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Estimation of soil carbon saturation and carbon sequestration potential of an agro-ecosystem in China

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Key words: Agro-ecosystem, biogeochemistry, China, DNDC model, cropland soil, upland, paddy field

SUMMARY

Soil is believed to be the most important sink for sequestering atmospheric carbon. Hence, estimating soil carbon sequestration potential has been carried out for different regions and agricultural practices. However, soil carbon saturation (SCS), a fundamental concept for estimating soil carbon sequestration potential, has not been estimated for countries or regions. In this study, we estimated SCS of agricultural land for most provinces in China for 1990 by the DNDC model, a carbon and nitrogen biogeochemical cycle model, in order to provide a basis for farmers to select the land use, tillage and fertilization regimes to sequester more carbon. The result showed that SCS was as low as 0.48% in Tianjin and up to 5.14% in Tibet. There was a positive correlation between SCS and the proportion of paddy field in a province. In 1990, cropland soil carbon sequestration potential (SCSP) in China was -0.969 Gt C (-2.706 to 0.767 Gt C). This suggests that agricultural soil will be a carbon source to the atmosphere if agricultural practices are not altered. However, SCSP differed between provinces in China. SCSP was highest in Tibet (7.9 t C ha^{-1}) and lowest in Heilongjiang Province ($-60.8 \text{ t C ha}^{-1}$), with a gradual decrease from south to north in China.

INTRODUCTION

Rising atmospheric carbon dioxide concentration is a concern because of its potential for altering climate. Since the beginning of the Industrial Revolution in the eighteenth century, atmospheric CO_2 has increased by more than 30%. The increase in fossil fuel burning and associated CO_2 emissions is expected to continue for the foreseeable future, and a doubling or even tripling of the preindustrial concentration of atmospheric CO_2 is possible by the end of the twenty-first century (Post *et al.* 2004). Management of vegetation and soils for terrestrial

carbon sequestration can remove significant amounts of CO_2 from the atmosphere and store it as carbon in the organic matter of ecosystems (Post *et al.* 2004). Soil is one of the largest organic carbon pools, so soil may be a very important potential sink for carbon storage. Human management such as tillage, fertilization and irrigation can change the quantity and quality of the agricultural soil carbon pool. This change not only affects soil fertility and crop yield, but also has an effect on carbon exchange between soil and the atmosphere (Li 2000).

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In order to prevent soil carbon from being released into the atmosphere, current trends of soil carbon change should be assessed and soil carbon sequestration potential (SCSP) should be estimated. In some developed countries, such as the USA, European Union and Canada, SCSP has been estimated (Lal *et al.* 1998; Smith *et al.* 1997; Freibauer *et al.* 2004; Yang *et al.* 2003). China, as one of the largest agricultural countries, providing food for one-fifth of the world population, has strongly changed soil quality and released large amounts of CO₂ into the atmosphere from croplands (Li *et al.* 2003; Wang *et al.* 2003). Soil carbon content in China has declined to a rather low level after cultivation for thousands of years. Up to now, the SCSP of China has not been estimated.

In previous studies, estimation of SCSP was based on field experiments that assumed that soil carbon sequestration rate did not change during many years under a specific agricultural practice (Lal *et al.* 1998; Smith *et al.* 1997). In fact, soil carbon sinks increase most rapidly soon after a carbon enhancing land management change has been implemented. Sink strength (i.e. the rate at which carbon is removed from the atmosphere) in soil becomes smaller as time goes on, as the soil carbon stock approaches a new equilibrium. At equilibrium, the sink is saturated: the carbon stock may have increased, but the sink strength has decreased to zero (Smith 2004). So SCSP should be estimated based on the following formula:

$$\text{SCSP} = \text{SCS} - \text{CSC} \quad (1)$$

where SCS and CSC are soil carbon saturation and current soil carbon, respectively. SCS is not easy to estimate because there are few agricultural practices lasting for more than 10 years due to the current rapid development of technology and economics, so the optimum method of estimating SCS is through modelling.

