J. Geogr. Sci. 2020, 30(6): 921-934
DOI: https://doi.org/10.1007/s11442-020-1762-3

Effects of land use and cultivation time on soil organic and inorganic carbon storage in deep soils

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Abstract: The vertical distribution and exchange mechanisms of soil organic and inorganic carbon (SOC, SIC) play an important role in assessing carbon (C) cycling and budgets. However, the impact of land use through time for deep soil C (below 100 cm) is not well known. To investigate deep C storage under different land uses and evaluate how it changes with time, we collected soil samples to a depth of 500 cm in a soil profile in the Gutun watershed on the Chinese Loess Plateau (CLP); and determined SOC, SIC, and bulk density. The magnitude of SOC stocks in the 0–500 cm depth range fell into the following ranking: shrubland (17.2 kg m^{-2}) > grassland (16.3 kg m^{-2}) > forestland (15.2 kg m^{-2}) > cropland (14.1 kg m^{-2}) > gully land (6.4 kg m^{-2}). The ranking for SIC stocks were: grassland (104.1 kg m^{-2}) > forestland (96.2 kg m^{-2}) > shrubland (90.6 kg m^{-2}) > cropland (82.4 kg m^{-2}) > gully land (50.3 kg m^{-2}). Respective SOC and SIC stocks were at least 1.6- and 2.1-fold higher within the 100–500 cm depth range, as compared to the 0–100 cm depth range. Overall SOC and SIC stocks decreased significantly from the 5th to the 15th year of cultivation in croplands, and generally increased up to the 70th year. Both SOC and SIC stocks showed a turning point at 15 years cultivation, which should be considered when evaluating soil C sequestration. Estimates of C stocks greatly depends on soil sampling depth, and understanding the influences of land use and time will improve soil productivity and conservation in regions with deep soils.

Keywords: cultivation time; deep soil; Gutun watershed; land use; inorganic carbon; organic carbon

Received: 2019-09-20 **Accepted:** 2020-03-05
Foundation: The Strategic Priority Research Program of the Chinese Academy of Sciences, No.XDB40000000; National Natural Science Foundation of China, No.41730108, No.41773141, No.41573136, No.41991252; National Research Program for Key Issues in Air Pollution Control, No.DQGG0105-02
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1 Introduction

Soils hold a large proportion of the world's carbon (C) in terrestrial ecosystems, and soils account for two-thirds of this amount, equivalent to 2–3 times the amount of C in the atmosphere (Trumbore, 2009; Díaz-Hernández, 2010). Soil carbon plays an active role in maintaining the global C balance (Xu *et al.*, 2019). Soil C includes soil organic carbon (SOC) and soil inorganic carbon (SIC). These carbon reservoirs act not only as a sink, but also as a source of atmospheric CO_2 (Díaz-Hernández, 2010), sensitive to climate change. SOC is especially sensitive, as SOC carbon sequestration and decomposition processes are controlled by both abiotic (e.g., climatic conditions) and biotic factors (e.g., vegetation belts, land use shifting). Lin and Zhang (2012) reported that increasing atmospheric temperature reduced SOC, whereas increasing atmospheric CO_2 concentration increased SOC inventories. Increasing these by only a few parts per thousand (0.4%) in global soils each year could remove an amount of CO_2 from the atmosphere equivalent to the amount emitted by fossil-fuels in the European Union (Rumpel *et al.*, 2018). Similar to other biotic factors, the distribution of vegetation belts and land use are expected to change under the conditions of global climate change (Adams *et al.*, 1990; Trumbore, 1997; Wang *et al.*, 2016), which would result in either sequestration or release of carbon in SOC. Therefore, an accurate evaluation of the amount and rate of C storage in soils is needed to understand the dynamics of C exchange between the soil and the atmosphere, and the biological influences involved.

Soil depth has a distinct influence on the amount of SOC storage (Wang *et al.*, 2015). Global stocks of SOC and SIC are approximately 1408 Pg (Batjes, 2016) and 695 - 1738 Pg (Schlesinger, 1982) in the 0–100 cm soil depth range, respectively. Batjes (1996) and (Esteban *et al.*, 2000) estimate that the global SOC stock would increase by 33% if SOC data were extended to depths of 100–200 cm, compared to the top 100 cm; indeed, the stock would further increase by 23% more if a depth of 300 cm was considered. Sommer *et al.* (2000) suggested that deep soils in the tropics may store large amounts of C below the uppermost 100 cm, potentially adding another ~50 Pg to the total global C pool. The SIC pool has received less attention than the SOC pool in deep soils (Civeira, 2013; Han *et al.*, 2018). As SIC is an essential component of carbon cycling in climate change models over a wide range of scales (Liu *et al.*, 2014; Zhang *et al.*, 2015; Civeira, 2016), it warrants increased attention. Understanding the distribution of both SOC and SIC storage in deep soil layers is necessary for assessing regional, continental, or global soil C storage and forecasting the consequences of global climate change.

Similarly, land use also greatly influences soil C stocks (Rumpel and Kögel-Knabner, 2011), as it affects the input and decomposition rate of organic matter in the soil (Ali *et al.*, 2017). In deep soils, SOC has a stronger association with vegetation, because deeper root systems may cause greater changes in profiles than those caused by climate change (Esteban *et al.*, 2000). Therefore, proper SOC management is needed for maintaining and mitigating the increasing of atmospheric CO_2 (Rumpel and Kögel-Knabner, 2011; Miltner *et al.*, 2012; Zhang *et al.*, 2014). This requires an accurate, reliable assessment of the C stored deep in the soil under different land uses.

