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Exploring land reclamation history: Soil organic carbon sequestration due to dramatic oasis agriculture expansion in arid region of Northwest China

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ABSTRACT

A better understanding of land reclamation history and its influence on soil organic carbon (SOC) is critical to SOC sequestration. The arid region, significantly influencing the global trend and inter-annual variability of the carbon sink, experienced the large-scale oasis agriculture expansion had significantly depleted native vegetation, and how this altered the soil carbon balance is still unclear. Taking the typical Tarim Basin as study area, this study proposed a spatial method of identifying agricultural reclamation histories and applied it to the specific field soil sampling design for exploring SOC changes under different histories, including the prior land use types changing to cropland and cultivation ages after the reclamation. Results showed that oasis agriculture area nearly doubled over nearly 40 years, majorly from grasslands and part from forests. Comparison of the SOC densities collected in 2015 to data in the late 1970s found an accumulation effect of SOC in agricultural practices, where croplands reclaimed before the late 1970s have a higher SOC density (1.86 kg C m^{-2}) than those reclaimed after the late 1970s. The change trend and magnitude in SOC density upon the prior land uses were significantly different, with a mean value of 0.37, 0.03, and −0.99 kg C m^{-2} for the previous cropland, grassland, and forest, respectively. An increase in the cultivation ages would raise the magnitude of SOC sequestration, where the SOC loss reclaimed from the grassland was recovered after nearly 30 years of farming activities, but that from the forest cannot be recovered even within as much as 40 years of cultivation. These findings provide a new insight to the significantly different effect of agricultural reclamation histories on the SOC dynamics and indicated the considerable potential of the carbon sink, if sustainably managed, in the arid region of Northwest China.

1. Introduction

Soil organic carbon (SOC) is a significant component of the earth's carbon reservoir, and its storage and fluxes play a major role in the global carbon budget (Lal, 2004). Meanwhile, SOC plays a key role in maintaining the balance of soil ecosystems and increasing soil fertility and crop productivity (Doran et al., 1999; Seely et al., 2010). Under drastic human disturbance and management, the potential for SOC to become a 'managed' sink has significant value for mitigating climate change (Stockmann et al., 2013). Therefore, the assessment of SOC change is vital to understand the carbon dynamics in terrestrial ecosystems.

SOC varies substantially across the globe depending on considerable environmental conditions and anthropogenic driving factors (Stockmann et al., 2013). Land use change, as the comprehensive characteristics of human activities, causes a change in land cover types and a change from one ecosystem to another (Guo and Gifford, 2002), which significantly modifies the earth's land surface and has multiple influences on SOC stock (Guo and Gifford, 2002; Li et al., 2016; Post and Kwon, 2000; Zhang et al., 2018). Cultivation, as one of the major land use types, has now covered nearly one-third of the global land surface and replaced most of the natural vegetation on the earth's surface (Godfray et al., 2010). The SOC pool in croplands was strongly affected by anthropogenic factors and can be managed on a shorter time scale; thus, cropland soils have great potential for an increase in carbon sequestration (Smith, 2004).

Meanwhile, it reported that that the mean sink, trend, and variability in carbon uptake by terrestrial ecosystems are dominated by distinct biogeographic regions (Ahlström et al., 2015). A meta-analysis found that cultivation caused a greater loss of SOC in tropical moist

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climates than in tropical dry, temperate moist, and temperate dry climates (Ogle et al., 2005). The North Rhine-Westphalia area in Germany showed an increase in the SOC of cropland soil during the 1980s but an exponential decrease from 1988 to 2015 (Steinmann et al., 2016). SOC decreased in the paddy and irrigated soils in arid Northwest China but increased under semiarid and semi-humid conditions in northeast and southwest China from China's second national soil survey in the 1980s (Wu et al., 2003). The results obtained by individual studies do not readily translate across regions (Wertebach et al., 2017). With the widely differing change trends and magnitudes of SOC reported for different biogeographic regions (Kopittke et al., 2017; Murty et al., 2002), uncertainties in the responses of SOC dynamic to natural soil variability and agricultural reclamation require in-depth investigations across different geographical zones worldwide.

Arid and semi-arid regions play a significant role on the global trend and inter-annual variability of carbon sink (Ahlström et al., 2015). The climate change and anthropogenic disturbance would highly influence arid and semi-arid regions (Hulme, 1996), which would easily result in the soil carbon variation and further loss (Qiu et al., 2012). Oasis agriculture ecosystem, surrounding by the desert ecosystems, is the specific artificial ecosystem and significantly alter the land surface and biogeochemical cycle in the arid regions, where environmental conditions are milder than desert ensuring fertility and allowing desert farming (Mekki et al., 2013). They formed naturally in river deltas or were established close to water sources for the irrigation, and significantly altered the land surface and biogeochemical cycle (Zhang et al., 2003). Different from other geographic regions, the water scarcity is the key issue in the oasis agriculture (Postel, 2014). Due to the dry and hot climate with little precipitation, almost the entire oasis agriculture relies on irrigation for plant growth in harsh conditions for resisting the drought (Wichern et al., 2004). In the arid region, weathering process would not produce large amounts of clay, which would result in the formation of original soil types with undifferential texture profiles and low soil fertility constraining the agricultural production (Nettleton and Peterson, 1983). With the reasonable oasis farming practices and managements, original soil types are gradually formed to Anthrosols with the improved soil structures and functions (Gong et al., 1999; Su et al., 2007).

As oasis agriculture expansion has become more common in the world, it is reported that SOC significantly decreased under the reclamation in multiple regions, for example, the clearing and cultivation of savanna in semiarid Senegal of West Africa (Elberling et al., 2003), cultivation in the arid Heihe River oasis-desert ecotone of northwest China (Lü et al., 2014), and the sandy grassland reclamation in the semiarid Horqin sandy steppe of northern China (Su et al., 2004). Also the desertification would easily accelerate the SOC loss (Zhao et al., 2009). In contrast, SOC would increase in the oasis agriculture located in the edge of Badanjilin Desert with the application of organic manures (Liu et al., 2011). Field experiments indicated that improved agricultural practices, including the reduced tillage, rotation cropping, and straw mulching, would provide the use of water and organic amendments to increase SOC storage in dry lands (Yang et al., 2017). Thus, it calls for a deep insight to how the oasis agriculture expansion influenced the SOC.

The agriculture expansion by depleting the native vegetation influence the SOC fate by the primary changes in land use and plant types, which are associated with the changes in the litter input, detritus and litter decomposition, root secretion and soil mineralization (Hobbie et al., 2006; Li et al., 2017; Yimer et al., 2007). Generally, the conversion from native vegetation to cropland might lead to massive losses in SOC (Berihu et al., 2017; Houghton et al., 2000; Lal, 2002; Lozano-García et al., 2016). Different crop types would directly determine the SOC sources to soils by the input crop residues and roots and indirectly influenced the nutrient utilization, and SOM decomposition and mineralization processes in the cultivated soils (Kong et al., 2005; McDaniel et al., 2014). For example, the SOC accumulation in paddy soils was favored by chemical protection through the binding of SOM to iron oxyhydrates (Stevenson and Cole, 1999), therefore, it found a higher SOC content of paddy soil than that of dry land (Pan et al., 2010; Wu et al., 2003). Also different management practices on the crop and soil would cause the SOC loss or sequester, such as the irrigation, fertilizer application, and crop rotation and tillage measure. Improving agricultural management such as no-till, straw returning, and the application of organic fertilizer can effectively recover and improve the SOC (Congreves et al., 2017; Hollinger et al., 2005; Smith, 2008; Zhou et al., 2015).

