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Effect of Large-Scale Cultivated Land Expansion on the Balance of Soil Carbon and Nitrogen in the Tarim Basin

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Abstract: Land reclamation influences the soil carbon and nitrogen cycling, but its scale and time effects on the balance of soil carbon and nitrogen are still uncertain. Taking the Tarim Basin as the study area, the impact of land reclamation on the soil organic carbon (SOC), total nitrogen (TN), and carbon to nitrogen (C:N) ratio was explored by the multiple temporal changes of land use and soil samples. Remote sensing detected that cropland nearly doubled in area from 1978 to 2015. Spatial analysis techniques were used to identify land changes, including the prior land uses and cultivation ages. Using land reclamation history information, a specially designed soil sampling was conducted in 2015 and compared to soil properties in ca. 1978. Results found a decoupling characteristic between the C:N ratio and SOC or TN, indicating that changes in SOC and TN do not correspond directly to changes in the C:N ratio. The land reclamation history coupled with the baseline effect has opposite impacts on the temporal rates of change in SOC, TN and C:N ratios. SOC and TN decreased during the initial stage of conversion to cropland and subsequently recovered with increasing cultivation time. By contrast, the C:N ratio for soils derived from grassland increased at the initial stage but the increase declined when cultivated longer, and the C:N ratio decreased for soils derived from forest and fluctuated with the cultivation time. Lower C:N ratios than the global average and its decreasing trend with increasing reclamation age were found in newly reclaimed croplands from grasslands. Sustainable agricultural management practices are suggested to enhance the accumulation of soil carbon and nitrogen, as well as to increase the C:N ratio to match the nitrogen deposition to a larger carbon sequestration.

Keywords: soil stoichiometry; land use change; soil organic carbon; nitrogen; Tarim Basin

1. Introduction

Soil carbon (C) and nitrogen (N) are the main sources of plant mineral nutrition and organic nutrients, which are the two primary factors affecting soil fertility [1,2]. They also play an important role in terrestrial soil C and N pools and global C and N cycles [3,4]. The ratio of soil organic carbon (SOC) and total nitrogen (TN), labeled as the C:N ratio, reliably indicates changes in soil microbial activity, decomposition, mineralization rates of SOC, and the cycle of soil C and N [5,6]. Moreover, the soil C:N ratio can be a good predictor of key parameters in the related C and N cycles, such as the dissolved organic carbon flux [7], nitrate leaching [8,9], and nitrous oxide emissions [10]. Therefore, understanding soil C and N content and their variation can help explore the mechanisms of soil C and N cycling and their coupling effects, and aid in enhancing soil C sequestration and reducing N losses in the ecosystem.

A high soil C:N ratio correlates with low organic matter (SOM) decomposition and mineralization rates while in soils with a low C:N ratio, SOM can be decomposed and mineralized relatively quickly [1]. SOC, TN, and the C:N ratio are influenced by many factors, such as climatic conditions (temperature, moisture), soil properties (soil texture, soil pH), terrain characteristics, and anthropogenic factors (land use and management) [2,11–13]. The soil C:N ratio and its variation are determined by gains (input of SOC and TN) and losses [11]. At the global scale, it has been shown that tundra, natural wetlands, and boreal forest can have a relatively wide range of soil C:N ratios, while croplands have a narrow range [2]. Land reclamation can alter the soil C and N bio-geochemical cycling and spatial-temporal characteristics of soil C:N ratios greatly [14–17]. The conversion from native vegetation to cropland decreases the input of vegetative tissues and increases soil temperatures to accelerate the litter decomposition and soil micro-organisms in the decomposition of soil C and N [18]. Reclamation activities can further cause C and N losses and change the soil C:N ratio [3]. Meanwhile, the increasing crop yields of land under sustainable agricultural management can enhance the input crop residues and roots, which can in turn, increase the SOM content and promote the accumulation of SOC and TN [19–21].

Generally, the dynamics of soil C:N ratios are determined by the relative changes in magnitude of SOC and TN contents [22,23]. Many case studies have found that forest converted to cropland results in a decrease in soil C:N ratio because of the high uptake and storage of N by trees [1,3,24,25]. In contrast, agricultural management can promote maintenance of crop residues at the soil surface, which may have beneficial impacts on soil fertility and increase the soil C:N ratio [1]. Plantation age also shows complex effects on the accumulation and decomposition of SOC and TN. For example, soil C:N ratios of cropland showed a significant increase over time at a sub-tropical site, although little change was observed at three temperate sites [11]. The above studies illustrate that the variation in soil C:N ratios during agricultural reclamation and management is complex and is not yet fully understood.

The dynamics of SOC, N, and the C:N ratio, which are affected by land use coupled with other physical factors, present significant spatial and temporal variations. Agricultural reclamation activities mean exploiting other land uses for croplands. Outcomes of reclamation are primarily the result of changes in plant types associated with the changes in the litter input, detritus and litter decomposition, root secretion and soil mineralization [14,26,27]. These changes are related to the prior land use type before the reclamation, which directly or indirectly influence the soil C, N, and their balance after the reclamation. Meanwhile, knowledge of the agricultural duration is important [28], because it is related to the cultivation intensity and the soil mellowing process. Thus, land reclamation history, including the different prior land use types and the duration age of the reclamation, will influence the fate of soil C and N. However, the effects of reclamation history remain uncertain [29], and this leads to difficulties in decision making and agriculture management. This calls for a deeper understanding of the impact that past and future land use changes can have on soil C:N ratios.

Arid and semi-arid regions are especially susceptible to human disturbance and climate change [30], which easily lead to land degradation and soil nutrient element loss [31–33]. Oasis agriculture is a specific ecosystem surrounded by the desert in an arid area, where environmental conditions are milder than the desert, ensuring fertility and allowing desert farming [34]. Aridisols, called Yermosols in the FAO-UNESCO classification (Food and Agriculture Organization-United Nations Educational, Scientific and Cultural Organization) [35], are the major original soil types, undisturbed by humans in arid regions [36]. The expansion of oasis agriculture disturbs the soil environment and may cause the loss of soil C and N. Under long-term sustainable tillage, fertilizing and irrigation of the oasis agriculture [37,38], Aridisols are gradually developed to Anthrosols with changes in C and N storage [35]. Thus, this calls for a deep understanding of how oasis agriculture influences the soil C and N.

