at several scales from small watersheds, including the catchment level, up to eco-regions.

The vulnerability of ecosystems and croplands to degradation has been well documented in extensive areas of China. One of the research foci of soil carbon studies could be the role of SOC in improving production capacity, resource and carbon efficiency as well as the functioning of our soil and ecosystems. These topics may again offer opportunities for developing SOC sequestration science with particular emphasis on the biophysical potential and the technical capacity of croplands under intensified farming. However, the lability of SOC and its relation to GHG emissions, in response to environmental changes should demand more profound, field-based monitoring in addition to laboratory studies.

Overall, following the international trends of global change and earth system science, carbon cycling studies of China’s croplands and ecosystems will be developed only with the innovation of research technologies in line with development in methodologies. Meanwhile, soil carbon sequestration science is likely to be further equipped with tools such as (molecular) biological and modern analytical technologies, with their integration at plot to region scales, combined with multiple disciplines and performed on multiple interfaces both in micro and macro levels. It is anticipated that a significant part of the ongoing studies of soil carbon sequestration in China will be focused on the response of carbon cycling to anthropogenic influences and global climate change.

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