The effects of cultivation and product removal on SOC have been widely examined and discussed in previous studies, however, the historical process of land reclamation—which was easily omitted from previous studies (Bouchoms et al., 2017; Schulp and Verburg, 2009)—influence the SOC dynamics. Changes in SOC were related to the prior condition of land use type and cultivation age after the reclamation (Berihu et al., 2017; Stockmann et al., 2013). Different prior land use types before the land reclamation and crop types after reclamation would directly determine the SOC sources to soils by different input vegetation residues and roots and indirectly influenced the nutrient utilization, and SOM decomposition and mineralization processes in the soils (Kong et al., 2005; McDaniel et al., 2014). Moreover, the cultivation age is related to the agricultural intensity and duration effect, which would further influence the SOC accumulation or decomposition process and magnitude (Post and Kwon, 2000; Zhang et al., 2016). Diachronic studies would help reveal the impact of the reclamation history process and its time effect on SOC. To better understand the effect of cultivation establishment and duration on the soil carbon balance, it calls for distinguishing the varying reclamation histories, including the prior land use and cultivation age. The novelty of this study was the idea of quantifying reclamation histories and its link to the soil organic carbon dynamics by a proposed spatial identification method. With the remote sensing and spatial detection techniques, our method can build a spatial explicit land reclamation trajectory and chronosequence and explore the SOC fate under not only the present-day land use but different reclamation histories.

The arid region of Northwest China was taken as our study area, which experienced a large-scale cropland expansion since 1949, reclaiming the native vegetation and even the desert to agricultural use (Liu et al., 2014a). Until now, site-specific measurements of SOC change in the arid region of Northwest China within a large-scale context were previously limited. To potentially improve regional estimates of SOC stocks and dynamics, the role of agricultural reclamation histories on the SOC stocks is necessary (Schulp and Verburg, 2009). Thus, the objectives of this study were to (1) propose a spatial identification method of quantifying agricultural reclamation histories; (2) apply the method to explore the impact of agricultural reclamation history on the SOC stock dynamics and potential for carbon sequestration in cultivated soils in the arid Northwest China.

2. Methods

2.1. Study area

The field survey was conducted in a typical region (Fig. 1) of the Tarim Basin, which was located in the southern Xinjiang, Northwest China. The study area is situated at roughly between 38.80°–42.28° N and 77.20–87.45 in the west and north of the Taklimakan Desert, which is the world's second largest shifting sand desert. The sandy desertification expansion with wind erosion from the Taklimakan Desert would easily encroach on the oasis land sources and future cause the decrease in farmlands near the Taklimakan Desert (Zhang et al., 2001). To prevent from threatens from the desert, farmland shelterbelts were built around the oasis agriculture. Thus, sand blown activity intensities rapidly decreased from the mobile sandy land to desert-oasis ecotone to oasis along the prevailing wind direction to sustain the food production

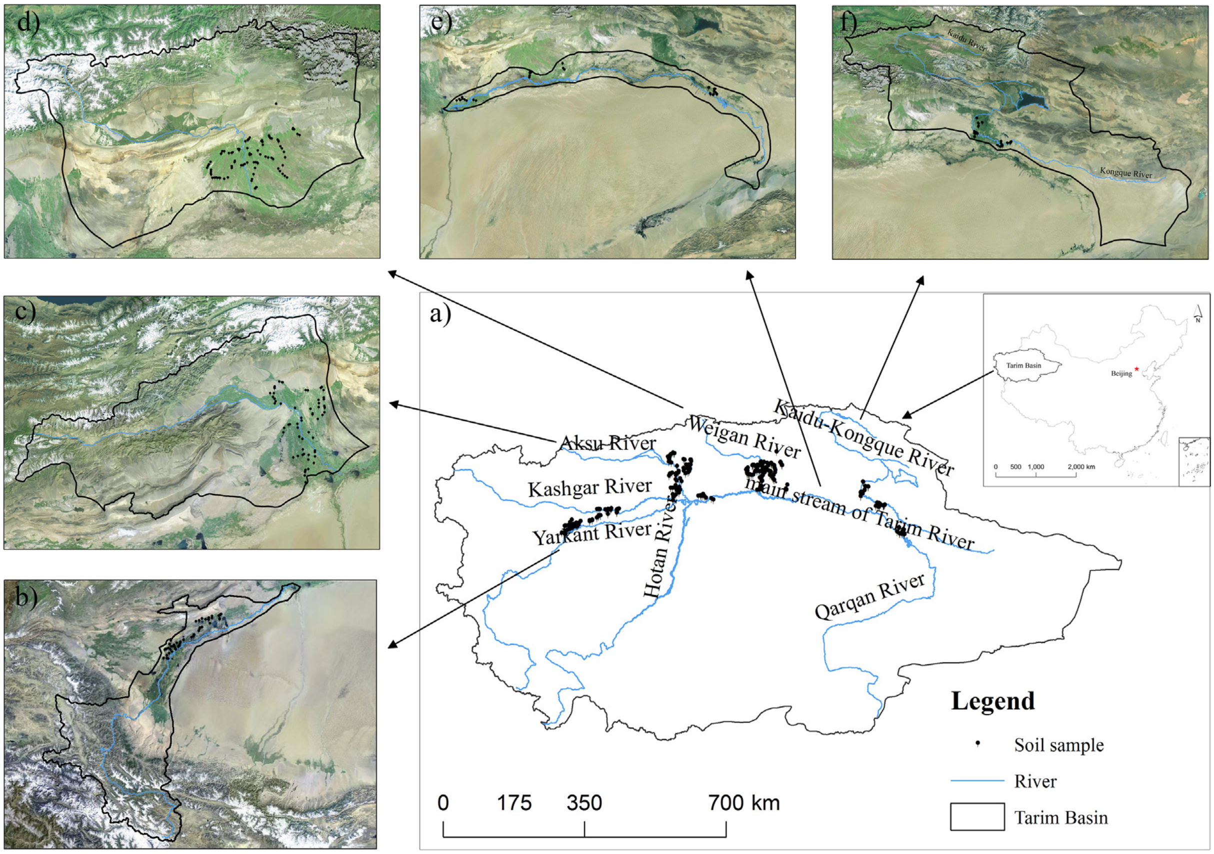

Fig. 1. Location and scope of a) typical area in the Tarim Basin consisting of b) Yarkant River Basin, c) Aksu River Basin, d) Weigan River Basin, e) main stream of Tarim River, and f) Kaidu-Kongque River Basin.

in the oasis agriculture (Mao et al., 2013). The study region consists of five test sub-basins: the Aksu River Basin, Kaidu-Kongque River Basin, main stream of Tarim River, Weigan River Basin, and Yarkant River Basin and was selected as a sparsely investigated but globally relevant region. The climate is extremely dry with the annual precipitation ranging from 50 to 100 mm but an huge annual evaporation ranging from 2000 to 3000 mm. To increase the water use efficiency, the sprinkler irrigation and drip irrigation were used in the Tarim Basin. The major crops include cotton, wheat, corn, and fruit. Glaciers, snowmelt, and precipitation in the surrounding mountains are the source of runoff for the Tarim Basin. They consisted of drought tolerant trees and shrubs, mainly including *Tamarix ramosissima*, *Populus euphratica*, *Phragmires communis*, *Poacynum hendersonii*, *and Alhagi sparsifolia.* The major original agricultural soil types in the study area is the Aridisols, named as Yermosols in the FAO-UNESCO classification (Food and Agriculture Organization-United Nations Educational, Scientific and Cultural Organization) (Eswaran et al., 1993; FAO-UNESCO, 1988). Aridisols are gradually formed to Anthrosols with the improved soil structures and functions with the reasonable farming practices and managements (Gong et al., 1999; Su et al., 2007).