The Tarim Basin contains the Taklimakan Desert, the world's second largest shifting sand desert [39]. It has experienced a significant expansion in oasis agriculture from its native vegetation, and even the desert since 1949 [40]. The cropland area in this region has nearly doubled since the 1980s [41,42], which was much higher than the average increase rate in the world [43]. Due to the extreme dry and hot climate with annual limited precipitation of 50–100 mm, almost the entire oasis agriculture relies on irrigation for crop growth in harsh conditions and to resist drought [44]. For the last few decades, land reclamation and the development of high-efficiency irrigation techniques has played an important role in this region [45], making the Tarim Basin one of the main agricultural production regions in China and one of the largest areas of oasis agriculture in the world. This dramatic expansion in cropland has significantly changed the nutrients in the cultivated soils, and has also caused the overuse of water sources and land desertification [46], which in turn, influence the terrestrial C and N cycles [47]. Proper management of such changes requires a deep understanding of the effects of the land reclamation history on the variation in SOC and TN and their balance. Thus, the Tarim Basin was selected as the study area to explore the relationship between the land reclamation history and changes in the soil C, N, and C:N ratio. The objectives of this study were to (1) design a soil sampling campaign from land use change histories to quantify the changes in the SOC and TN dynamics of the cultivated topsoil, and (2) investigate the effects of the land reclamation history on these changes and the coupled relationships between SOC and TN.

2. Methods

2.1. Study Area

The Tarim Basin, located in the south of Xinjiang Province, Northwest China, was selected as our study region. It is located between 38°–43° N latitude and 76°–87° E longitude. Five typical sub-basins, the Aksu River Basin, the Kaidu-Kongque River Basin, the mainstream of Tarim River Basin, the Weigan River Basin, and the Yarkant River Basin, were selected as the case study sites with a total area of 311,765 km^2 (Figure 1). They lie within an extremely dry climate zone, with high temperatures of 20–30 °C in the summer and low temperatures of −10 to −20 °C in winter, a mean annual precipitation of 50–100 mm, and an annual evaporation of 2000–3000 mm [48]. Landscapes in the study area majorly consist of the desert, grassland, cropland, and forest. Native forests with shrubs, mainly including the *Populus euphratica* Oliv. and *Tamarix ramosissima* Ledeb. [49], are located in the riparian zone with an adequate water supply for vegetation growth. These climatic conditions have resulted in a specific oasis agriculture, with widespread use of highly efficient water-saving irrigation techniques.

2.2. Conceptual Framework for Exploring Impacts of Land Reclamation History on Soil C and N

Figure 2 showed the framework for exploring how land reclamation history influences the soil properties. Using the land use maps at different time nodes and spatial overlaying techniques, the land change histories at each location were identified from ca. 1978 to 2015. Also, the specific land reclamation history, including the prior land use before the reclamation and the duration age after the reclamation were extracted. Meanwhile, the simultaneous changes of SOC, TN, and C:N ratio were collected by purposive survey sampling in 2015 and the soil dataset in ca. 1978. Based on the statistical test, the impact of land reclamation history on SOC, TN, and the C:N ratio can be analyzed.

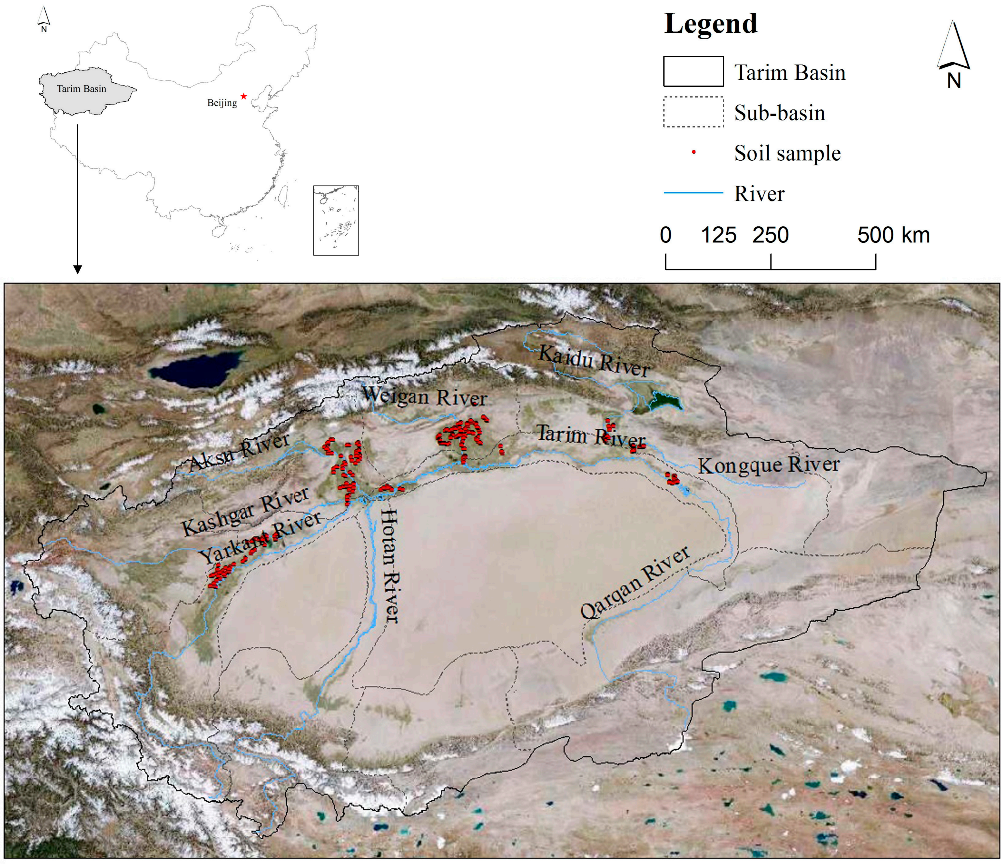

Figure 1. Location and soil sampling sites in the area of the Tarim Basin.