Most studies involving C-stock evaluation in different land-use types are currently based on data acquired from indirect sources, such as soil-series maps, agriculture-related reports, and the like (Schlesinger, 1982; Eswaran, 1993; Batjes, 1996; Zhang *et al.*, 2004; Díaz-Hernández, 2010). For example, Chinese soil C budgets are usually based on the database from the Chinese Second National Soil Survey conducted in the 1980s (Zhang *et al.*, 2004; Wang *et al.*, 2010). Although it is easier and less expensive to sample and analyze soils to shallow depths, the lack of bulk density (BD) data for deep soils contributes to what may be a considerable error in the estimates of soil C reserves. Currently, most studies on soil C stocks typically extend to depths of 100 cm, whereas only a few studies have reported SOC to depths of 300 cm (Harper and Tibbett, 2013; Bi *et al.*, 2018). Plant roots in deep soils have a significant capacity to sequester C and thus may markedly increase soil C storage calculations. Data to calculate deep soil C reserves to depths of at least 500 cm are much less commonly available, although critical for improving deep-soil C assessments.

There is a large area and thick package of loess (640,000 km^2) in northwest China, called the Chinese Loess Plateau (CLP), which holds 1239.85 Tg of C to a depth of 20 cm (Fu *et al.*, 2014). In order to meet food requirements for the growing human population, land reclamation started in the 1950's, whereby approximately 336 km^2 of cropland was opened by 2012, partly under the well-known "Grain for Green" program that has been supported since 1999 by the central government of the People's Republic of China. Since then, several studies have been conducted to elucidate the effect of land cultivation on soil C stocks. Some researchers studied SOC and SIC stocks under grassland, forestland, and shrubland at different restoration times (Wang *et al.*, 2016; Liu *et al.*, 2017). The results of such studies showed that SIC decreased, while SOC increased with vegetation restoration. Jaiarree *et al.* (2011) reported that SOC stocks were reduced by 47% after 12 years of cultivation. However, studies of SOC and SIC over time of cultivation in reclaimed croplands are lacking. Estimating the changes in deep soil C storage under reclaimed croplands at different timescales would complement those findings and facilitate refined estimates of SOC and SIC stocks, which in turn can be associated with fixed atmospheric CO_2.

Therefore, the objective of this research is to investigate deep SOC and SIC stocks under cropland, forestland, grassland, shrubland and gully land types over 70 years following reclamation of croplands. In particular, we address the following key questions:

1) How do SOC and SIC stocks change with soil depth under five land-use types?
2) How do these deep-soil C stocks respond to different land-use types?
3) Which land use is optimal for C storage in our study area?
4) How do these stocks vary with time?

2 Material and methods

2.1 Study site

The Gutun watershed (36°46′39″–37°03′34″N, 109°41′02″–109°56′58″E) on the Chinese Loess Plateau (CLP) covers approximately 24 km^2, 46 km east of Yan'an city in Shaanxi Province (Figure 1). The study area is characterized by a temperate sub-humid climate with annual mean temperature and precipitation of 9.7℃ and 541 mm, respectively; most of the precipitation occurs between June and September (Zhao *et al.*, 2019).

In all, 21 representative profiles within the Gutun watershed were categorized based on predominant land use as grassland (two profiles), shrubland (one profile), forestland (two

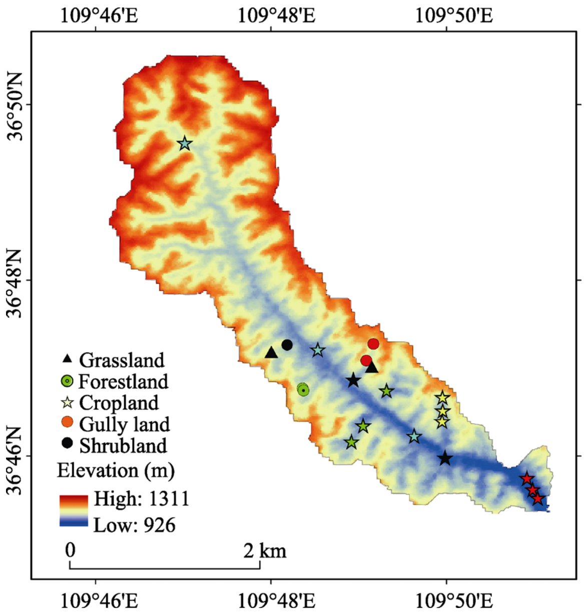

Figure 1 Location of the study area and sampling points (n=21 profiles) under different land use types within the Gutun watershed. Cropland includes five restoration time frames: RC-5 (light blue star), RC-15 (light green star), RC-35 (yellow star), RC-60 (red star), RC-70 (black star).

profiles), cropland (14 profiles), and gully land (two profiles), through field surveys, a work of time consuming and costly. Figure 1 shows that all grassland, shrubland, and forestland profiles were collected from the ridge, and there are several similar ridges in our study area. Moreover, cropland included five communities at different stages of cultivation, such as RC5 (three profiles), RC15 (three profiles), RC35 (three profiles), RC60 (three profiles), and RC70 (two profiles). Limited by a vast, hilly-gully area and drought, local governments and farmers had to open wasteland for cultivation by cutting mountain ridges to solve food shortages, resulting in a series of unique cropland sequences. We verified the cultivation age by interviewing local elders. The selected five cropland sites have been identified under continued cultivation for 5, 15, 35, 60, and at least 70 years (Figure 1).

2.2 Soil sampling and laboratory analysis

Soil samples were collected from 1 m × 1 m quadrats located by GPS from March to April in 2017. The litter in each site was cleared before sampling. Every site was excavated to a depth of 500 cm, or until the calcification layer or overflow layer was reached. We used 421 sampling points located on the ridges to determine bulk density (BD) at 10 cm intervals in the 0–20 cm top-soil layer, and at 20 cm intervals at depths from 20 to 500 cm. Another 421 samples were collected to determine total carbon (TC), SIC, soil water content (SWC), and particle composition.