From 1949 to the late 1980s, the area of irrigated oases increased nearly five times (Chen, 2014). In recent decades in the Tarim Basin, the overuse of agricultural water resulted in the serious destruction of natural vegetation with agricultural reclamation (Zhang et al., 2003). Agricultural reclamation from other land use types has significantly affected the soil carbon balance (Wang et al., 2014). With the degraded ecosystem of the Tarim Basin, an ecological restoration project such as the forest establishment and transfusing water in the Lower Reaches of the Tarim River was implemented since 2000, which would influence future cropland changes. Thus, it calls for a deep understanding of how the land reclamation influenced the SOC in the study area.

2.2. Agricultural reclamation history detection

We designed the soil sample distribution to account for the current land use and historical agricultural reclamation history. The detailed description of agricultural reclamation history detection process was shown in the previous study (Xu et al., 2019a) and summarized as follows. The land use maps from different periods in our study were mapped by the visual interpretation classified from Landsat4-5 MSS/TM and Landsat-8 Operational Land Imager (OLI) images. The images were collected at five time nodes: 1978, 1990, 2000, 2010, and 2015. The geometric corrections were performed using the digital elevation model with 50 ground control points for each image, which were taken from 1:50,000 topographic maps (provided by the Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences). This resulted in a root mean square spatial positioning error of less than 0.5 pixels for each image. The atmospheric corrections were executed by the FLAASH module, and the fusion of multispectral and Landsat-8 OLI images was performed by the Gram-Schmidt Pan Sharpening module from the Environment for Visualizing Images software.

The land use maps were mapped into six classes, including cropland, forest, grassland, water, construction land, and unused land. Field validation pointed recorded with GPS in 2015 and high resolution remote sensing validation points from Google Earth were used to test classification accuracy. The overall accuracy and kappa coefficient, as the accuracy indicators, were calculated for total accuracy assessment of the land use map in 2010 and 2015. The kappa coefficient and overall accuracy in 2010 and 2015 indicated the high classification accuracies with 0.913, 0.906 and 92.30%, 91.35%, respectively. With the same operator of visual interpretation, the land use mapping accuracies in 1978, 1990, and 2000 were assumed to be similar to those in 2010 and 2015. Thus, land use maps can be suitable for the subsequent analysis.

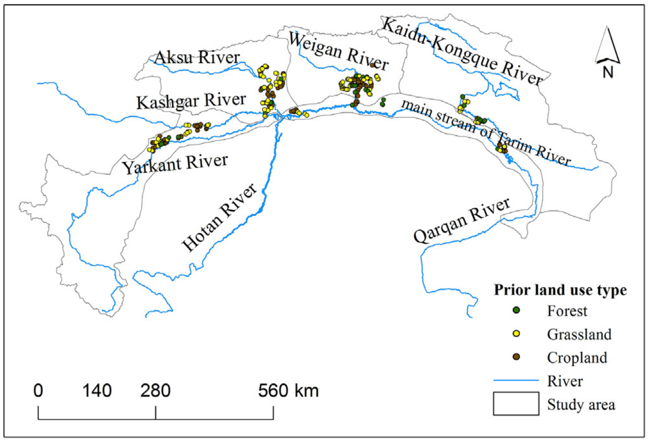

Fig. 2. Spatial distribution of prior land use types of the soil sampling plots.

The grassland is the main source of oasis agriculture expansion in the Tarim basin, and limited croplands reclaimed from forests and less from other land use types (Liu et al., 2014a; Xu et al., 2019a). Thus, the effects of agricultural reclamation history on the SOC dynamics were examined by the change from the grassland and forest to croplands in this study. This study proposed a spatial identification method of quantifying agricultural reclamation histories using the land use maps at the different time nodes. The agricultural reclamation histories, including the information of prior land use types changing to oasis agriculture and the cultivation ages after the reclamation, was identified according to the land use change trajectory by the following equation.

$$LUCT = \{Luc_{t1}, Luc_{t2}, \ldots\ldots, Luc_{tn}\} \quad (1)$$

where the $LUCT$ is the land use change trajectory; Luc_{t1}, Luc_{t2}, and Luc_{tn} mean the land use type at the time node of t1, t2, and tn, and there are five time nodes in this study, i.e. t1 = 1978, t2 = 1990, t3 = 2000, t4 = 2010, and t5 = 2015. The cropland, grassland, and forest were labeled as C, G, and F, respectively. It is noted that the land use change may occurred before 1978, for example, the grassland may be degraded from the forest before 1978. Thus, the prior land use types were limited at 1978. This time node is close to the initial time of the compared soil properties data in our study. In addition, in limited areas land use changes occurred more than once from 1978 to 2015, these regions were identified by our method but not taken into consideration in this study. The detailed identification process by the spatial detection technique is as follows.

First, the land use maps at five time nodes were spatial overlaid and spatial distribution of cropland in 2015 (Luc_{2015} = C) was extracted, and other land use types were excluded as this study focused on the oasis agriculture expansion. Then specific trajectory agricultural reclamation history with the Luc_{2015} = C were calculated at each location. Secondly, the prior land use type in 1978 (Luc_{1978}) was identified from the land use map and grouped into four categories: cropland (C), grassland (G), forest (F), and others. Specially, Luc_{1978} = C means that the cropland were reclaimed before 1978 and these croplands were labeled as the referenced cropland. Thirdly, the agricultural reclamation history occurred in the grassland and forest (Luc_{1978} = G and F) was detected by comparing the land use types in the 1990, 2000, and 2010. For example, the agricultural reclamation trajectory of {F, F, C, C, C} means that the reclamation of forest to cropland occurred in the period of 1991 to 2000, where the land use type was forest in 1990 and the land use type changed to cropland at the time ranging from 1991 to 2000. Then the cultivation age at this agricultural reclamation trajectory can be calculated as 16–25 years. Using this method, the cultivation ages of croplands were grouped as follows: newly (1–5 y), young (6–15 y), medium (16-25 y), old (26–37 y), referenced (before 1978). Finally, three agricultural reclamation history types, i.e. cropland from forest, cropland from grassland, and unchanged cropland over nearly four decades, with five discrete cultivation ages were identified for the soil sampling campaign design.

2.3. Soil sample in the late 1970s and 2015

Soil samples were collected from five test sub-basins with an average area of 6000 km^2 (Fig. 1). The test sub-basins were located at an average distance of approximately 200 km apart from each other with a minimum distance of approximately 115 km. To examine the impact of agricultural reclamation on SOC stocks, soil sampling was conducted in the agricultural soils in 2015 for the three agricultural reclamation history types. Then the cultivation ages at each soil plot was identified from the above spatial identification method with multi-temporal land use maps. Taken the traffic accessibility of roads into consideration, soil sampling survey was conducted on the basis of agricultural reclamation history. The minimum distance between soil sampling plots of the same agricultural reclamation history type was 1 km to minimize autocorrelation effects. Finally, 30–80 plots for each sub-basin were selected for the soil sampling, and the total number of soil samples was 270. Meanwhile, the agricultural reclamation history by the land use maps was validated and corrected in the field soil survey. The details of soils samples and their corresponding agricultural reclamation histories were shown in Fig. 2 and Table 1.

To perform the comparison of SOC dynamics between different land reclamation histories, the soil samples were majorly collected from the same soil classifications type. Most of collected soil samples were the Irrigation-silted Soil (Aric Anthrols in the FAO-UNESCO classification), except for soils in the newly reclaimed croplands, which would be gradually formed to the Irrigation-silted Soil. Irrigation-silted Soil is a specific soil classification type formed under the agricultural cultivation, fertilizing, irrigation process, where the new anthraquic epipedon and moisture regime are formed with the soil mellowing process (Gong et al., 1999). Then its improved soil physical properties, and increased soil nutrients, including the organic matter, nitrogen, phosphorus, and potassium, which is beneficial for production in the oasis agriculture under the long-term reasonable cultivation.