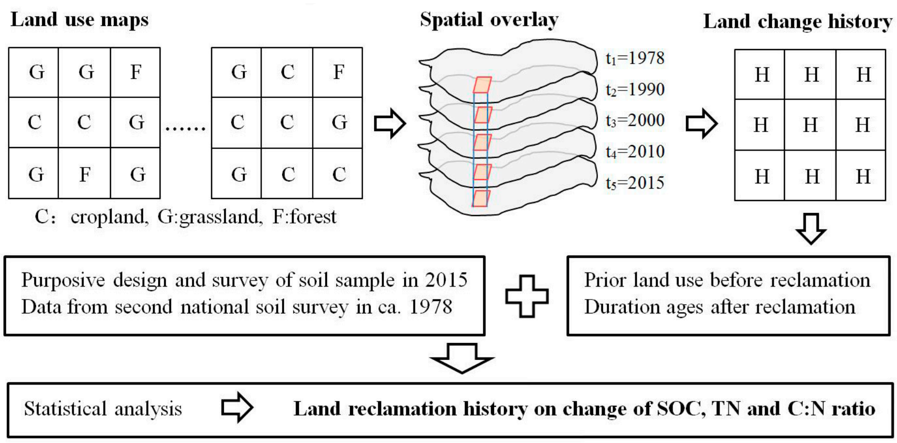

Figure 2. Conceptual framework for exploring impacts of land reclamation history on soil C and N.

2.3. Land Use Change History Detection

The soil sampling strategy was designed on the basis of the land reclamation history, which included land use prior to reclamation indicating the original soil nutrient status, while the cropland age was used to characterize the duration of management practices. To examine the land use change history on the SOC and TN dynamics from ca. 1980 (national soil surveys in 1978 to 1982) to 2015 (soil survey in this study), five time nodes, i.e., 1978, 1990, 2000, 2010, and 2015, of remote sensing images from Landsat MSS/TM and Landsat-8 Operational Land Imager (OLI) images were collected to map the land use via visual interpretation with a local expert tutorial on land use interpretation by ourselves. The paths and rows covering the study area are shown in Table S1. Preprocessing, including the application of geometric and atmospheric corrections, was conducted using ENVI 5.1 (ITT Visual

Information Solutions Inc.). Images within ±2 y of the time node were used as a proxy when there were no effective cloud-free images from a particular node.

The land use maps were divided into seven classes: cropland, forest, grassland, water body, built-up land, bare land, and glacier. As the majority of the croplands were derived from grassland, with a minority from forest and other land use types [47], this study focused on the effects of grassland and forest conversion to croplands on the SOC and TN dynamics. Using spatial overlay techniques in ArcGIS 10.1 (ESRI Inc., Redlands, CA, USA) for the land use vector maps with seven classes at the five time nodes, the overlaying vector polygon representing the land use change trajectory from ca. 1978 to 2015 was obtained. With the overlaying land use maps, the time nodes where the reclamations occurred were obtained, and the land use prior to the reclamation was identified. Grassland, forest, and cropland were labeled as G, F, and C, respectively, and the land use types for each of the five time nodes were identified. For example, "G→G→C→C→C" indicates the reclamation of grassland to cropland in the period of 1990 to 2000. The label "C→C→C→C→C", indicates that the cropland was asserted before 1978, and land with this history of use was used as a reference for this study. Following labeling for land use, the asserted croplands were grouped according to age as follows: asserted between 2010 and 2015 (new, 1–5 years), 2000 and 2010 (young, 6–15 years), 1990 and 2000 (medium, 16–25 years), 1978 and 1990 (old, 26–37 years). In addition, in some areas land use changes occurred more than once, and cases where cropland transferred to other land use types because of abandonment or build-up and occupation were excluded in this study. Thus, cropland, grassland, and forest were the three prior land use types in this study. Finally, three land use change types, i.e., unchanged cropland, cropland from grassland, and cropland from forest over nearly four decades, with five discrete reclamation ages were identified for the design of the soil sampling campaign.

2.4. Soil Sampling Design, Collection, and Laboratory Methods

Since we were particularly interested in the effect of land reclamation history, soil sampling conducted in 2015 was only carried out for cropland with different reclamation histories. First, the range of cropland in 2015 was extracted and 280 soil plots were identified in the croplands of five sub-basins by a random sampling strategy. A minimum distance of 1000 m between plots of the same category of land use change history was set. Next, three land use change types and five discrete reclamation ages from 1978 to 2015 in the designed soil plots were identified based on the spatial overlay techniques mentioned in Section 2.1. If the area of the vector polygon for overlaying land use maps was smaller than 1 km^2, the corresponding soil plots were excluded to minimize geolocalization errors of land use interpretation and make the resolution of land use maps consistent with soil C and N data. Finally, we collected samples from a total of 270 soil sample plots, including 126, 103, and 41 plots of unchanged cropland, cropland from grassland, and cropland from forest between 1978 and 2015, respectively. At each sampling plot of 10 m × 10 m, five sites, four at the corners and one in the center of the plot, were selected. According to the Genetic Soil Classification of China [38], the main soil type of the soil samples is irrigation-silted soil (Aric Anthrols in the FAO-UNESCO classification). Irrigation-silted soil is a type of Anthrosol and formed the new anthraquic epipedon in the soil irragric process and mellowing process under cultivation, which means soil materials are silted with irrigation water [38].

The soil C and N distribution within soil profile is highly influenced by management practices, especially tillage systems [50]. As soil disturbance by agricultural tillage is a primary cause of the historical change of soil nutrients, the tillage zone or management zone, mainly including the 0–20 cm soil layer, was sampled using a soil auger of 5 cm diameter. Soil samples were transported to the laboratory and preprocessing was conducted. Soil clods were crushed, and litter and living roots, stones (>2 mm), and visible plant remains were removed. Next, the soil samples were air-dried in the shade and passed through a 2 mm sieve. SOC and TN were measured by the H_2SO_4-$K_2Cr_2O_7$ oxidation method [51] and Kjeldahl procedure [52], respectively. Soil C:N fractions were calculated as the mass ratio of SOC to TN.