A portion of each soil sample was used to measure SWC gravimetrically from weight loss after drying at 105℃ (Wang *et al.*, 2016). The remaining soil in each sample was air-dried and then sieved through a 2 mm mesh after removing debris. Soil texture was determined by laser diffraction using a Mastersizer 3000 (Malvern Instruments, England). The total carbon (TC) was measured by using an elemental analyzer at a combustion temperature of 950℃ (Vario EL cube, Elemental Analyzer, Elementar, Germany). As SIC refers to the carbonate minerals in the soil, such as $CaCO_3$, $MgCO_3$ (Wu *et al.*, 2009; Liu *et al.*, 2017), SIC content was measured by acid hydrolysis, which released SIC as CO_2. Finally, SOC content was calculated by subtraction of SIC content from TC content. All the experiments were performed at the Xi'an Accelerator Mass Spectrometry Center.

2.3 Calculation of SOC storage and SIC storage

Stored SOC and SIC (kg m^{-2}) were calculated using the following equations (Grimm *et al.*, 2008):

$$SOC_{\text{stock}} = SOC \times BD \times (1 - F_{\text{contet}}) \times \Delta d \times 0.01 \quad (1)$$

$$SIC_{\text{stock}} = SIC \times BD \times (1 - F_{\text{contet}}) \times \Delta d \times 0.01 \quad (2)$$

where, SOC_{stock} and SIC_{stock} represent SOC and SIC storage, respectively; SOC and SIC are the SOC and SIC contents (g kg^{-1}), respectively; BD is the soil bulk density (g cm^{-3}); the occurrence of coarse fragments in the loessal soils of the Chinese Loess Plateau is rare, therefore, F_{content} is usually negligible in the CLP; Δd represents the soil layer thickness (cm).

Two-way ANOVA analysis was applied to determine the significance of any effects from land use and cropland reclamation time on SOC, SIC and the other parameters under study. All the differences were evaluated at a significance level of 0.05. Statistical analyses were performed using Origin 2018b, SPSS 22, Sigmaplot 12.5 and Figures of sampling sites were drawn by ArcMap 10.2 software.

3 Results

3.1 Soil basic characteristics

Table 1 shows that soil texture was similar in all soil layers under the five land-use types studied. Both the highest proportion of silt and clay content and the lowest sand content were found in gully land soils. Silt content increased gradually with soil depth, whereas sand content decreased.

Table 1 Soil properties under five land-use types in the Gutun watershed on the Chinese Loess Plateau

Land-use type	Texture (%)			BD*(g cm^{-3})	SWC(g kg^{-1})	SOC(g kg^{-1})	SIC(g kg^{-1})
	Sand	Silt	Clay				
Grassland	19.2±3.8ab	78.2±3.6a	2.6±0.3bc	1.3±0.1b	126.0±20.3b	2.96±2.22a	16.77±3.00a
Shrubland	19.7±3.0ab	77.6±2.8a	2.7±0.4bc	1.3±0.1b	92.8±47.5c	2.76±1.75ab	13.79±2.40bc
Forestland	22.3±4.5a	75.4±4.3a	2.3±0.4c	1.3±0.1b	71.7±19.4c	2.58±1.22ab	14.82±1.81ab
Cropland	22.1±5.4a	75.1±5.0a	2.8±0.7b	1.5±0.2ab	177.2±51.6a	2.04±1.10ab	12.38±3.18c
Gully land	18.6±4.2b	78.2±3.8a	3.2±0.6a	1.4±0.1a	197.7±31.0a	1.84±1.29b	14.22±2.65bc

*BD, bulk density; SWC, soil water content; SOC, soil organic carbon; SIC, soil inorganic carbon. Different lowercase letters within columns indicate significant differences among land-use types.

3.2 Carbon content under different land uses and various times of cropland cultivation

The variability of BD was small (<10%) throughout the soil profile under each land-use type, but overall, it increased with depth. Cropland showed the highest BD values, ranging from 1.01 to 1.82 g cm^{-3}, followed by gully land. Shrubland, forestland, and grassland were comparable in BD, with uniformly low levels (Table 1).

Land use significantly affected SWC ($p < 0.05$), with the following ranking: gully land > cropland > grassland > shrubland > forestland (Table 1). There were obvious changes in SWC between top and deep soil layers; SWC increased with depth in gully land and croplands, in agreement with most farmland in China (Zhu *et al.*, 2019), whereas in forestland, it varied over a wide range and decreased to <100 g kg^{-1} below 40 cm depth, which is classified as a dried soil layer (Wang *et al.*, 2004).

The mean SOC of all 21 soil profiles and the 0–500 cm soil profile was 2.24±1.39 g kg^{-1} (n=

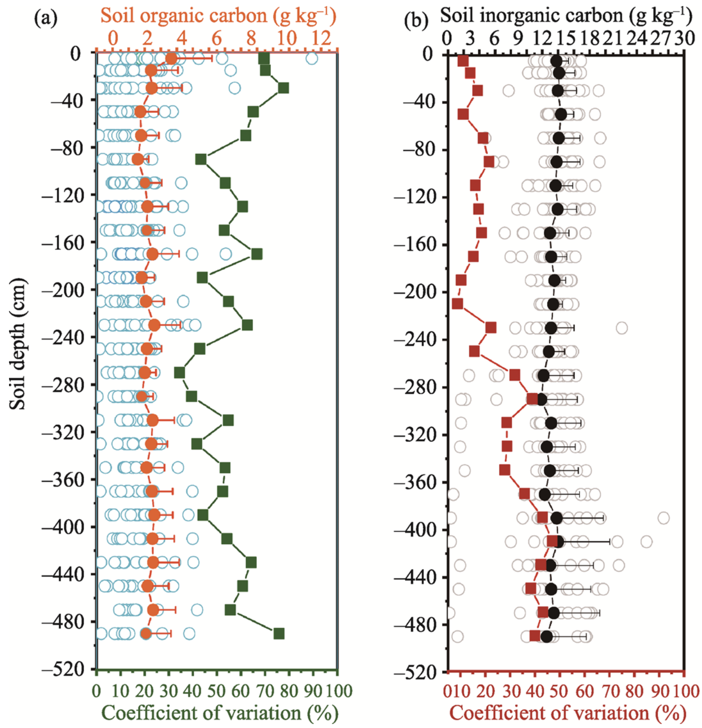

Figure 2 Vertical distribution of SOC and SIC along 500-cm deep soil profiles. (a) SOC content (open blue circles), means (closed red circles), and the coefficient of variations (green squares); (b) SIC content (open light grey circles), means (closed black circles), and the coefficient of variations (dark red squares).