The SOC pools for the plow layer were the most susceptible to anthropogenic alteration, thus soil samples were collected at the topsoil layer of 0–20 cm depth. Five sites were selected at each sampling plot (10 m × 10 m) by a soil auger (5 cm diameter), four at the corners and one in the center of the plot. Then the five soil samples were mixed into one sampling bag at each plot. The exact location of the soil sampling plot is measured by the GPS in the center of the plot. SOC and SBD were measured by the H_2SO_4-$K_2Cr_2O_7$ oxidation method (Nelson and Sommers, 1996) and cutting ring method with the volume of 100 cm^3

Table 1
Description of soil samples in the Tarim Basin.

Total number of soil samples		270
Number in five sub-basins	Aksu River Basin	63
	Kaidu-Kongque River Basin	43
	Main stream of Tarim River	35
	Weigan River Basin	79
	Yarkant River Basin	50
Number of different prior land uses	Cropland	126
	Grassland	103
	Forest	41
Number of different cultivation age classifications	Newly	24
	Young	26
	Medium	47
	Old	47
	Reference	126

and inner diameter of 5 cm (Li et al., 2007), respectively.

Data of soil organic matter (SOM) and SBD in the late 1970s were obtained from a comprehensive 30 × 30 arc-second resolution gridded soil characteristics data set of China, which was calculated by the filed soil data in the 1979–1982 national soil survey and provided by the Cold and Arid Regions Science Data Center at Lanzhou (Shangguan et al., 2013). The SOM was measured by the same chemical analysis method as those used in 2015, which directly measured the SOC content and calculated the SOM using van Bemmelen's index, assuming that SOM contained 58% of SOC (Shangguan et al., 2013). Using the spatial coordinates of 270 soil samples collected in 2015 as the reference, the data of SOM and SBD in the same location in late 1970s were extracted from the gridded soil characteristics data set of China.

2.4. Soil organic carbon density calculation

The SOC density (SOC per area) was calculated by the following equation:

$$SOCD = SOC \times T \times BD \times (1 - \rho)/100 \quad (2)$$

where *SOCD* is the soil organic carbon density, unit: $kg\,C\,m^{-2}$; *SOC* means the soil organic carbon, unit: $g\,kg^{-1}$; *T* denotes the layer thickness, unit: cm; *BD* is the bulk density, unit: $g\,cm^{-3}$; ρ is the volume percentage of $^{>}$2 mm gravel.

The SOC change between the late 1970s and 2015 was calculated as follows:

$$\Delta SOCD = SOCD_{2015} - SOCD_{1970s} \quad (3)$$

where ΔSOCD is the SOC dynamics between the late 1970s and 2015, unit: $kg\,C\,m^{-2}$; $SOCD_{2015}$ and $SOCD_{1970s}$ denotes the SOC density in 2015 and SOC density in the late 1970s, which are calculated by the Eq. (2).

2.5. Statistical analysis

The normality and homogeneity of variance for data was checked. A paired-samples *t*-test was used to check the significance of SOC change in 270 soil plots between the late 1970s and 2015. Statistical significance and highly statistical significance were determined as a 95% confidence level at $p < 0.05$ and a 99% confidence level at $p < 0.01$, respectively. Significance of differences in SOC density levels and changes between different agricultural reclamation history were tested with a one-way analysis of variance (ANOVA) followed by the Tamhane post hoc tests ($p < 0.05$) in the SPSS18.0 statistical package. OriginPro 9.0 (Originlab Inc., USA) was used for displayed the statistical analysis results and drawing figures.

3. Results

3.1. Overall descriptions of land reclamation histories and SOC dynamics

According to the spatial overlaying of land use maps in five time nodes (1978, 1990, 2000, 2010, and 2015), the agricultural reclamation histories were extracted, including the prior land use types changing to oasis agriculture and the cultivation ages after the reclamation (Fig. 3). The cropland area was nearly double from the late 1970s to 2015, which increased from 17200 km^2 to 32300 km^2. The major source of newly reclaimed cropland was the grassland, and the second source was the forest, where two prior land use types accounted for nearly seventy percent and seventeen percent of the total newly reclaimed cropland area, respectively (Fig. 3a). Using the spatial identification method, the cultivation ages were calculated and grouped to five classes. Areas of the old (26–37 y) medium (16–25 y), young (6–15 y), and newly (1–5 y) reclaimed croplands were 1700 km^2, 2200 km^2, 6100 km^2 and 5100 km^2, respectively (Fig. 3a). Based on the spatial distribution of agricultural reclamation histories, the specific

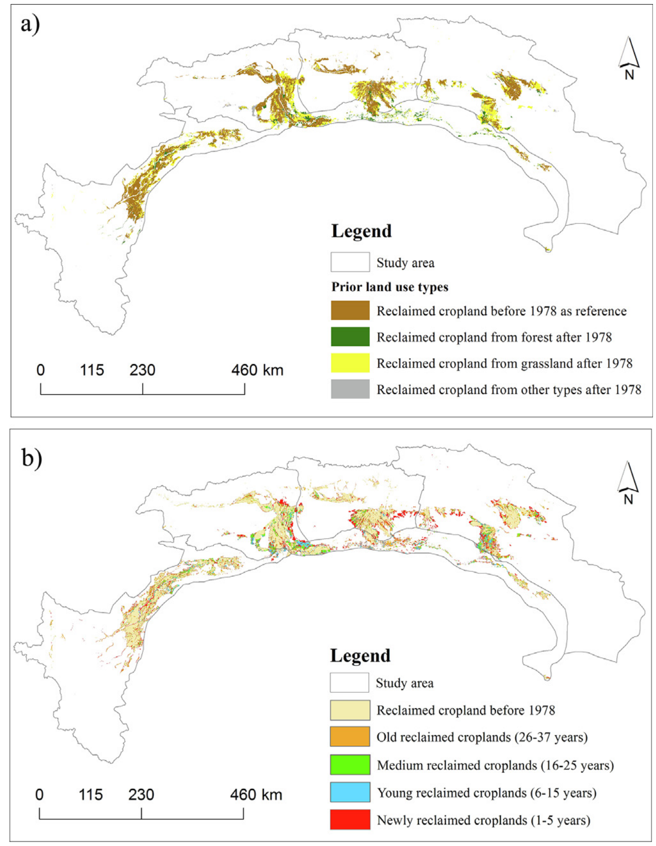

Fig. 3. Spatial distribution of the agricultural reclamation histories a) prior land use types, b) cultivation ages.

Table 2
Statistical characteristics of soil properties.

		Average	Standard deviation	Maximum	Minimum
SOC content	late 1970s	6.44	2.90	16.85	3.42
($g\,kg^{-1}$)	2015	6.61	1.96	17.65	2.26
Soil bulk density	late 1970s	1.30	0.18	1.75	0.93
($g\,cm^{-3}$)	2015	1.29	0.16	1.61	1.05
SOC density	late 1970s	1.66	0.65	3.91	0.41
($kg\,C\,m^{-2}$)	2015	1.71	0.46	4.07	0.31

soil sampling was designed and conducted and the information of reclamation histories were used to explored the impact of oasis agriculture on the SOC stock dynamics.