To compare simultaneous changes in soil properties and land use, the SOM and TN from ca. 1978 were obtained from the soil characteristics database of China, which were measured by the same chemical analysis methods as those used in 2015. This data has a resolution of 30 × 30 arc-seconds, and was generated from soil data collected in the 1979–1982 national soil survey. As the designed soil plots were located in the overlaying land use vector polygon with an area of larger than 1 km^2 (close to 30 × 30 arc-seconds), the spatial resolution of land reclamation histories and soil properties in the plot were consistent and could be compared and analyzed. The data was provided by the Cold and Arid Regions Science Data Center at Lanzhou [53] and downloaded from their website (http://westdc.westgis.ac.cn/data). The SOC was then calculated from SOM values, using the Bemmelen index of 0.58, which was widely used in previous studies [54,55]. Since the soil data set consists of eight vertical layers with different depths, the SOC and TN at the study depth of 0–20 cm were estimated by a weighted depth method provided by Yan, et al. [19].

2.5. Statistical Analysis

Statistical analysis was carried out using the SPSS18.0 statistical package (SPSS Inc., New York, NY, USA). Differences in variation of SOC, TN, and C:N ratio for the 270 soil plots between ca. 1978 and 2015 were calculated using paired-samples *t*-tests, using 270 pairs in the same spatial coordinates. The significance of differences in the levels and variations of SOC, TN, and C:N ratio in plots with different land reclamation histories were tested with one-way analysis of variance (ANOVA) and least-significant-difference (LSD) methods, followed by Tamhane post hoc tests ($p < 0.05$).

3. Results

3.1. Land Reclamation from 1978 to 2015 in Typical Areas of the Tarim Basin

The classification accuracy of land use maps was assessed by a total of 2000 ground-reference data-points in the five sub-basins, including the field validation investigations with GPS in 2015, and points from high resolution images from Google Earth in 2010 and 2015. The ground-reference data-points were randomly collated by the stratified land use types. This assessment found a high classification accuracy, with kappa coefficients of 0.913 and 0.906 and an overall accuracy of 92.30% and 91.35% for the 2010 and 2015 data, respectively. Since the visual interpretation methods used for other year were similar, it was assumed that the classification accuracies of land use maps for 1990 and 2000 were similar to those for the 2010 and 2015 maps. Similar to previous studies using the multiple Landsat MSS/TM images for long time series of land use change detection [56,57], the land use map in 1978 interpreted by the same executor with the same satellite and similar images could be relied upon. Figure 3 shows the land use maps for 1978 and 2015.

Croplands accounted for 10.37% of the total area of the five sub-basins of the Tarim Basin in 2015. Areas of croplands were 1.72×10^4, 1.89×10^4, 2.11×10^4, 2.72×10^4, and 3.23×10^4 km^2 for the five time nodes of 1978, 1990, 2000, 2010, and 2015, respectively. The cropland area nearly doubled with a significantly increased rate of 88.37% from 1978 to 2015. Most of them mainly expanded in the vicinity of their existing areas. The assarted croplands were converted from grassland, forest, bare land, and water body, with the proportions of 70.35%, 16.89%, 9.56%, and 3.20%, respectively.