421), which is lower than values measured at other sites in the CLP (Ma *et al.*, 2012; Wang *et al.*, 2016; Liu *et al.*, 2017). Overall, surface SOC was higher than that in the subsoil (Figure 2). Land use influenced SOC content significantly ($p < 0.05$) (Table 2). In grassland, forestland, and shrubland, SOC values were generally higher than those in cropland or gully land in the same soil layers (Table 3). Grasslands were exceptional in that SOC of the 0–60 cm layer, which was significantly higher than that in the 60–500 cm layer ($p < 0.05$), while no such difference was observed for shrubland, forestland, or gully land ($p > 0.05$) (Table 3).

Cultivation time influenced SOC content significantly ($p < 0.05$) (Table 2). The corresponding overall mean SOC content for the 500 cm soil profile decreased in the following order: RC70 > RC35 > RC5 > RC60 > RC15 (Table 4). R15 had the lowest SOC content, which may be caused by agricultural disturbance and rainfall, summer rainfall especially can accelerate the transport of soil organic matter (Zeng *et al.*, 2019). Additionally, SOC content was significantly influenced by soil depth ($p < 0.05$) (Table 2); thus, SOC content in the uppermost soil layers was higher than that in deeper layers, especially under RC35 and RC70. We also observed that SOC content was basically unchanged (estimated at every 100 cm interval), from 100 to 500 cm depth, under five reclaimed croplands. Furthermore, SOC content from 100 to 500 cm depth was significantly higher under RC5, RC35, and RC70 than under RC15 or RC60.

In general, SIC was found to be much higher than SOC in this study, ranging from 0.17 to 27.4 g kg^{-1}. Average SIC was 13.4 g kg^{-1}, with a relatively small coefficient of variation of 24.8%; further, the mean SIC content was approximately six times greater that of the corresponding SOC content. Mean SIC content decreased with depth along the 0–500 cm profile, with deeper soil layers containing slightly lower amounts of SIC than the overlying layers (Figure 2). In line with SOC, grasslands also showed the highest mean SIC; further, SIC content in grassland and shrubland was significantly higher than in any other land-use type ($p < 0.05$) (Tables 1 and 3). SIC was significantly influenced by cultivation time over 70 years ($p < 0.05$) (Table 2), with RC15 showing extremely low SIC values in the 300–500 cm depth interval (Table 4).

Table 2 Two-way ANOVA* F and *p*-values for land-use type, cultivation time, and soil depth effects on soil BD (g cm^{-3}), SWC (g kg^{-1}), SOC content (g kg^{-1}), SIC content (g kg^{-1}), SOC stocks (kg m^{-2}), and SIC stocks (kg m^{-2}) in Gutun watershed

Factor of variation	BD		SWC		SOC		SIC		SOCS		SICS	
	F	*p*	F	*p*	F	*p*	F	*p*	F	*p*	F	*p*
Land-use types	24.32	0.000	79.060	0.000	11.852	0.000	25.320	0.000	3.452	0.009	6.222	0.000
Soil depth	2.310	0.033	6.080	0.000	4.434	0.000	2.121	0.000	4.651	0.000	17.781	0.000
Time	112.59	0.000	36.283	0.000	18.082	0.000	31.666	0.000	21.867	0.000	13.365	0.000

Note: Analysis of variance; BD, bulk density; SWC, soil water content; SOC, soil organic carbon; SIC, soil inorganic carbon

Table 3 Vertical distribution of SOC and SIC contents (g kg^{-1}) under five land-use types

Depth (cm)		0–20	20–60	60–100	100–200	200–300	300–400	400–500
SOC	Grassland	7.26±4.56aA	3.93±3.05aAB	2.38±0.93aB	2.51±1.12aB	3.09±1.68aB	2.27±0.61aB	1.88±1.35bB
	Shrubland	3.79±1.52abA	1.55±0.8aB	1.07±0.2aB	2.89±2.71aA	2.71±1.25abA	1.77±0.58aB	4.40±1.33aA
	Forestland	3.29±0.94abA	2.90±1.57aA	2.38±1.49aA	2.08±0.89aA	2.39±0.84abA	3.19±1.61aA	2.03±0.51bA
	Cropland	2.52±1.25bA	1.81±1.25aAB	1.46±0.63aB	1.99±1.05aAB	1.89±0.86bAB	2.34±1.07aAB	2.22±1.30bAB
	Gully land	1.68±1.27bA	1.61±1.14aA	2.03±1.57aA	2.26±1.77aA	1.42±0.39bA		
SIC	Grassland	14.97±1.39abB	17.2±2.0abAB	17.4±2.2abAB	16.25±0.92aB	14.18±1.86aB	17.45±3.7aAB	20.18±2.58aA
	Shrubland	16.91±0.01aA	16.55±0.21aA	16.45±0.07aA	14.3±2.9abAB	13.31±1.13aB	13.21±1.01bB	10.96±1.44bB
	Forestland	14.27±1.37abA	13.97±1.96abA	14.42±1.61abA	14.75±1.12abA	14.57±1.20aA	14.76±2.63aA	17.01±0.53abA
	Cropland	13.40±1.61bA	13.39±1.44bA	13.05±2.77bA	12.68±1.69bA	11.99±3.47aA	11.52±4.16bA	11.34±5.04bA
	Gully land	15.10±1.40abA	15.66±1.72abA	14.91±1.07abA	14.17±2.86abA	11.88±3.68aA		

Note: different lowercase letters within columns indicate significant differences among land use types ($p < 0.05$); different uppercase letters within rows indicate significant differences among different soil layers in the same land-use type ($p < 0.05$).