Table 2 shows the statistical characteristics of SOC content, SBD, and SOC density in the typical region of the Tarim Basin. The average SOC content in the late 1970s (6.44 $g\,kg^{-1}$) is lower than that in 2015 (6.61 $g\,kg^{-1}$) without a significant difference, and the average SBD in the late 1970s (1.30 $g\,cm^{-3}$) is slightly higher than that in 2015 (1.29 $g\,cm^{-3}$). Using the SOC content and SBD, the average calculated SOC density of 270 soil plots is 1.71 $kg\,C\,m^{-2}$ ranging from 0.31 to 4.07 $kg\,C\,m^{-2}$ in 2015. Most of SOC density values fall into the ranges from 1.0 to 2.5 $kg\,C\,m^{-2}$.

Based on the 270 observed values of soil sample plots in 2015 and the extracted values from the soil characteristics data set of national soil census in the same location, it showed that the average SOC density in 2015 is 0.05 $kg\,C\,m^{-2}$ higher than that in the late 1970s without a significant difference (Fig. 4). About 67.78% of the total observations showed an increasing trend in SOC density at a significant level of 99%, but 32.22% showed a decrease in SOC density at a significant level of 99%. In 270 soil plots, there was no significant difference between the

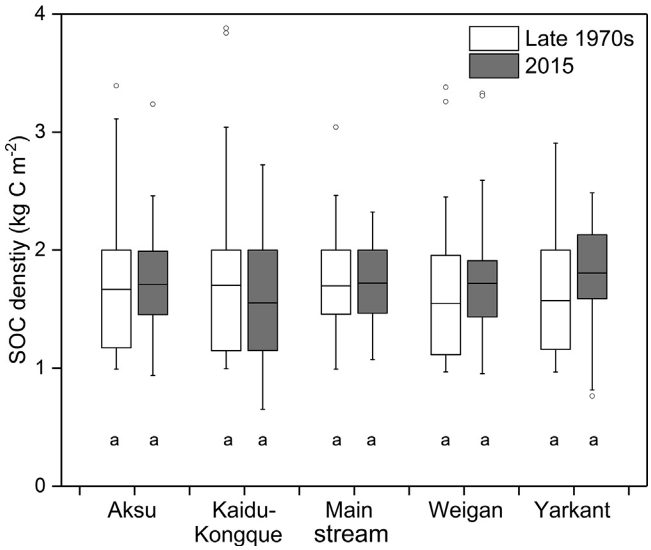

Fig. 4. Soil organic carbon density in the late 1970s and 2015. Box represents the 25th and 75th percentile, line in the boxes means the median value, whisker represents 1.5 times the length of the box from either end of the box (1.5 times the interquartile range), circle represents outliers and extremes. Group differences after one-way ANOVA ($P < 0.05$) was indicated by different lowercase letters. Same as follow.

SOC densities across the five test sub-regions. Additionally, it observed a higher SOC density in 2015 than that in the late 1970s without a significant difference, except for the Kaidu-Kongque River Basin, of which the SOC density in 2015 is lower than that in late 1970s. With the large scale of agricultural reclamation and farming activities, the standard deviations of SOC content, SBD, and SOC density in the 270 plots were 2.90 g kg^{-1}, 0.18 g cm^{-3}, and 0.65 kg C m^{-2} in the late 1970s, which were higher than those of 1.96 g kg^{-1}, 0.16 g cm^{-3}, and 0.46 kg C m^{-2} in 2015.

3.2. Effects of prior land use on SOC density and dynamics

Variation in measured SOC and its dynamics can be partly explained by the differences in prior land use (Figs. 5 and 6). The order of SOC content in 2015 for three prior land use is as follows: cropland (7.29 g kg^{-1}) > forest (6.21 g kg^{-1}) > grassland (5.93 g kg^{-1}) and the bulk densities upon them were close. The difference of SOC density upon three land use types was similar to those of SOC content in 2015 (Fig. 4). In what was previously cropland—meaning the soil was reclaimed before the late 1970s—there is a higher SOC density (1.86 kg C m^{-2}) with a significant level of 95% compared those reclaimed after the late 1970s (Fig. 5). The SOC density in previously forested land (1.60 kg C m^{-2}) is slightly higher than that of grassland (1.53 kg C m^{-2}), without a significant difference. Similar to the total difference, the mean SOC densities reclaimed before the late 1970s are still the highest in five sub-basins, with significant differences observed for the Aksu River Basin, main stream of Tarim River, and Weigan River Basin (Fig. 4).

Comparing the soil characteristics between late 1970s and 2015, it shows that the change of SBD slightly offset that of SOC content, which would jointly result in the change of SOC density (Figs. 5 and 6). The change in SOC density between three prior land use types for the cropland, grassland, and forest were 0.37, 0.03, and −0.99 kg C m^{-2}, respectively (Fig. 6). The SOC density of the prior land use as the cropland increased from 1.49 to 1.86 kg C m^{-2} at a significant level of 99%, which includes 82.31% increased plots and only 17.69% decreased plots. The SOC density of what was previously grassland is slightly higher than that of in the late 1970s with a non-significant difference. In contrast, the SOC density reclaimed from the forest as the prior land use decreased from 2.59 to 1.60 kg C m^{-2} at a significant level of 99%, including over 20% increased plots and nearly 80% decreased plots. Across the five test sub-regions (Fig. 6), the increased values of the SOC density in plots that were previously cropland were the highest, except for the Yarkant River Basin. Also the changes in SOC density reclaimed from the forest in five test sub-regions were negative.

3.3. Effects of agricultural cultivation age on SOC density and dynamics

Table 3 shows the SOC contents, bulk densities, and SOC densities within different cultivation ages. An increase in the cultivation age resulted in an increase in SOC sequestration (Table 3, Fig. 7). The mean SOC density of newly reclaimed croplands (1.34 kg C m^{-2}) was lower than that of the old reclaimed croplands (1.71 kg C m^{-2}). However, SOC of the croplands reclaimed after the late 1970s were still lower than that of the referenced cropland reclaimed before the late 1970s (1.86 kg C m^{-2}) but were not significantly different (Fig. 7a). The two

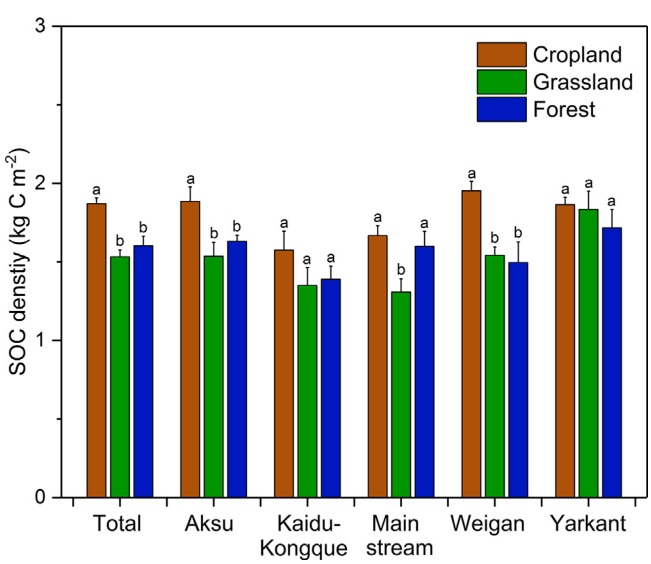

Fig. 5. Soil organic carbon density with different land uses in 2015. Bar length gives the mean value, vertical whisker for each column indicate standard errors of the mean. Group differences after one-way ANOVA ($P < 0.05$) was indicated by different lowercase letters. Same as follow.