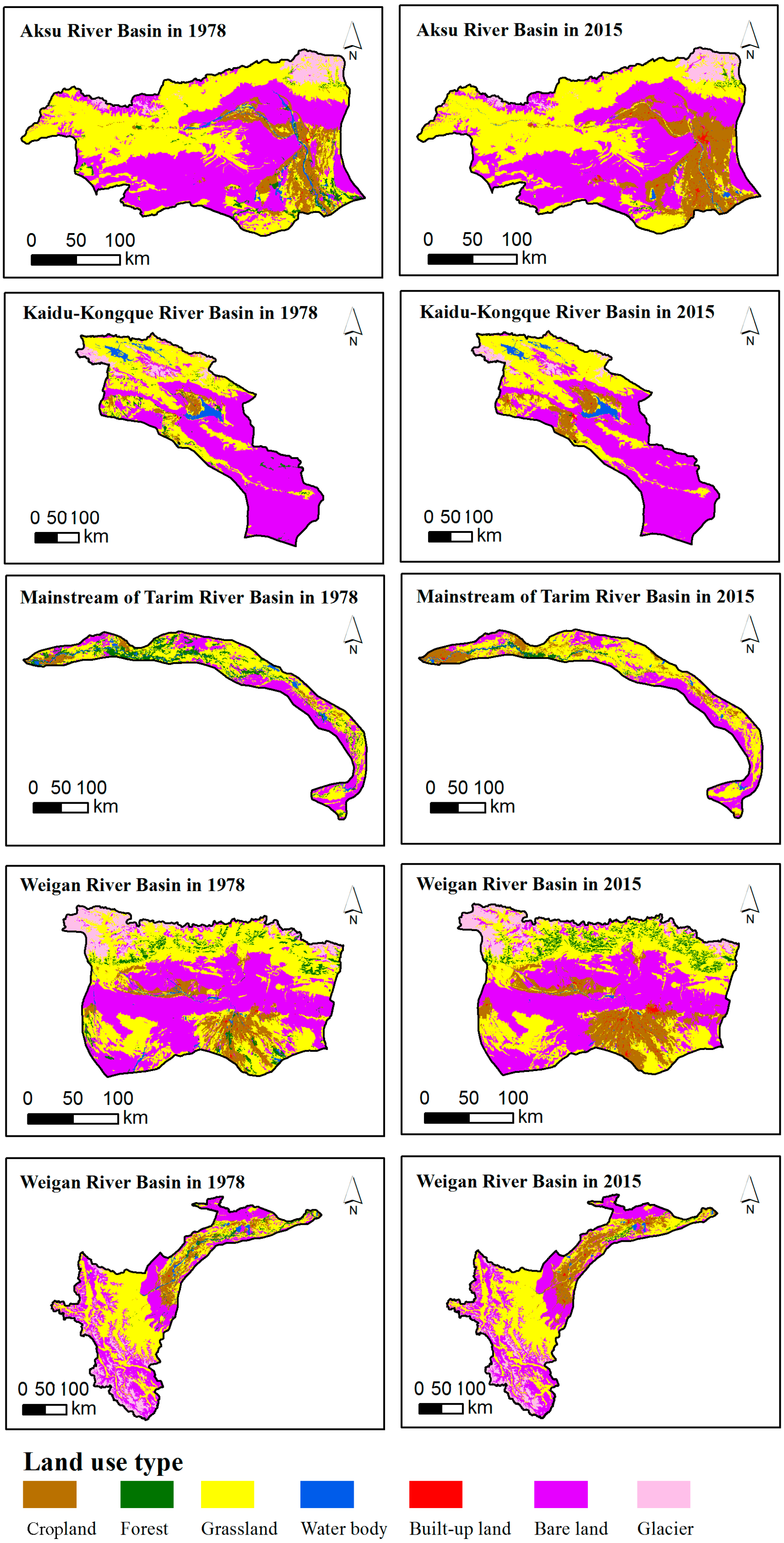

Figure 3. Land use maps of 1978 and 2015 in typical areas of the Tarim Basin.

3.2. Status and Change in Soil C, N and C:N

Table 1 shows the statistical characteristics of SOC, TN, and C:N ratios in the Tarim Basin. The mean values of these parameters increased from ca.1978 to 2015 with varying magnitudes, but do not show a significant change ($p < 0.05$). The mean SOC content is 6.61 g/kg, with an increase of 0.17 g/kg from ca.1978 to 2015. The TN contents, meanwhile, increased from 0.63 g/kg to 0.65 g/kg. It was found that the TN content is highly correlated with the SOC content in 270 soil sample plots, showing high Pearson's correlation coefficients of 0.938 and 0.925 in ca. 1978 and 2015, respectively. Although the range of contents of SOC and TN increased from ca. 1978 to 2015 (Table 1), their standard deviations decreased. With cultivation practices, the standard deviation of SOC and TN in 270 plots show increases from 1.96 g/kg and 0.22 g/kg, respectively, in ca. 1978, to 2.90 g/kg and 0.28 g/kg, respectively, in 2015.

The change in statistical characteristics for the C:N ratio is similar to those of SOC and TN content. The mean C:N ratio is 10.22 in 2015, ranging from 6.11 to 17.25. Most of these values fall in the range from 9.0 (10% quantile) to 11.5 (90% quantile). A larger increase in SOC over TN resulted in a slight increase of 0.11 in the C:N ratio from circa (ca.) 1978 to 2015, with no significant change at the 95% confidence level. Long-term cultivation has tended to homogenize the soil C:N ratio, resulting in a decrease in standard deviation, from 1.73 in ca. 1978 to 1.21 in 2015, separating the soil plots as two groups, i.e., the increased values from ca. 1978 to 2015 and decreased values at this period. Using the paired-samples *t*-test, two-third of the total observations showed an increasing trend in SOC and TN at a significant level of 99%, and other one-third showed a significant decrease. In contrast, about 59.26% of the total observations showed an increasing trend in C:N ratio at a non-significant level of 95%, with the remainder showing a decrease at a significant level of 95%. Thus, a deep exploration of change in soil C and N based on the different land reclamation histories is called for.

Table 1. Statistical characteristics of soil properties.

		Mean	Standard Deviation	Maximum	Minimum
Soil bulk density (g cm^{-3})	ca.1978	1.30	0.18	1.75	0.93
	2015	1.29	0.16	1.61	1.05
SOC content (g/kg)	ca.1978	6.44	2.90	16.85	3.42
	2015	6.61	1.96	17.65	2.26
TN content (g/kg)	ca.1978	0.63	0.28	1.67	0.29
	2015	0.65	0.22	1.76	0.19
C:N ratio	ca.1978	10.11	1.73	14.90	7.33
	2015	10.22	1.21	17.25	6.11

3.3. Effects of Land Reclamation History on SOC and TN

The selected sites presented significant differences ($p < 0.05$) in SOC and TN contents in 2015, depending on their prior land uses (Figure 4a,b). The SOC and TN contents of cropland soils for lands assarted before 1978 were 7.29 g/kg and 0.74 g/kg, respectively. These values were significantly higher than those for soils from land with prior use as grassland and forest assarted in the study period. The SOC content in previously forested land (6.21 g/kg) is slightly higher than that for land that was previously grassland (5.93 g/kg), and the TN content of soil from forest (0.59 g/kg) is close to that from grassland (0.58 g/kg). Comparing the SOC and TN contents in ca. 1978 and 2015, differences in change values according to prior land use were also significant ($p < 0.05$) (Figure 4c,d). In 2015, SOC and TN content in those sites previously used as cropland had significantly increased, as indicated by the paired-samples *t*-test ($p < 0.05$), the largest increases being 1.59 g/kg and 0.15 g/kg, respectively. Sites where prior land use was grassland showed an increase in SOC content of 0.17 g/kg and a slight decrease in TN content. In contrast, the SOC and TN content in previously forested land showed a significant decrease of 4.18 g/kg and 0.30 g/kg, respectively.

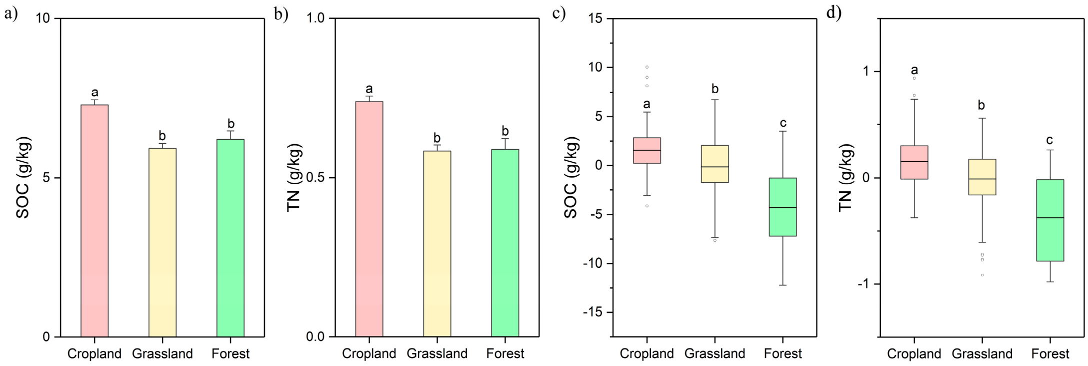

Figure 4. Soil C and N for different prior land uses: (**a**) Soil organic carbon content in 2015, (**b**) Total nitrogen content in 2015, (**c**) Change of soil organic carbon content, (**d**) Change of total nitrogen content. Note: 1. Group differences after one-way ANOVA ($p < 0.05$) was indicated by different lowercase letters. 2. Bar length gives the mean value, vertical whisker of bar for each column indicate standard errors of the mean. 3. Line within the boxes gives the median value, box means the 25th and 75th percentile, whisker of box 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. The same as below.