Table 4 Vertical distribution of SOC and SIC contents (g kg^{-1}) from RC5 to RC70 croplands in Gutun watershed

Depth (cm)		0–20	20–60	60–100	100–200	200–300	300–400	400–500
SOC	RC5	2.02±1aAB	1.41±0.94bB	1.63±0.78aAB	2.35±0.96abAB	1.87±0.35bcAB	2.96±0.48abA	2.6±0.77aAB
	RC15	1.82±0.5bA	1.51±1.82bA	1.13±0.66aA	1.45±0.88bA	1.3±0.89cA	1±0.76cA	0.72±0.53bA
	RC35	3.3±0.83aA	2.4±1.07aAB	1.69±0.26aB	2.12±0.43abAB	2.34±0.53abAB	2.49±0.43abAB	2.9±1.5aAB
	RC60	2.61±1.96aA	1.61±1.14bA	1.4±0.75aA	1.69±0.45bA	1.79±0.6cA	2.35±1.28bA	2.03±1.31abA
	RC70	3.04±1.18aAB	2.26±1.25aAB	1.50±0.57aB	2.66±1.90aAB	3.03±1.02aAB	3.45±0.77aA	
SIC	RC5	11.95±1.41bA	12.47±2.5aA	12.66±2.9abA	12.29±1.67bA	13.56±1.45aA	12.9±1.64aA	12.75±2.99aA
	RC15	14.07±2.21abA	14.29±1.2aA	14.31±1.11aA	12.83±1bAB	10.46±5.41aAB	6.16±5.2bBC	0.94±0.63bC
	RC35	13.64±0.37abA	13.44±0.73aA	14.39±1.09aA	13.5±0.51bA	13.12±1aA	12.99±1.82aA	14.13±3.16aA
	RC60	14.65±1.39aA	13.52±0.93aAB	13.32±0.83abAB	13.17±0.94bAB	12.33±0.9aB	13.26±1.93aAB	12.9±1.26aAB
	RC70	12.35±0.25abA	13.13±0.82aA	9.65±5.08bA	16.43±3.24aA	10.53±3.87aA	13.09±1.48aA	

Note: different lowercase letters within columns indicate significant differences among five reclamation times ($p < 0.05$), while different uppercase letters indicate significant differences between different soil layers at the same reclamation time ($p < 0.05$).

3.3 Carbon storage under different land uses and various reclamation times of croplands

3.3.1 SOC stocks

Overall, SOC reserves were relatively small in the 0–500 cm soil profile; accounting for 11–16% of the TC stocks, and decreasing abundances as follows: shrubland (17.2 kg m^{-2}) > grassland (16.2 kg m^{-2}) > forestland (15.2 kg m^{-2}) > cropland (14.1 kg m^{-2}) > gully land (6.37 kg m^{-2}) (Figure 3). The spatial distribution of the integral SOC stocks under five land uses are shown in Figure 4a. It shows gully land sites and RC15 had the lowest SOC stocks, while land with natural vegetation tended to have higher SOC stocks (Figure 4a). The proportion of C below 100 cm depth accounted for approximately 87%, 71%, 78%, 82%, and 62% of the integral SOC (0–500 cm) under the five land-use types studied, in the order given above. SOC was concentrated in the grassland surface soils, which was consistent with that of Bi *et al*. (2018). Figure 5a shows that the SOC stock in the 0–20 cm top layer was significantly higher than those in the 400–500 cm interval (p < 0.05). In contrast, the vertical distribution pattern in shrublands reached deeper, with more SOC stored in the subsoil (Figure 5b).

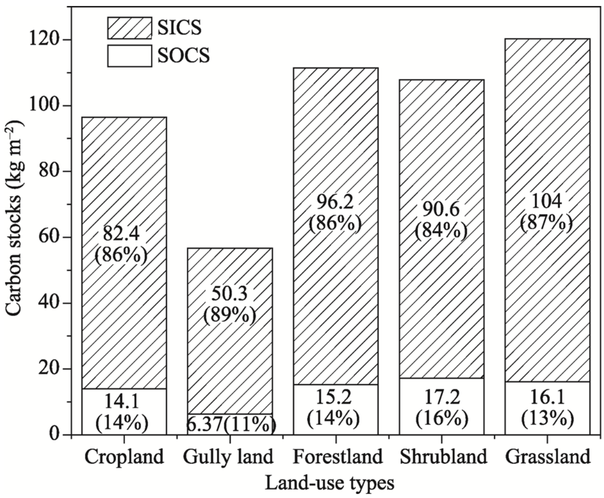

Figure 3 Percentage of SOC and SIC stocks in 0–500-cm soil profiles for five land-use types