A number of soil organic matter (SOM) models have been developed. Most assume first order kinetics for the decomposition of various conceptual pools of organic matter (McGill 1996; Paustian 1994), which means that equilibrium carbon stocks are linearly proportional to carbon inputs (Paustian *et al.* 1997). These models predict that soil carbon stocks can, in theory, be increased without limit, provided that carbon inputs increase without limit, i.e. there are no assumptions of soil carbon saturation (SCS). While these models have

been largely successful in representing SOM dynamics under current conditions and management practices (e.g. Parton *et al.* 1987, 1994; Paustian *et al.*, 1992; Powlson *et al.* 1996), usually for soils with low to moderate carbon levels (e.g. < 5%), there is some question of their validity for projecting longer term SOM dynamics under scenarios of ever increasing carbon inputs (e.g. Donigian *et al.* 1997). Such scenarios are particularly relevant to the development of new technology designed to promote soil carbon sequestration through increasing plant carbon inputs. While many long-term field experiments exhibit a proportional relationship between carbon inputs and soil carbon content across treatments (Larson *et al.* 1972; Paustian *et al.* 1997), some experiments in high carbon soils show little or no increase in soil carbon content with two- to three-fold increases in carbon inputs (Campbell *et al.* 1991; Paustian *et al.* 1997; Solberg *et al.* 1997), which is consistent with a saturation phenomenon (Six *et al.* 2002). A recently developed process-based biogeochemical model, DNDC (denitrification-decomposition) model, has considered soil carbon saturation (Li *et al.* 1994).

This paper is based on the concept of SCS and estimates Chinese agricultural soil carbon pools of each county using the DNDC model. The SCS of each province in China and estimated SCSP of cropland of each province are assessed and comparisons are made between soil carbon sequestration in upland and paddy fields.

METHODS

DNDC model

We conducted agroecosystem biogeochemical simulations, tracking the cycles of C and N in all cropland in China. The denitrification-decomposition (DNDC) model was used to predict interacting effects of environmental factors (e.g. climate, soil properties and land use and management) on crop yield, soil fertility, nitrogen leaching and trace gas emissions to the atmosphere. The core of DNDC is a soil biogeochemical model describing C and N transport and transformation driven by a series of soil environmental factors such as temperature, moisture, redox potential (i.e. Eh), pH and substrate concentration gradients. Sub-models for soil climate, decomposition, nitrification, denitrification and fermentation have been

incorporated in DNDC to track the coupled C and N biochemical or geochemical reactions in the soil (Li *et al.* 1992, 1994; Li 2000). In addition, a crop growth submodel has been integrated with the biogeochemical submodels to simulate plant photosynthesis, respiration, C allocation, litter production and water and N uptake from the soil (Zhang *et al.* 2002). Basic physical, chemical and biological laws governing the relevant reactions, as well as empirical equations developed from field and laboratory observations, are utilized to construct the model framework. DNDC is driven by daily meteorological data, soil properties, vegetation status and anthropogenic activities, including farming management (Table 1). DNDC simulates the daily dynamics of soil climate profiles; plant development and growth; soil C and N pools, fluxes of CO₂, CH₄, N₂O, NO, N₂ and NH₃; and N leaching. DNDC has been validated against numerous field observations regarding soil organic carbon (SOC) dynamics and trace gas emissions in agroecosystems worldwide (Li *et al.* 1992, 1994, 1996, 1997, 2003; Smith *et al.* 1997, 1999; Wang *et al.* 1997; Frolking *et al.* 1998; Plant *et al.* 1998; Xiu *et al.* 1999; Li 2000; Brown *et al.* 2002; Zhang *et al.* 2002; Wang *et al.* 2001; Han *et al.* 2003). These results indicated that DNDC was able to produce reasonable predictions for SOC dynamics and trace gas emissions from croplands across climate zones, soil types and agricultural management regimes. The DNDC model is available free to download via the internet (www.dnnc.sr.unh.edu).

Estimating cropland soil carbon pool and its change for all counties in China

We conducted county-scale simulations for all counties in China with cropland. The database compiled to run the DNDC simulations contained daily weather data, soil properties, crop acreage, crop types and rotations, and farming practices (e.g. tillage, fertilization, manure amendment and irrigation) at county or county-cluster scale, based on information for the year 1990 (Table 1). Data sources used in the DNDC model for China are listed below:

1. Daily precipitation and maximum and minimum air temperature

Data from 610 weather stations across China were acquired from the National Center for

Atmospheric Research and Data Support Center. Station data was assigned to each county on a nearest neighbour basis. Earlier simulations with only 175 stations yielded very similar results, and we were confident that the uncertainty in our results due to lack of spatial interpolation of weather data was small.