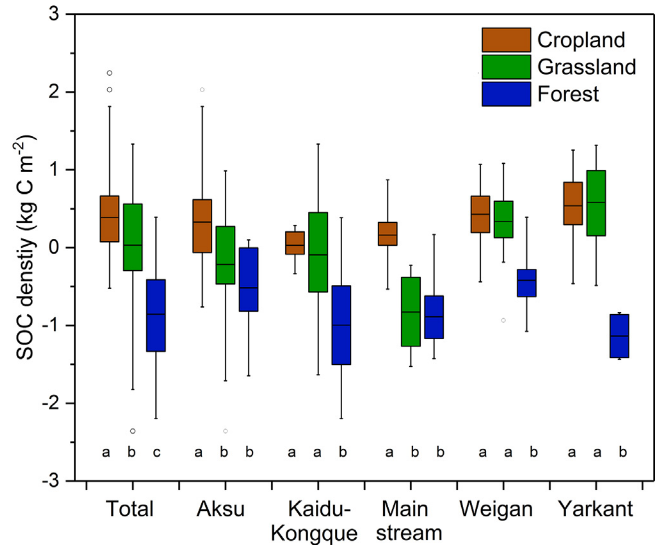

Fig. 6. Change of soil organic carbon density with different land uses between late 1970s and 2015.

Table 3
Soil properties within different cultivation ages between late 1970s and 2015.

			Newly reclamation	Young reclamation	Medium reclamation	Old reclamation
Reclamation from grassland	SOC content	late 1970s	5.65 ± 0.60	5.81 ± 0.36	5.83 ± 0.66	5.71 ± 0.65
	($g\,kg^{-1}$)	2015	5.17 ± 0.28	5.49 ± 0.41	5.76 ± 0.51	6.60 ± 0.45
	Soil bulk density	late 1970s	1.31 ± 0.20	1.31 ± 0.17	1.31 ± 0.15	1.30 ± 0.18
	($g\,cm^{-3}$)	2015	1.31 ± 0.16	1.32 ± 0.18	1.29 ± 0.21	1.28 ± 0.20
	SOC density	late 1970s	1.48 ± 0.57	1.52 ± 0.28	1.53 ± 0.66	1.48 ± 0.66
	($kg\,C\,m^{-2}$)	2015	1.35 ± 0.29	1.45 ± 0.32	1.49 ± 0.51	1.69 ± 0.37
Reclamation from forest	SOC content	late 1970s	11.96 ± 3.76	10.36 ± 4.05	10.41 ± 3.66	9.86 ± 3.85
	($g\,kg^{-1}$)	2015	5.23 ± 1.30	6.36 ± 1.40	6.12 ± 1.90	6.95 ± 1.39
	Soil bulk density	late 1970s	1.21 ± 0.21	1.23 ± 0.21	1.24 ± 0.23	1.25 ± 0.20
	($g\,cm^{-3}$)	2015	1.32 ± 0.15	1.29 ± 0.16	1.30 ± 0.18	1.28 ± 0.16
	SOC density	late 1970s	2.87 ± 0.79	2.52 ± 0.89	2.55 ± 0.78	2.45 ± 0.77
	($kg\,C\,m^{-2}$)	2015	1.32 ± 0.29	1.66 ± 0.27	1.59 ± 0.41	1.77 ± 0.32

Note: Data are means ± SD.

different prior land uses exhibited a similar change in SOC density with increasing cultivation age, but those reclaimed from the forest are slightly higher than those from the grassland (Table 3, Fig. 7b, c). The SOC densities in both cases of the old reclaimed croplands were significantly larger than that of the newly reclaimed cropland at a significant level of 95%. The SOC densities of old croplands reclaimed from the grassland (1.69 $kg\,C\,m^{-2}$) and forest (1.77 $kg\,C\,m^{-2}$) did not differ from that of the referenced cropland.

Compared to the values between late 1970s and 2015, the increase in the cultivation age and change in SOC density indicate that SOC densities would be different from the prior land use as grassland and forest after nearly 30 y of farming activities (Fig. 8, Table 3). The conversion from the grassland and forest to cropland lead to the SOC loss, thus the initial decrease of SOC density is the largest in the newly reclaimed soils, which is lower than that in the old reclaimed soils at a significant level of 99%. Subsequently, an increase in the cultivation age resulted in an increase in SOC sequestration (Table 3, Fig. 8). The decreased magnitude of SOC densities narrowed as the cultivation ages increased, with mean values of −0.70, −0.37, and −0.26 $kg\,C\,m^{-2}$ in newly, young, and medium reclaimed croplands, respectively (Fig. 8a). When the cultivated soils were managed longer, the change in SOC densities in old reclaimed croplands from the grassland turn to be positive with a mean increase of 0.21 $kg\,C\,m^{-2}$ (Fig. 8b, Table 3), which was significantly different from the reclaimed croplands with shorter periods of reclamation. However, the change is still negative with a decrease of 0.68 $kg\,C\,m^{-2}$ in that reclaimed from the forest (Fig. 8c, Table 3), indicating that the soil carbon loss by the reclamation from the forest could not be recovered within nearly four decades of farming activities.

4. Discussion

Better understanding the effect of land use change on the soil carbon balance at large spatial scale is still changeling. Having enough detailed, directly measured data is the basis for a robust result (Bouchoms et al., 2017; Schulp and Verburg, 2009). A rapid cropland expansion has occurred in the arid region of Northwest China in the last 40 years (Chen, 2014; Jia et al., 2004). There is still a lot of uncertainty regarding how this significant change influenced the carbon balance. To assess the effect of cultivation, this study implemented a large scale soil sampling survey and design based on different agricultural reclamation histories within nearly 40 years. The results of this research can serve as a better reference for the regional assessment of the soil carbon balance than previous studies with limited samples and literature (Huang and Sun, 2006; Yan et al., 2011). Moreover, it provided a new insight to the significantly different effect from the various agricultural reclamation histories—including different prior land use types and agricultural cultivation ages—on the SOC sequestration in the arid region of Northwest China.

4.1. Effect of agricultural reclamation history on SOC change

Reclaiming the soil and plowing croplands destroyed the soil structure and the physical protective layer of SOM, reduced the nutrient status and humus content, and exposed the surface SOM to the air (Gelaw et al., 2014). Also the tillage practices promoted the soil respiration and enhanced the mineralization rate of SOM (Houghton et al., 2000; Lal, 2002). Thus, the conversion from native vegetation to cropland would lead to the rapid loss of SOC content early on

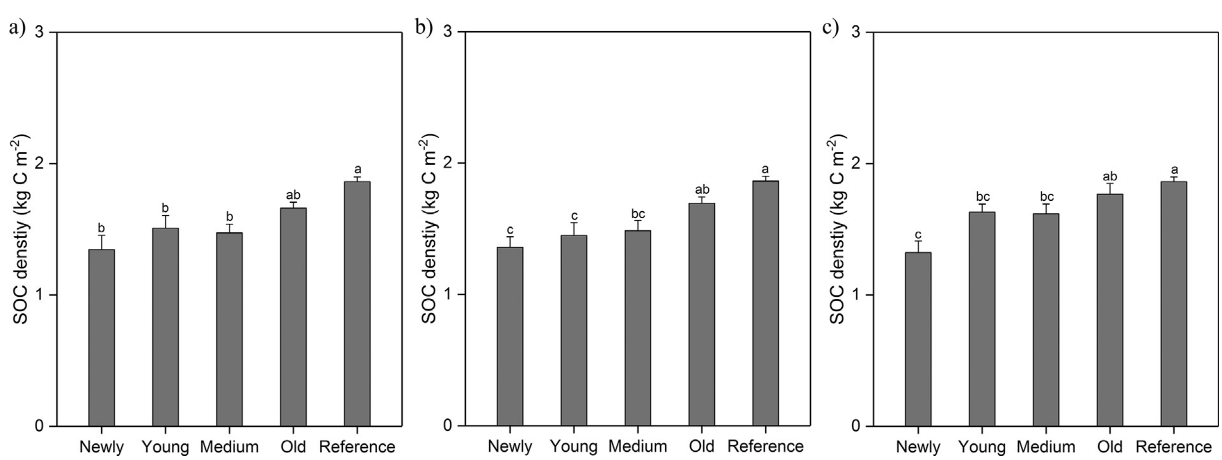

Fig. 7. Soil organic carbon density with different cultivation ages in 2015 a) all plots, b) plots reclaimed from grassland, c) plots reclaimed from forest. Cultivation ages classification: newly (1–5 y), young (6–15 y), medium (16–25 y), old (26–37 y), referenced (before 1978).