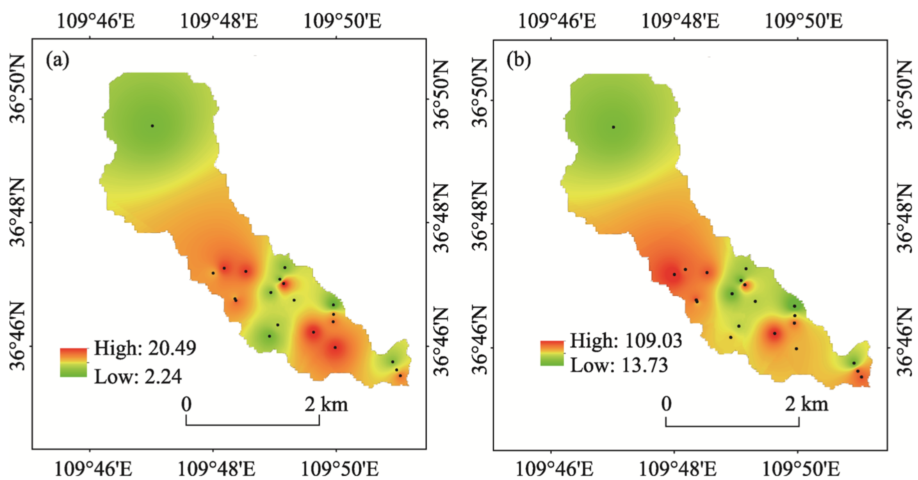

Figure 4 Spatial distribution of soil organic carbon stocks (a) and soil inorganic carbon stocks (b) in Gutun watershed

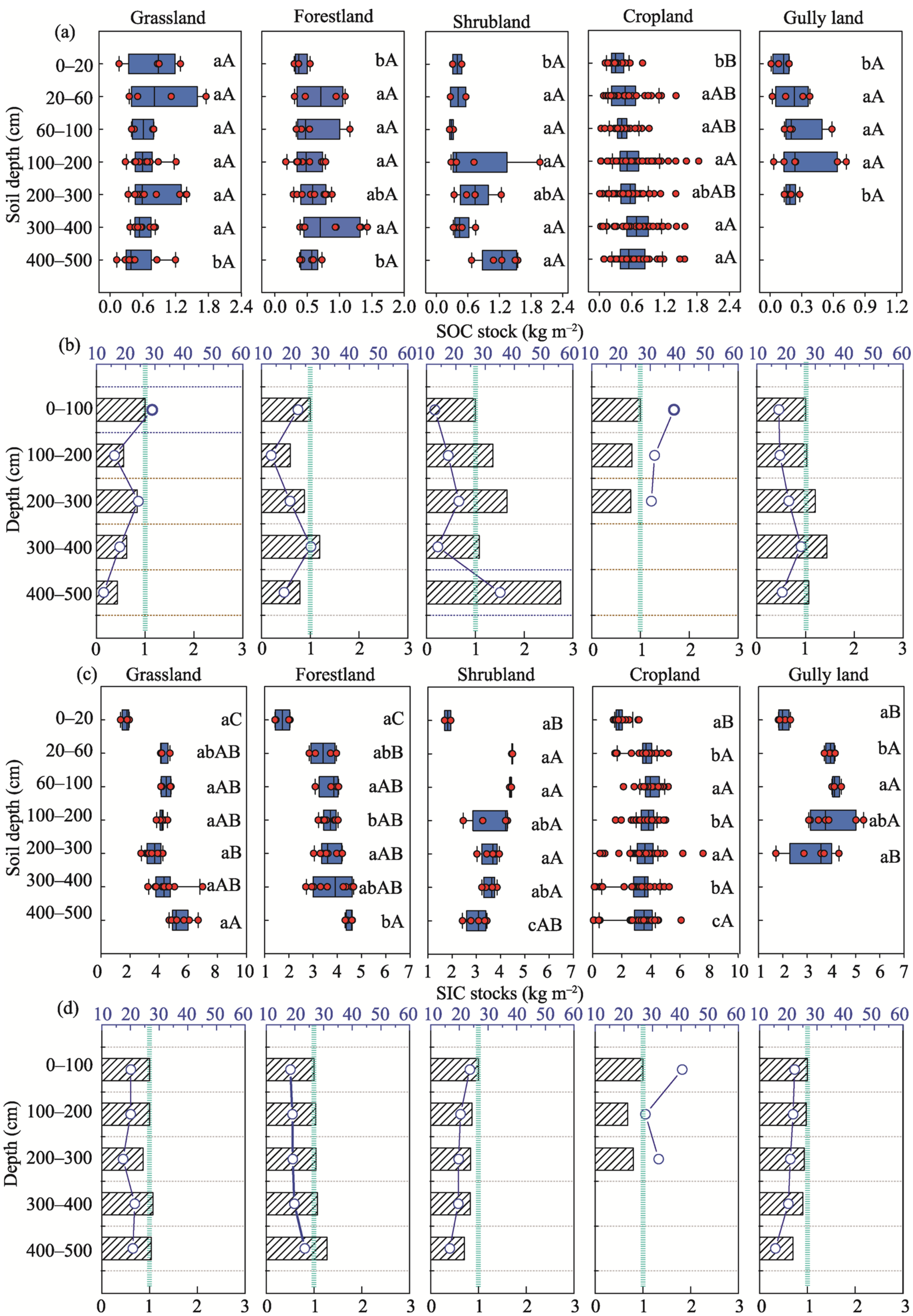

Figure 5 Soil carbon stocks. (a) SOC stock; (c) SIC stock. (b) and (d) showed the percentage within the bars are proportions of stocks in a 100-cm thick layer compared to the upper 100 cm. Blue circles represent the ratio of the carbon stocks in a given 100-cm layer to the 0–500 cm complete profile. Different lowercase letters indicate significant differences among land uses ($p < 0.05$), while uppercase letters indicate significant differences among different soil layers within the same land-use type ($p < 0.05$).