2. Soils (organic matter content, pH, texture, bulk density)

Soils were initialized at high and low soil organic carbon (SOC) content, based on digitization of the map of soil organic matter (Institute of Soil Science, 1986) and information published by the National Soil Survey Office of China (1993–1997). SCS results were based on the mean of the high and low SOC simulations. Soil pH, bulk density and texture data were taken from the Institute of Soil Science (1986).

3. Farming management (fertilization, tillage, planting and harvest dates, manure inputs, crop residue management) and cropland areas (hectares per county of all single, double and triple crop rotations)

General data on crop tillage, planting and harvest dates, crop residue management and crop varieties were taken from the Central Radio and Television School of Agriculture (1995), Huang *et al.* (1997), Cui *et al.* (1994), Liu and Mu (1993) and Beijing Agricultural University (1992). Shen (1998) reported that, based on national statistics, an average of 20% of total crop residue (leaves + stems + roots) was returned to the soil. All root biomass (for non-tuber crops) was re-incorporated into the soil as organic matter. The county database of fertilizer use (kg N) and manure input (kg C and kg N) to soil assembled by the Research Center for Eco-Environmental Sciences, Beijing (see, e.g. Li *et al.* 2003). Manure production was based on animal and human populations from this database, standard manure production rates (IPCC 1997) and field application rates of 20% for animal manure and 10% for human manure. Areas in each of 48 single and multiple crop rotations (e.g. winter wheat/rice) were estimated by combining a county statistical database on crop sown areas from the Research Center for Eco-Environmental Sciences, Beijing (see Frolking *et al.* 1999) with a Landsat thematic mapper-derived land cover map for all

Table 1 Denitrification-decomposition (DNDC) model input and output variables

Model input data
Soil properties (county ranges): SOC, bulk density, pH, texture
Daily weather: precipitation, maximum and minimum air temperature
Cropland areas (ha per county): all single, double and triple crop rotations
Farming management: fertilization, tillage, planting and harvest dates, manure inputs, crop residue management
Model output
Crop productivity: grain, stem and root yield (kg C and N/ha), N uptake and fixation by legumes
Trace gas fluxes: CH ₄ , CO ₂ , NH ₃ , NO, N ₂ O, N ₂
Soil organic C and N pools
Soil inorganic N content

of mainland China (see Liu and Buheasier 2000).

Simulation outputs included a range of soil, plant and trace gas C and N pools and fluxes (0–0.3 m) (Table 1). The total C or N fluxes from each county were calculated by summing crop area-weighted fluxes from each crop rotation in each county, and county totals were aggregated to national totals. Reported changes in SOC (0–0.3 m) thus represented the loss or gain in SOC over a one-year crop rotation, based on initialization of SOC pools to 1990 levels from available soil data.

Estimation of SCS for provinces

More and more researchers consider that under the given condition of climate, topographic form and parent material, if the mode of land use is not changed, the soil carbon pool will stabilize (Smith 2004), which is known as SCS. However, estimating soil carbon saturation is not easy. Generally, there are two methods: one suggests that, after SOM model running through many years, SCS is the soil carbon content which has reached stabilization; the other suggests that, if we can find the formula of the relationship between cropland SOM content and its change after one year of cultivation, SCS might be the SOM content when soil carbon change after one year of cultivation equals zero. In this paper, we adopted the latter method to obtain SCS of cropland for each province of China.

Based on cropland soil carbon pool (or original content of SOM) and its change after one year of cultivation for each county of China, estimated using the DNDC model, through regression analysis we elicited the fitting relationship curve between the above-mentioned parameters. On the curve,

Figure 1 Relationship between original SOM content and change in SOC after one year cultivation in Jiangsu Province

the soil carbon pool (or original SOM content) when soil carbon change equalled zero was SCS. Using Arcview GIS software, we drew the distribution map of SCS in China.