With the increasing reclamation age, the accumulation of SOC and TN in soil from land derived from grassland and forest increased (Figure 5a–d). The mean SOC and TN content in the newly assarted soils were the lowest, and were significantly lower than those in the old assarted soils ($p < 0.05$). In addition, SOC and TN content for old assarted soils were lower than the reference cropland assarted before 1978, but were not significantly different. The SOC content in land that was previously grassland and forest increased significantly from 5.17 and 5.23 g/kg in the newly assarted soils to 6.60 and 6.95 g/kg in the old assarted soils, respectively (Figure 5a,c). Similarly, the TN content in land that was previously grassland and forest increased significantly from 0.51 and 0.47 g/kg in the newly assarted soils to 0.66 and 0.66 g/kg in the old assarted soils, respectively (Figure 5b,d).

An increase in the reclamation age resulted in an accumulation in SOC and TN at a significance level of 95% (Figure 5e–h). Compared to the initial SOC and TN levels prior to reclamation, changes in content for new, young, and medium assarted soils were negative. The decreases in the newly assarted soils were the largest, and increasing reclamation age resulted in increases in SOC and TN stocks. A slight decrease in SOC and TN content in the sites which were previously grassland was observed, with a larger decrease for previously forested sites. For example, the changes in SOC content for new, young, and medium croplands derived from grassland are −0.48, −0.32, and −0.07 g/kg, respectively; and those for croplands derived from forest are −6.03, −3.90, and −4.19 g/kg, respectively. With a longer cultivation age, the change in SOC and TN in old croplands derived from grassland was positive, with mean values of 0.89 and 0.09 g/kg, respectively, which were significantly higher than those of newly assarted croplands with mean changes of −0.48 and −0.06 ($p < 0.05$) (Figure 5e,f). In contrast, changes in SOC and TN in soils from old croplands derived from forested lands were still negative, with mean values of −2.91 and −0.25 g/kg, respectively (Figure 5g,h).

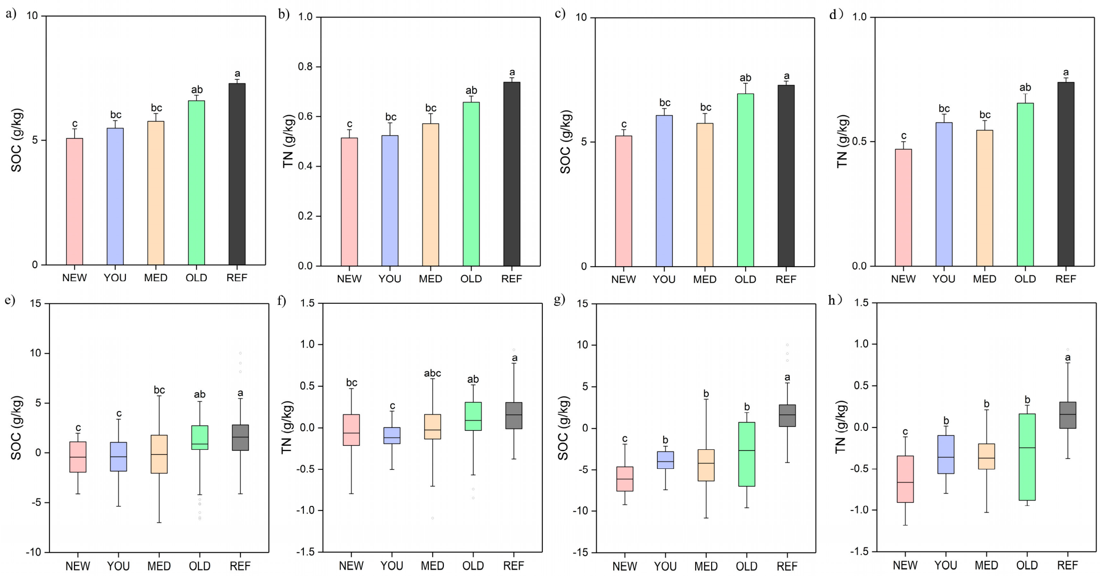

Figure 5. Impact of reclamation ages on soil C and N: (**a**) Soil organic carbon content in 2015 assarted from grassland, (**b**) Total nitrogen content in 2015 assarted from grassland, (**c**) Soil organic carbon content in 2015 assarted from forest, (**d**) Total nitrogen content in 2015 assarted from forest, (**e**) Change of soil organic carbon content assarted from grassland, (**f**) Change of total nitrogen content assarted from grassland, (**g**) Change of soil organic carbon content assarted from forest, (**h**) Change of total nitrogen content assarted from forest. NEW = newly assarted (1–5 years), YOU = young assarted (6–15 years), MED = medium assarted (16–25 years), OLD = old assarted (26–37 years), REF = referenced cropland assarted before 1978.

3.4. Effects of Land Reclamation History on Soil C:N Ratio

Compared to the difference in SOC and TN levels for different prior land uses, the C:N ratios showed opposite characteristics (Figure 6a). The C:N ratio in previously forested land (10.85) was significantly higher than where the prior land use was cropland or grassland (9.96 and 10.29, respectively). Comparing the changes with the three prior land uses in the past four decades, the C:N ratios showed non-significant variations ($p < 0.05$) (Figure 6b), of 0.05, 0.32, and −0.25 for sites with prior land use as cropland, grassland, and forest, respectively. The C:N ratio for sites with prior land use as cropland increased slightly, from 9.91 to 9.96 in two periods of ca. 1978 and 2015, with a non-significant change as indicated by the paired-samples *t*-test ($p < 0.05$). In contrast, the C:N ratio for soils from grassland sites increased from 9.97 to 10.29, and the ratio for forest sites decreased from 11.10 to 10.85.