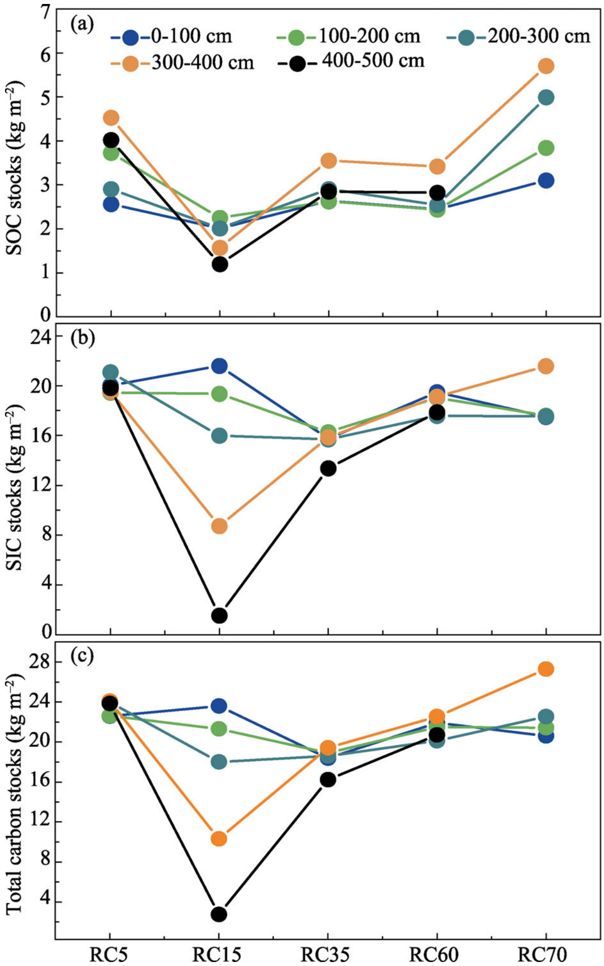

Figure 6 Changes in carbon stocks with time at different sub-layers: (a) SOC stocks, (b) SIC stocks, and (c) TC stocks at 100-cm intervals

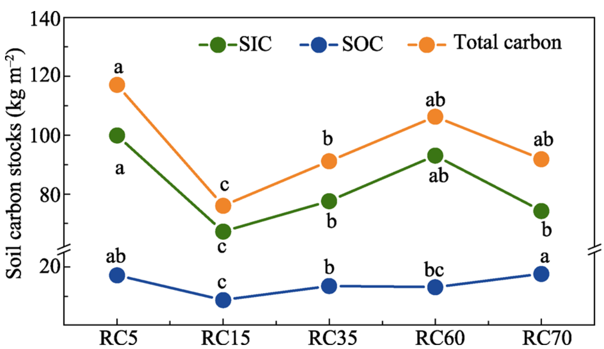

Figure 7 Changes in SOC, SIC, and TC stocks with time in 0–500 cm soil profiles

The integral SOC stocks under RC5, RC15, RC35, RC60, and RC70 were 17.2, 8.77, 13.5, 13.2, and 18.1 kg m^{-2}, respectively, and the SOC stocks at 100 cm intervals followed the same pattern: RC70 > RC5 > RC35 > RC60 > RC15 (Figure 6a). The lowest SOC stock was observed in RC15, the highest was observed in RC70; moreover, the SOC stock was slightly lower under RC60 than under RC35.

Different lowercase letters indicate significant differences (p<0.05) among croplands under five different cultivation times.

Cultivation time significantly affected SOC stocks in reclaimed croplands, according to the two-way ANOVA (p<0.05) (Table 2). If we ignore the stocks in RC5, a consistent temporal trend was observed, showing that SOC stocks increased gradually in the reclaimed croplands, which is in agreement with the result of Liu *et al.* (2017), who reported that SOC stocks increased with restoration time. SOC values in RC5 were significantly higher than in RC15 (p<0.05) (Figure 7), suggesting that cultivation has led to soil C losses over at least 15 years, with SOC losses of approximately 49% of soil C stocks, whereas SOC stocks in RC70 increased 2.7% relative to RC5.

3.3.2 SIC stocks

SIC stocks ranged from 50.3 to 104.1 kg m^{-2}, accounting for 84%–89% of TC stocks (Figure 3) and were approximately six times greater than SOC stocks. The contribution to SIC stocks in the 0–500 cm soil layer was mainly in the form of inorganic C for the five land-use types (Figures 3 and 6). The density of the overall SIC stocks ranked in the following order: grassland > forestland > shrubland > cropland > gully land (Figure 3). The SIC spatial distribution of SIC stocks were similar to

SOC stocks (Figures 4a and 4b). Natural vegetation also had higher SIC stocks than cropland. Both soil depth and land-use type influenced SIC stocks significantly (p<0.05) (Table 2). There was no significant variation of SIC stocks among land-use types at a depth of 0–20 cm, and no clear pattern was observed at 20–400 cm. Regarding the depth range from 400 to 500 cm in terms of land use, SIC ranked in the following order: grassland > forestland > shrubland ≈ cropland (Figure 5c). In addition, SIC stocks in grassland and forestland increased with soil depth, whereas an opposite trend was observed for shrubland and cropland (Figure 5d).

Cultivation time significantly affected SIC stocks ($p < 0.05$) (Table 2). For example, a consistent decrease in SIC values with depth was observed for RC15, after which, values for the 0–200 cm section of the soil profile decreased slightly with time, while deep soil SIC values (i.e., at 200–500 cm) increased with time (Figure 6b). Trends for TC stocks were similar, as they were dominated by the SIC component (Figures 5c and 6).

4 Discussion

4.1 Sources of variation in SOC and SIC distributions under five land use types

The overall C stocks in grassland, forestland, and shrubland were 23.8, 15.0, and 11.4 kg m^{-2}, respectively; all higher than the C stocks in cropland, and gully land, where they were the lowest (Figure 3). In other words, grassland, forestland and shrubland all showed a higher capacity to fix C compared to cropland; these results are consistent with those of Ali *et al.* (2017) and Wang *et al.* (2016).