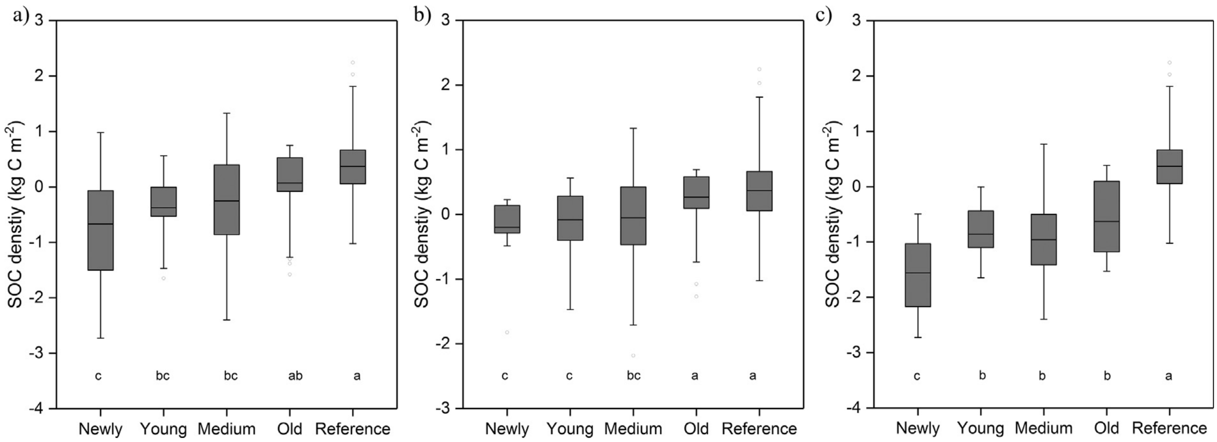

Fig. 8. Change of soil organic carbon density with different cultivation ages between late 1970s and 2015 a) all plots, b) plots reclaimed from grassland, c) plots reclaimed from forest. Cultivation ages classification: newly (1–5 y), young (6–15 y), medium (16–25 y), old (26–37 y), referenced (before 1978).

(Houghton et al., 2000; Lal, 2002; Lozano-García et al., 2016). In addition, the agricultural reclamation would break soil aggregates and compact existing soil, which resulted that the SBD of forest soils is usually lower than cropland soils (Murty et al., 2002). Thus, the change of SBD was positive in soils reclaimed from the forest in this study, which slightly offset the decrease of SOC content. In the initial reclamation stage, the SOC declined markedly under the cultivation and SOC density of the newly reclaimed croplands were the lowest (Fig. 7). And even the change in SOC density in land that underwent fewer than 25 y of reclamation was initially negative (Fig. 8).

With the increase in the cultivation age, an accumulation effect of SOC density was found in this study. Agricultural activities, such as the application of chemical fertilizer and organic manure and irrigation, either enhance the crop yield or bring organic materials into agroecosystems (Schulp and Verburg, 2009). With highly efficient agricultural production and conservative irrigation techniques, the average wheat, corn, and cotton yields in the Xinjiang Province have increased 3.2, 2.4, and 4.2 times, respectively, from 1978 to 2015 (values were calculated from data in Xinjiang Statistical Yearbooks). The increased yields greatly enhanced the soil carbon input through roots, root exudates, stubble, and crop residue (Yan et al., 2011). Another factor to the increase in the SOC with the increase in the cultivation age was anthropogenic mellowing process of soils under the long-term cultivation. The reasonable agricultural managements promoted the anthropogenic mellowing process of soils to improve the soil structure and function and enhance the accumulation effect of SOC (Shen et al., 2008). Also several sustainable agricultural practices, such as returning straw to the field, applying organic manure, and conservative tillage measurements were used to increase crop yields and SOC density (Jia et al., 2004). Under the near 40y of cultivation, a significant increase in the SOC density of the referenced croplands reclaimed before 1978 was observed (Figs. 4 and 5). As the reclamation duration increased, the accumulation of SOC increased (Figs. 6 and 7), which is consistent with previous studies that examined different geographical regions (Akala and Lal, 2001; Zhang et al., 2016). Although the SOC decreased in early stage of reclamation, losses of SOC recovered with increase in the cultivation ages (Figs. 5–7). Our findings confirmed the effectiveness of farming activities in the arid region of Northwest China, which are beneficial to soil carbon accumulation.

With the different prior land uses and cultivation ages, the change in SOC density from the grassland and forest in the study period was complex. The change in the SOC density depended on its preexisting condition and varied with the native vegetation, climate, soil type, management practices and time since conversion (Bellamy et al., 2005; Murty et al., 2002; Yan et al., 2011). Yan et al. (2011) found a negative correlation between the change in SOC and its initial value, meaning that when the SOC content is higher, the loss of soil carbon is faster, and when the SOC content is lower, its increasing potential is higher. Thus, the different changes in SOC density from the forest and grassland can be explained by their individual initial values of SOC and the associated changes of the vegetation and soil structure and functions. The mean SOC density of plots reclaimed from forests was slightly larger than that from grasslands (Figs. 4 and 6), which might be attributed to the expense of initial SOC stock. Compared to the initial values before reclamation (Table 3), the loss of SOC from the forest to cropland (1.55 kg C m^{-2}) was very close the global level of 1.60 kg C m^{-2} from a meta-analysis (Kopittke et al., 2017) with an average time length of 62 years since conversion and an average sampling depth of 17 cm, but that the loss from the grassland to cropland was much lower (0.13 kg C m^{-2}). The soil carbon loss caused by the reclamation from the grassland was recovered within nearly 30 years of agricultural management (Fig. 8). In the Tarim Basin, the uncultivated grassland, primarily desert steppe, was limited by water resources and a lower rate of bioaccumulation (Shan et al., 2008), resulting in a relatively low level of initial SOC (Huang and Sun, 2006; Wang et al., 2014). After reclamation, the conditions of soil moisture and biomass growth improved, which can increase the aboveground and underground biomass and result in the soil carbon accumulation with increased cultivation ages (Li et al., 2006). Therefore, with over 30 years of cultivation, the SOC density reclaimed from the grassland was larger than that of the initial grassland.

In contrast, the increase of SOC under the long-term cultivation is small relative to the initial decrease from reclaimed forests (Fig. 8), consistent with a global meta-analysis (Kopittke et al., 2017). The status of SOC is closely relevant to land-use types (Don et al., 2011; Lozano-García et al., 2017; Post and Kwon, 2000). The conversion from the forest to cropland decreased inputs of vegetative tissues and increased soil temperatures to accelerate the litter decomposition and soil microorganisms of the decomposition of SOM (Li and Wu, 2017; Wang et al., 2019). Especially, the conversion significantly altered the microclimate and decreased the vegetation and litter cover, which would expose the soil to be susceptible to the wind erosion and easily cause the SOC loss in the semi-arid region (Zhao et al., 2005). Thus, the SOC density of reclaimed forest, mainly the wood in the river valley plain (Wang et al., 2014), were the higher than that of the cropland. Even after as much as 40 y of cultivation, the SOC density in the old reclaimed croplands from the forest was still lower than the initial value.