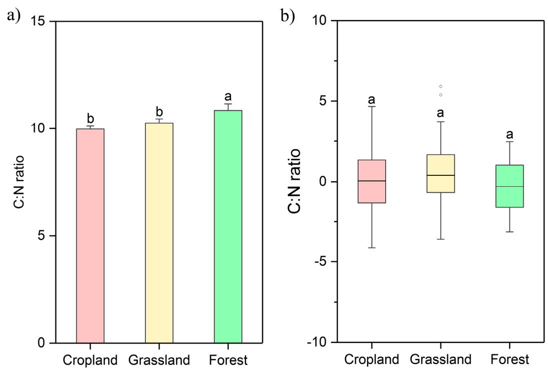

Figure 6. Soil C:N ratio for different prior land uses: (**a**) Values in 2015, (**b**) Changes from ca.1978 to 2015.

Although the SOC and TN changed significantly with increasing reclamation age, the change in soil C:N ratios shows different trends (Figure 7a,b). With an increase in the reclamation age, C:N ratios with prior land use as grassland significantly decreased from 10.79 in the newly asserted soils to 9.92 in the old asserted soils at a 95% confidence level (Figure 7a). The C:N ratio of old asserted soils was close to the C:N ratio of 9.96 in the reference cropland soils asserted prior to 1978. In contrast, relatively little variation, with a non-significant difference in C:N ratios, was found for soils from previously forested land (Figure 7b). C:N ratios from the previously forested land are 10.98, 11.01, 10.83, and 10.87 for the new, young, medium, and old asserted soils, respectively.

Changes in C:N ratios in two periods of ca. 1978 and 2015 were found to have relatively less variation (Figure 7c,d). The changes in C:N ratios for grassland tended to be positive, but that increased magnitude tended to diminish with increasing reclamation age (Figure 7c). The mean increase in C:N ratio was 0.89 for newly asserted soils, which is significantly higher than those in medium and old asserted soils, with mean values of 0.28 and 0.06 at a 95% confidence level, respectively. Moreover, for previously forested land, the change in the magnitude of the C:N ratios did not tend to vary significantly with an increase in the reclamation age, being −0.43, −0.21, −0.23, −0.15 for new, young, medium, and old asserted soils, respectively (Figure 7d).

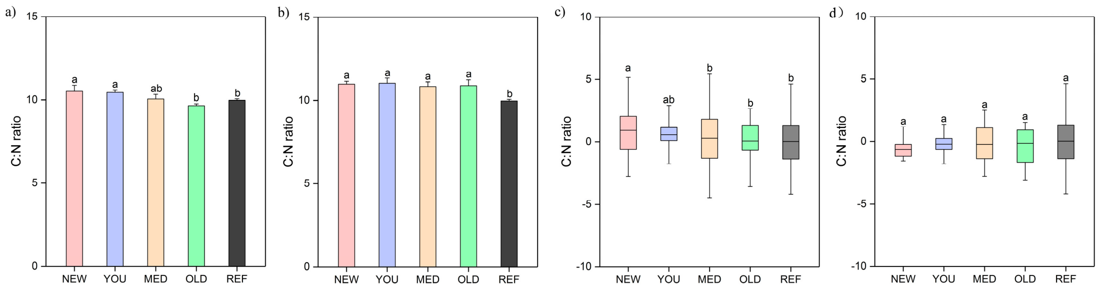

Figure 7. Impact of reclamation ages on soil C:N ratio: (**a**) Values in 2015 asserted from grassland, (**b**) values in 2015 asserted from forest, (**c**) Changes asserted from grassland, (**d**) Changes asserted from forest. NEW = newly asserted (1–5 years), YOU = young asserted (6–15 years), MED = medium asserted (16–25 years), OLD = old asserted (26–37 years), REF = referenced cropland asserted before 1978. NEW = newly asserted (1–5 years), YOU = young asserted (6–15 years), MED = medium asserted (16–25 years), OLD = old asserted (26–37 years), REF = referenced cropland asserted before 1978.

4. Discussion

Land use change history is closely related to soil C and N dynamics [1,29]. Numerous studies have explored the relationship between soil C and N, however, the balance between them and their coupling relationship remains uncertain [55]. This study investigated how large-scale cultivation has affected the SOC, TN, and C:N ratio. Using remote sensing and GIS techniques, this research identified the land use change history, which indicated that cropland has nearly doubled in typical regions of the Tarim Basin over the last four decades. According to different land reclamation histories, large-scale soil sampling was conducted to quantify the spatial variability of soil C and N. The multiple temporal changes of land use and soil proprieties using a repeated soil sampling strategy allowed the investigation of the time effects of reclamation on the soil C:N ratio [22,58]. Results found that the changes in soil C:N ratios are significantly different from the changes in SOC and TN under different land reclamation histories. This research can serve as a better reference for the soil C and N balance in ecological interactions and processes [59].

Land reclamation from grassland and forest in the study area resulted in SOC and TN loss during the initial reclamation stages, but these recovered with increasing reclamation age (Figure 5), which is in accordance with previous studies [18,60,61]. Anthropogenic disturbances frequently destroy the initial soil structure and accelerate the mineralization and decomposition process of SOM, which can intensify losses of C and N [62–64]. In the study area, the scarce water resources and low rate of bioaccumulation limited the growth of uncultivated grassland, primarily desert steppe [65], which resulted in a low level of initial SOC and TN [47,66]. After reclamation, the conditions of soil moisture and biomass growth improved in the arid regions; processes which can increase the above- and below-ground biomass, and result in soil C and N accumulation with increasing reclamation age [67]. The high-efficiency agricultural production in the Tarin Basin increases the crop yield with enhanced soil C and N input through crop residues and also enhances the anthropogenic mellowing process of soils to improve the soil structure and function, which further promotes the accumulation of soil C and N [68]. Improved agricultural practices, including applying organic manure, and conservative tillage measures are used in oasis agriculture, which enhances the soil C and N storage by providing water, organic amendments, and increased crop residue is returned to the soil [19,69,70].