Different land-use types are associated with diverse plant communities that influence SOC due to variability in plant productivity, soil quality, and soil C turnover time (Esteban *et al.*, 2000; Wiesmeier *et al.*, 2012). In the present study, land use significantly influenced integral SOC stocks ($p < 0.05$) (Table 2). In particular, the grassland SOC-stock was highest among the five land-use types in the top (0–60 cm) soil (Figure 5a), because grasses grow seasonally and die off every winter, leaving plant litter on the ground surface, facilitating the accumulation of organic C and rhizosphere microbiota, who use decaying organic matter as a source of energy.

As Deng *et al.* (2014) reported, biomass in cropland disturbed by human tillage activities tends to increase organic decomposition and C losses; therefore, cropland usually shows lower SOC contents than other land-use types. The present study showed that, although SOC content exhibited the same trends as described previously (Wang *et al.*, 2016; Liu *et al.*, 2017; Yang *et al.*, 2018) (Table 3), in the cropland top soil layer (0–20 cm), with SOC stocks slightly lower than in the grassland, and similar to those found at 20–400 cm depth; but significantly higher than SOC stocks of either grassland or forestland at depths of 400–500 cm ($p < 0.05$) (Figure 5a). This could be attributed to harvest practices of farmers in the area, whereby maize straw is allowed to lay fallow on the ground until November; this method reduces soil erosion and organic C losses, maintaining SOC reserves at a level comparable to those found in grassland or forestland. On the other hand, the calculated Pearson correlation coefficient showed that SOC was positively and significantly influenced by SWC ($p < 0.05$), and it was directly related to BD (Equation 1). BD was significantly higher in cropland than in either grassland or forestland ($p < 0.05$) (Table 1). Furthermore, we found higher SWC in cropland than in other land-use types, as dissolved OC transformed by organic manure might be leached from the surface and subsequently transported into deeper soil layers by groundwater (Wang *et al.*, 2016; Zhu *et al.,* 2018), resulting in relatively high SOC stocks under farmlands in deep soils.

We also found that some SIC was stored in the subsoils of grassland and forestland (Figure 5d). This could be attributed to the inherent high water-conservation capacity of these land-uses, allowing a greater proportion of water to percolate downward and eventually form carbonates that accumulate in the deeper soil layers.

4.2 Management strategy of carbon under reclaimed croplands

SOC stocks decreased from RC5 to RC15 and then steadily increased up to a maximum value in RC70 (Figure 6a). The second higher, overall initial SOC stocks were observed in RC5 (Figure 6a). This could be attributed to the relatively large amounts of C introduced in the soil when organic manure was used to fertilize the new cropland. After approximately 15 years under the constant influence of agricultural activities, a large amount of C is decomposed and readily removed by rainwater as it moves through the soil. This presumably accounts for the observed SOC reduction in RC15, reflecting conditions that are not conducive to C fixation. Total SOC stocks subsequently increased with time in RC35 and RC60, which were not significantly different from one another ($p > 0.05$), while SOC stocks in RC35 were slightly higher than in RC60 (Figures 5a and 6). This small difference may have been caused by the introduction of a nursery in RC35, which enhanced soil C sequestration.

The integral stocks of SOC and SIC were consistently lower in cropland than in grassland, forestland or shrubland (Table 1), probably because of soil C loss during ploughing after reclamation (Deng *et al.*, 2014), and the ability of crops to fix C is lower compared to that of grass or forest. Several scientists have recommended enclosing croplands and allowing the restoration of natural grasslands to increase SOC stocks (Albaladejo *et al.*, 2013; Liu *et al.*, 2017) to avoid the abovementioned problem. However, land cultivation in support of the growing human population in the CLP region is already insufficient. Therefore, we can neither enclose all the cropland, nor plant reclaimed croplands with nurseries or turn them into grasslands. Nevertheless, Li *et al.* (2016) and Cardinael *et al.* (2017) demonstrated the advantages of alternative agroforestry systems to efficiently enhance SOC stocks in agricultural lands to mitigate climate change. Our results are consistent with such an approach. Therefore, we advise local governments to pursue turf culture or nursery establishment in newly reclaimed croplands for some years, followed by the adoption of an agroforestry approach to increase both grain production and C sequestration. Such programs should be continuously monitored to gain a comprehensive understanding of the evolution of SOC and SIC inventories with cultivation time.

5 Conclusions

Both SOC and SIC should be estimated over broad areas to evaluate C stocks and their relationship with different land-use types on the CLP. 1) Grassland, shrubland, and forestland showed the greatest capacity to accumulate C in soil profiles from the surface to a depth of 500 cm, compared to either cropland or gully land. 2) SIC stocks in these five land-use types contributed to 84%–89% of TC stocks, which was much higher than SOC stocks. 3) Moreover, the amounts of SOC and SIC in deep soil layers (100–500 cm) were greater than those in the 0–100 cm soil depth range. Moreover, it is necessary to accurately quantify the amount of C sequestered and cycled with time. Our data clearly show that cultivation time significantly influenced SOC and SIC stocks. 4) Soils that were reclaimed 15 years ago for cropping are regarded as poor soils that can optimal for neither crop growth nor C fixation. 5) Planting a small nursery in the RC35 cropland is better than planting corn to sequester C. 6) Cultivation has led to C losses equivalent to approximately 60 years of C accumulation, with a TC loss of approximately 23% in the 0–500 cm soil profile on the CLP. Therefore, we suggest that local governments consider laying sod or establishing nurseries in newly reclaimed croplands for several years, prior to introducing grain cropping or developing an agroforestry system whereby grain production and C sequestration might be fostered.

Acknowledgements

We would like to express sincere thanks to the Belt & Road Center for Earth Environment Studies and CAS Key Technology Talent Program.

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