Taking Jiangsu and Liaoning Provinces as examples, we explained how to estimate SCS (Figures 1 and 2). In the Figures, each point represented the average data for each county. When SOM content (or SOC density) was very high, after one year of cultivation, loss of SOC was also very high. As SOM content (or SOC density) decreased, loss of SOC also decreased. After soil reached a certain SOM content (or SOC density), SOC content changed little and began to increase. The specific SOM content in Jiangsu Province was 0.93%, that is, under the condition of climate, fertilization level and traditional tillage in 1990, SCS of Jiangsu Province was 0.93%. In a similar manner, cropland SCS of Liaoning Province was found to be 35.0 t C ha⁻¹.

Figure 2 Relationship between SOC density and change after one year cultivation in Liaoning Province

Herein, SCS could be expressed in two ways: SOM content (%) and SOC density (t C ha^{-1}). Because most experimental reports of soil carbon are currently expressed in SOM content in China, the SCS in SOM content could easily be compared with experimental field reports. For calculation of SCSP, SCS in SOC density was preferred.

Factors influencing SCS

Multiple regression analyses were performed on SCS, mean annual air temperature and rainfall in 1990, and proportion of paddy field to investigate factors influencing SCS.

Comparison of carbon sequestration between upland and paddy field

To assess the influence of land use on SCS, we estimated changes in SOC after a one-year cultivation of upland (represented by corn) and paddy field (represented by wet rice), separately for each county, using the DNDC model.

Cropland SCSP in China

SCSP was estimated from formula (1) and its distribution was drawn with ArcView. The DNDC model operated on county scale. So, DNDC model output data, including soil carbon pools and soil carbon changes after one year of cultivation, were also county-based. Using the abovementioned method, we obtained the province-based soil carbon saturations. The original soil carbon sequestration

potential (SCSP) was county-based, and the average SCSP for a province was calculated as the sum of the weighted area from different counties to obtain the total SCSP in China.

RESULTS AND DISCUSSION

Cropland SCS and its distribution in China

The SCS ranged from 0.48% in Tianjin City to 5.14% in Tibet for 1990 data (Table 2). The SCS of cropland was lower in North China, from which SCS increased to the north, south and west. For Sichuan and Qinghai Provinces, there was no SCS estimated because the correlation (R) between initial soil carbon content and its change after one-year cultivation at the provincial scale was not significant at a confidence level of 0.05 (Table 2).

Using multiple regression analysis, we found that SCS (%) was related to the proportion of paddy field (PADDY, %) and mean annual air temperature (TEMP, °C) at provincial level in northern parts of China, including North, Northeast and Northwest China and Tibet. The equation was as follows:

$$\text{SCS} = 2.746 + 0.0105 \text{ PADDY} - 0.141 \text{ TEMP} \quad (p < 0.01) \quad (2)$$

The SCS increased with proportion of paddy and decreased with the air temperature. The SCS in North China was the lowest because of the lower proportion of paddy and higher air temperature.

In southern parts of China, except for Tibet, the SCS was related to the proportion of paddy, as shown in the following equation:

$$\text{SCS} = 0.938 + 0.0087 \text{ PADDY} \quad (p < 0.05) \quad (3)$$

In the southern parts of China, the climate is humid, and the agrotypes are mainly wet rice. Flooded soil formed by planting wet rice reduced SOM decomposition. The agrotypes in North China are mainly wheat, and SOM decomposes rapidly. So soil carbon saturation in the southern parts of China was higher than that in North China.

Difference in carbon sequestration between uplands and paddy fields in China

Based on our estimation from the DNDC model, average change in SOC per hectare after one-year

Table 2 Cropland SCS and SCSP for every province of China (0–0.3 m)