C and N cycling are tightly coupled in ecosystems [71] and TN change in soils is generally assumed to follow variation in SOC, since both elements are bound into organic compounds [72,73]. The high correlation between these parameters was confirmed in this study. Land use change and management practices can alter C and N bio-geochemical cycling, and the change in soil C:N ratio can be used to determine the relative input and output of SOC and TN [23]. This study found that land reclamation history change had an opposite effect on C:N ratio, compared to the trends observed for SOC and TN. The magnitude of changes observed for C:N ratios were also smaller than those observed for SOC and TN (Figures 4–7). This implied that the change in C:N ratio is complex and does not show consistency with either C or N variations.

Different land use regulates C and N source availability, soil microbial activities, and therefore litter decomposition rates [74–76]. In general, forested soils had a higher C:N ratio, which is to be expected since trees take up more N and store it within their biomass rather than in the soil, and also, microbial decomposers of forested soils have higher C:N ratios than cultivated soils [3,25]. This resulted in a significant decrease in C:N ratios when forests were converted to croplands (Figure 6). In contrast, the conversion from grassland to cropland resulted in an increase in C:N ratios but a decrease in SOC and TN (Figures 4 and 6) in the initial reclamation process, indicating a greater loss of N compared to that of SOC. This may be partly explained by baseline effects [58]. In the Tarim Basin, the uncultivated grassland, primarily desert steppe, was limited by water resources and a lower rate of bioaccumulation [65], resulting in a lower level of initial SOC than TN [47,66]. Cultivation with adequate water supplies and fertilizer application would significantly improve soil physicochemical properties [77]. Land reclamation enhanced the C input of the litter returned to the soil and sped up nutrient cycling, resulting in an increase in the soil C:N ratio [23,78]. This, in turn, can result in relatively lower SOC losses, and more SOC accumulation compared to TN to increase the C:N ratio at the initial reclamation stage.

Moreover, as the age of cultivated soils increased, the different accumulation rates of C and N in the soils resulted in a change of C:N ratio [79]. With increasing reclamation age, it was found that the increases in C:N ratios for sites previously used as grassland tended to be less (Figure 7c). The increased N accumulation in the soil may be partly due to the overuse of N fertilizer, an effective way to increase crop biomass and yield, enhancing the N deposition in soils [80]. An experimental site receiving synthetic N fertilization over a 40–50 year period indicated a net decline in soil C [81]. Thus, the C:N ratio decreased according to the smaller change rate of SOC accumulation than N deposition. In addition, C:N ratios from previously forested land stayed relatively stable, indicating similar accumulation rates and a relative balance between SOC and TN. The variations in soil C:N ratio are not only caused by C and N inputs, but also by decomposition in soils [11]. Soil micro-organisms in the previously forested soils may enhance nitrogen-induced increases in the C uptake in the soil [82]. The underlying mechanisms of these variations and the longer time monitoring of C:N ratios require further study.

The global mean value of soil C:N ratios (0–30 cm) in cropland is 12.5 [2], which is much higher than the mean level for our study area (10.22), and the highest value for sites derived from forest (10.85). In addition, the C:N ratios for sites derived from grassland with low cropland ages tended to decrease with increasing reclamation age. A reduction in the soil C:N ratio could disrupt the balance between soil C and N cycling and cause loss of N through leaching and denitrification processes [1,22,83]. These results highlight the importance of effective agricultural management for the soils in the study area. Although the change in C:N ratios for cropland asserted before 1978 has remained relatively stable over the last four decades, it was found that over 10% of these C:N ratios were larger than 12.50, indicating that it is possible to increase the C:N ratio with the use of sustainable agricultural management. For example, no-tillage can increase soil C:N ratios as compared to the use of traditional pillow tillage [1,84,85]. In addition, using N fertilizer more efficiently and decreasing the overall amounts used would effectively decrease the input of N to soils [80,86]. Management efforts in the region should focus on how to enhance the accumulation of soil C and N, and also to better understand their coupling characteristics in order that N deposition might be matched with C sequestration [87].

5. Conclusions

To reveal the effect of land use changes on the balance of soil C and N, a purpose designed sampling strategy, along with the gathering of information on different land use change histories, was conducted in representative areas within the Tarim Basin. Based on the visual interpretation of data from remote sensing, cropland area nearly doubled in four decades in the study area, where over 70% of new cropland was asserted mainly from grasslands, a small fraction from forest, and few from other land use types. Using GIS spatial analysis techniques, three prior land uses and five types of cropland age were identified. The status and change in soil C, N, and their fractions were investigated under the different land reclamation histories. Results found that the prior land use significantly influenced the soil C and N. Meanwhile, the relative magnitudes of C:N ratios for the various land uses were,: forest > grassland > cropland. For soils assarted before 1978, SOC and TN significantly increased, but the C:N ratio increased slightly by 0.05 without a significant difference. An increase was found in the SOC, TN, and C:N ratio where prior land use was grassland, but these decreased in soils derived from forest between 1978 and 2015. The change in magnitudes of SOC and TN with a significant difference between three prior land uses is larger than that C:N ratio with a non-significant difference. SOC and TN decreased in the initial stage of the reclamation process and did not recover in the short term. After 30 years of cultivation, the decrease in initial SOC and TN values for land recovered from grassland had recovered. SOC and TN loss from land derived from forest, however, was not completely recovered even after 40 years of agricultural management. With increasing reclamation age, the increase in C:N ratios of soils from land derived from grassland was less, but remained relatively stable for land derived from forest. The findings in this study indicated near opposite effects of land reclamation history on the soil C and N and C:N ratios. Differences in the variation of the soil C:N ratio are determined by the relative input and output of SOC and TN under the different land reclamation processes and associated cultivation practices. Since the C:N ratios are much lower than the global average and show a decreasing trend in soils derived from grasslands, the application of sustainable agricultural management is suggested to increase not only SOC and TN, but also the C:N ratio, matching N deposition with the currently larger amount of carbon sequestration.

Supplementary Materials: The following are available online at http://www.mdpi.com/2073-4395/9/2/86/s1, Table S1: Landsat image description.

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

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