With our novel spatial identification method, this study demonstrated that the different fates of SOC in oasis agriculture of the Tarim Basin were greatly related to their individual agricultural reclamation history with in the same present-day land use, where land use types of all soil sampling sites were cropland. A global meta-analysis found that the initial decrease magnitude of SOC by the conversion from the native vegetation to cropland was large relative to the increase of SOC in the subsequently conversion with different farmland managements (Kopittke et al., 2017). This is consistent with the change trend of SOC in forested croplands but was different from that in the soils reclaimed from grassland in our study. Previous case studies have implied that cultivation-induced SOC depletion was likely often overestimated (Lozano-García et al., 2016; Wiesmeier et al., 2012), which was confirmed by this study. Agricultural reclamation history, including the prior land use types related to the initial SOC stocks and cultivation ages related to the accumulation effect of SOC, would significantly influence the SOC dynamics. Thus, differences from reclamation histories could be used to explain why negative impacts of agricultural reclamation activities on the SOC stocks were found in previous case studies (Elberling et al., 2003; Lü et al., 2014; Su et al., 2004) but positive impacts were shown in other cases (Liu et al., 2011; Yang et al., 2017). Agricultural reclamation history was suggested to be spatially quantified by our proposed spatial identification method and taken into consideration to the examination of land use change on SOC dynamics. It can provide more information to better understand the causes and trends of SOC change under impacts of different histories (Lal, 2018; Schulp and Verburg, 2009).

4.2. Potential of carbon sequestration in the cultivated soils

The water supply and land suitability is the precondition of oasis land reclamation activities. Water resources have exceeded their capacities due to the large area of cropland expansion (Meng et al., 2009) in the arid region of Northwest China. Additionally, the fragile ecosystem in this arid region is vulnerable to climate change and land desertification (Wang et al., 2012), which are potential threats to sustainable agriculture and could lead to land abandonment. Thus, the water scarcity and land desertification limit call for the optimization of oasis agriculture in the arid region of Northwest China. Linking the hydrologic and carbon cycles through water conservation is crucial to soil carbon sequestration in dry land (Lal, 2004). On the basis of water and land resource capacities and the finding of varying agricultural reclamation histories influencing SOC stocks by our proposed method, two following land reclamation and management strategies can be suggested to enhance the regional SOC sequestration.

The first strategy is to proceed with responsible agricultural reclamation from the desert steppe but limit the reclamation from the forests, where SOC loss recovered after nearly 30 years of cultivation in reclaimed grasslands but fail in reclaimed forests after 40 years of cultivation. For the last forty years, agricultural reclamation in the arid west China region has played an important role in realizing the balance of the requisition–compensation of cropland throughout the country (Liu et al., 2014b). The newly reclaimed croplands were largely sourced in the arid region of Northwest China (Zuo et al., 2014). Reclaimed soils from the desert steppe present great potential to sequester SOC because of the initial low level of SOC from the desert steppe and the improvement of soil moisture conditions and nutrient inputs to soils. Thus, reasonable future agricultural reclamation was suggested to be beneficial to the carbon sequestration in the arid region of Northwest China. Until now, it seemed that a steady-state equilibrium had not yet been reached in our study area, where the SOC density of part plots was greater than two times the average value, and the SOC density with the short cultivation ages was still lower. Meanwhile, SOC may not increase indefinitely with the duration of farming, irrespective of improved management practices (Steinmann et al., 2016). The decomposition of high SOC stocks has been found in several case studies (Bellamy et al., 2005; Steinmann et al., 2016). Additionally, the soil carbon loss occurred in several plots with high SOC density before 1978. This calls for future studies to explore the reason behind these results as well as improved managements.

The second strategy is to sustainable manage the current croplands coupled with increased water use efficiency and desertification control measures instead of large-scale returning croplands to natural vegetation with the cultivation duration effect. Unlike other case studies (Nadal-Romero et al., 2016; Wertebach et al., 2017) in which land abandonment and afforestation or grasslands was an efficient strategy for environmental restoration and carbon sequestration (Xu et al., 2019b), large scale afforestation was not suitable for abandoned land due to the limited water supply and extreme dry climate (Wang et al., 2015). Returning the croplands to desert steppe would lead to a lower SOC density than that of the croplands with the appropriate long-term agricultural practices. Except for croplands exceeding the water and land resource capacities, sustainable management of the current croplands would be a better carbon sequestration strategy. Improving the agricultural water use efficiency and developing the non-conventional water resource utilization technologies are potential ways to increase the water supply and sustain agriculture in the study area (Li et al., 2015). Moreover, measures to combat land desertification—for example, wind-shelter forests protecting farmlands—would be especially necessary in newly reclaimed croplands (Wang et al., 2015). Long-term sustainably managing oasis farming in the arid region and the SOC accumulation effect of increased cultivation duration will make up for the soil loss with the land reclamation and further enhance potential carbon sinks in the future.

5. Conclusions

A large area of agricultural reclamation in the arid west China region has played an important role in both the food security in China and the regional carbon balance. Changes in the SOC stock in the cultivated topsoil within nearly four decades were examined in the Tarim Basin. Based on the remote sensing and spatial detection techniques, this study proposed a spatial identification method of quantifying agricultural reclamation histories and designed the soil sample experiment according to the reclamation history, including the different previous land uses and cultivation ages. Two-hundred and seventy soil samples were collected from plots and compared to the data from the second national soil survey at the same spatial coordinates. The cropland area was nearly double from the late 1970s to 2015 in the study area, which majorly sourced from grasslands, partly from forests and few from others. The results found a mean SOC density of 1.71 $kg\,C\,m^{-2}$, which is 0.05 $kg\,C\,m^{-2}$ higher than that in the late 1970s. With different reclamation histories, the significant increase of SOC density in soil reclaimed before the late 1970s validated the accumulation effect of SOC in the agricultural practices. Thus, the prior land use as croplands exhibits the highest SOC density of 1.86 $kg\,C\,m^{-2}$ with an increase of 0.37 $kg\,C\,m^{-2}$ from late 1970s to 2015 at a significant level of 99%. The preexisting condition from the forest and grassland and the associated changes of the vegetation and soil structure and functions would influence the different changes in SOC density after the reclamation. The SOC densities of two prior land uses, forest and grassland, are 1.60 and 1.53 $kg\,C\,m^{-2}$ with the change of -0.99 and 0.03 $kg\,C\,m^{-2}$, respectively. The conversion from the native vegetation to cropland lead to the SOC loss, thus the initial decrease of SOC density is the largest in the newly reclaimed soils. As the cultivation age increased, the SOC sequestration enhanced and the decreased magnitude of SOC density shrink. After nearly three decades of management, the SOC density of the old reclaimed croplands was significantly higher than that of newly reclaimed croplands and its change trend turn to be positive. Moreover, the SOC density would be significantly larger than that of the prior land use as the grassland after nearly three decades of agricultural practices, indicating a significant SOC sequestration. However, the soil carbon loss by the reclamation of the forest still did not recover within nearly four decades of agricultural management. Findings from the large scale of soil samples in the arid region of Northwest China demonstrated the effect of different agricultural reclamation histories on the SOC dynamics. The arid region of Northwest China is a potential carbon sink provided the agricultural practices therein are managed sustainably.

Author contributions

E.Q., H.Z. and Y.X. conceived and designed the experiments. E.Q. and Y.X. analyzed the data. E.Q. and H.Z. wrote and revised the paper.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2019.105746.

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