Province	Number of counties	SCS (%)	R	SCS (tC ha ⁻¹)	CSC (tC ha ⁻¹)	Mean SCSP (tC ha ⁻¹)	Total SCSP (Mt C)
Beijing	15	1.04	0.5539 *	21.9	21.0 (12.9–29.0)	0.9 (–7.1–9.0)	0.4 (–2.9–3.7)
Tianjin	12	0.48	0.7667 **	8.2	16.7 (12.0–21.4)	–8.5 (–13.2–3.8)	–3.6 (–5.6–1.6)
Hebei	151	0.73	0.4403 **	16.6	20.4 (11.7–29.2)	–3.8 (–12.6–4.9)	–25.4 (–82.8–31.9)
Shanxi	111	0.54	0.4701 **	13.2	25.5 (15.2–35.8)	–12.3 (–22.7–2.0)	–45.5 (–83.7–7.3)
Inner Mongolia	90	2.37	0.6580 **	46.8	62.8 (19.2–106.4)	–16.0 (–59.6–27.6)	–79.5 (–296.4–137.3)
Liaoning	74	1.91	0.8401 **	35.0	48.2 (21.8–74.6)	–13.2 (–38.8–14.0)	–43.1 (–134.6–48.4)
Jilin	48	2.25	0.7623 **	44.2	81.6 (43.2–120.1)	–37.4 (–75.8–1.1)	–148.3 (–300.8–4.2)
Heilongjiang	80	1.88	0.8250 **	35.5	96.3 (55.4–137.2)	–60.8 (–101.7–19.9)	–421.4 (–704.9–137.9)
Shanghai	11	0.81	0.8432 **	16.5	29.9 (20.6–39.3)	–13.4 (–22.8–4.1)	–4.1 (–7.0–1.2)
Jiangsu	75	0.93	0.7262 **	19.5	27.9 (15.8–39.9)	–8.4 (–20.3–3.7)	–37.7 (–92.1–16.7)
Zhejiang	78	1.53	0.5822 **	30.2	31.0 (19.6–42.5)	–0.8 (–12.3–10.6)	–1.5 (–21.7–18.6)
Anhui	83	0.93	0.6603 **	24.0	23.9 (13.5–34.2)	0.1 (–10.2–10.5)	0.5 (–44.5–45.5)
Fujian	70	1.48	0.7462 **	28.6	33.2 (19.1–47.4)	–4.6 (–18.8–9.5)	–5.7 (–23.2–11.7)
Jiangxi	92	1.39	0.7306 **	30.5	30.9 (17.7–44.1)	–0.4 (–13.6–12.8)	–0.9 (–31.6–29.7)
Shandong	129	0.92	0.7257 **	19.9	24.2 (12.7–35.8)	–4.3 (–15.9–7.2)	–30.1 (–109.9–49.6)
Henan	138	1.06	0.6286 **	22.5	24.4 (12.1–36.8)	–1.9 (–14.3–10.4)	–13.7 (–99.7–72.4)
Hubei	70	1.15	0.4001 **	25.8	30.7 (19.4–42.0)	–4.9 (–16.2–6.4)	–15.8 (–52.1–20.5)
Hunan	105	1.84	0.3189 **	36.0	32.0 (20.1–43.8)	4.0 (–7.8–16.0)	13.5 (–25.7–52.8)
Guangdong	104	2.26	0.5240 **	42.0	38.2 (24.1–52.2)	3.8 (–10.3–17.9)	9.6 (–25.8–45.0)
Guangxi	88	2.07	0.8207 **	40.2	51.3 (21.4–81.3)	–11.1 (–41.1–18.8)	–28.8 (–106.1–48.5)
Sichuan	208	–	0.1006	–	–	–	–
Guizhou	82	2.36	0.5907 **	45.4	41.0 (21.8–60.3)	4.4 (–14.9–23.7)	8.4 (–28.5–45.3)
Yunnan	126	2.11	0.7365 **	40.4	41.2 (21.4–61.1)	–0.8 (–20.7–19.0)	–2.5 (–61.4–56.3)
Tibet	77	5.14	0.6420 **	95.8	88.0 (30.0–145.9)	7.9 (–50.0–65.8)	1.8 (–11.6–15.2)
Shaanxi	107	0.91	0.6408 **	19.5	26.9 (12.7–41.2)	–7.4 (–21.7–6.8)	–26.6 (–77.6–24.5)
Gansu	86	1.27	0.5508 **	27.4	30.1 (10.3–50.0)	–2.7 (–22.6–17.1)	–9.4 (–76.9–58.1)
Qinghai	40	–	0.2276	–	–	–	–
Ningxia	20	1.68	0.5124 *	32.2	24.6 (9.7–39.4)	7.6 (–7.2–22.5)	6.1 (–5.7–17.9)
Xinjiang	84	1.70	0.7779 **	35.9	60.8 (9.9–111.6)	–24.9 (–75.7–26.0)	–54.8 (–166.7–57.2)
Hainan	19	1.77	0.8225 **	34.9	63.6 (25.0–102.2)	–28.7 (–67.3–9.9)	–11.3 (–26.4–3.9)
The whole of China						–11.1 (–31.5–8.9)	–969.4 (–2705.6–766.8)

* significant at $\alpha = 0.05$ probability

** significant at $\alpha = 0.01$ probability

cultivation in corn fields in China was $-1.35 \text{ t C ha}^{-1}$, while that in wet rice fields was $-0.71 \text{ t C ha}^{-1}$. The loss of SOC in corn fields was 1.9-times that in wet rice fields (Figure 4). After one year of cultivation, there were four provinces in China whose SOC contents were increasing, while corn field SOC in 26 provinces was decreasing. However, in wet rice fields, there were five provinces whose SOC contents were increasing, while in 25 provinces SOC contents were decreasing. In addition, there were eight provinces where the loss of SOC after one-year cultivation in wet rice fields was more than that in corn fields, and 22 provinces where the loss of SOC in wet rice fields was less than

that in corn fields. Therefore, we could conclude that paddy fields had larger carbon sequestration than uplands in China, probably because flooded soil during planting of wet rice reduced SOM decomposition.

Cropland SCSP and its distribution in China

Under the conditions of land use, tillage, fertilization and climate in 1990, cropland soil carbon sequestration potential in China was $-0.969 (-2.706 - 0.767) \text{ Gt C}$ (Table 2), suggesting cropland soils in China could reach a relative

Figure 3 Distribution of cropland soil carbon saturation (% of SOM content for top 0–0.3 m of soil) for each province in China. The black lines mark provincial boundaries

Figure 4 Comparison of change in SOC after one-year cultivation between upland and paddy field for most provinces of China

equilibrium state (soil carbon saturation) by releasing 0.969 Gt C to the atmosphere. This implied that current agricultural practices made cropland a carbon source to the atmosphere.

Total SCSP of Hunan Province was the highest (13.5 Mt C), while Heilongjiang Province was the lowest (–421.4 Mt C). There were 21 provinces (70% of provinces of China) where cropland SCSP

Figure 5 Distribution of cropland soil carbon sequestration potential (t C per ha for the top 0–0.3 m of soil) for each province in China. The black lines mark provincial boundaries

was negative and would continue to release carbon to the atmosphere.

Cropland SCSP per hectare in Tibet was the highest (7.9 t C ha^{-1}) of all provinces in China (Figure 5), while Heilongjiang Province was the lowest ($-60.8 \text{ t C ha}^{-1}$). Mean SCSP decreased gradually from south to north, especially in North-east China, which was probably lower because of higher current soil carbon compared with SCS. This also meant that the current planting system in the northern parts of China should be changed to enhance soil carbon sequestration potential.

In this research, changes in cropland SOC after one year of cultivation for most provinces in China were less than zero, and SCSP for most provinces was also less than zero. However, this view has been challenged by some soil scientists who investigated soils in North China and the Yangtze River Delta where cropland SOM content has increased in recent years. We should note that in this paper, 1990s conditions were used for the simulations of cropland soil carbon dynamics and fluxes. The database of 1990 was available, comprehensive and the latest we could obtain. At present, it is possible that increases in manure application, crop yield, crop biomass and return of crop residue into soils have caused an increase in SOM content.

CONCLUSIONS

We obtained cropland SCS of most provinces of China. This could provide the basis for farmers to understand the state of soil carbon and to select land-use mode, tillage and fertilization techniques to sequester more carbon. Cropland SCS was lower in North China and increased elsewhere because it was related to the proportion of paddy field, which had more carbon sequestration capacity than upland areas. Under the 1990 conditions of land-use mode, tillage, fertilization and climate, cropland SCSP in China was -0.969 ($-2.706 - 0.767$) Gt C. The mean SCSP decreased gradually from south to north. In order to sequester more carbon in cropland soils, new agricultural management systems should be developed so as to increase crop yield while returning crop residues into the soil.

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