Contribution of cropland expansion to regional carbon stocks in an arid area of China: a case study in Xinjiang

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\textbf{ABSTRACT}
There has been an increasing number of studies on the potential effects of land-use change on the carbon (C) balance. However, few of these studies have focused on arid regions. Cropland in Xinjiang, a typical arid region in China, has expanded dramatically over the last 40 years. This study applied the Carbon Bookkeeping Model to estimate the changes in C stocks resulting from cropland expansion in Xinjiang from 1975 to 2015. The results showed that the area of cropland increased by a factor of 1.6. This increase was driven by advancements in agricultural technology and favorable agricultural policies. The increase in cropland area of 2.03 Mha ($M = 10^6$) was the result of the clearing of 4.09 Mha land for cropland and the conversion of 2.06 Mha cropland to other land cover types. The expansion in cropland resulted in substantial sequestration of C, with that in Xinjiang amounting to 94.24 Tg C (1Tg = 10\textsuperscript{12} g), accounting for 1.4% of the regional C stocks. Land clearing for cropland (LCC) had the greatest contribution to C sequestration in Xinjiang. The rate of increase in C density through LCC was 0.61 Mg C ha\textsuperscript{-1} a\textsuperscript{-1} and 1.54 Mg C ha\textsuperscript{-1} a\textsuperscript{-1} from 1975 to 2004 and 2005 to 2015, respectively. C sequestration due to cropland loss (CLO) of 29.40 Tg C was attributed to the expansion of built-up land and afforestation. Sustainable agricultural activities represented by large-scale clearing for cropland were a major C sink in Xinjiang. Therefore, sustainable management of cropland is essential for maintaining a high C density and preventing loss of C to the atmosphere through cropland abandonment in the future.

\textbf{KEYWORDS}
Cropland expansion; carbon stocks; Bookkeeping model; Arid region; Xinjiang

\textbf{Introduction}
Increasing concentrations of atmospheric greenhouse gases have contributed to climate change. However, obtaining a deeper understanding of the effect of anthropogenic activities on climate change has remained a challenge [1–3]. Land use/cover change (L UCC) is one of the human activities that have major effects on terrestrial ecosystem carbon (C) stocks and to C emissions [4, 5]. Thus, estimating the sources and sinks of C is essential for the construction of global and regional C budgets and for mitigating C emissions [6].

Ecosystem C stocks are the result of the CO\textsubscript{2} flow balance. However, L UCC often results in disruption of the ecosystem C flow balance, leading to the release of C to the atmosphere [6, 7]. Several new methods have been developed in recent decades for the estimation of the net terrestrial C flux [4, 8, 9]. Although previous studies showed that the net C flux of L UCC started before industrialization, the flux was particularly prevalent after 1850, ranging from 108 to 188 Pg C (1Pg = 10\textsuperscript{15} g), with the majority resulting from tropical deforestation [10–13]. Nevertheless, large uncertainties remain associated with the estimation of the C budget at both global and regional scales [14–17].

Previous studies on the terrestrial C flux mainly focused on tropical rain forests and temperate monsoon forests characterized by high C densities [17–20]. However, since drylands occupy a large proportion of the global land area, they play an increasingly important role in the C cycle [9, 21]. Nevertheless, the role of dryland ecosystems in the terrestrial C flux has received relatively little attention [22], highlighting the need for improved
understanding of the dynamics of the C cycle in arid regions [2, 23].

The northwest arid and semi-arid regions of China have witnessed significant LUCC over the past few decades [2]. In particular, Xinjiang, encompassing 52.88% of all arid land area in China, experienced cropland expansion as the primary form of LUCC [24, 25]. Xinjiang has experienced the greatest rate of cropland expansion in China due to the intensification of oasis agriculture [26]. The rate of land clearing for croplands (LCC) in Xinjiang since 2005 has been the highest since that during the "Great Leap Forward" [27]. Moreover, the acceleration of urbanization, ecological construction, and cropland abandonment has resulted in large-scale cropland loss (CLO) [26]. The intensification of agricultural activities has not only promoted the evolution and expansion of oases but also profoundly changed local C stocks [28–30]. It has generally been accepted that the clearing of the arid area in China has been of benefit to regional C stocks [29, 31, 32]. However, there remains a need for further quantification of the impact of cropland expansion on the C budget.

The present study aimed to investigate the contributions of LCC and CLO to C stocks in Xinjiang using a localized Bookkeeping Model that has been widely used to explore the effect of LUCC on the C balance [1, 5, 13, 33]. The present study characterized LCC and CLO and their driving factors in Xinjiang from 1975 to 2015 and clarified the contributions of LCC and CLO to regional C stocks based on the estimation of C fluxes. The objectives of the present study were to (1) improve understanding of the response of the C cycle to the expansion of oasis agriculture; (2) provide a policy reference for the rational development of regional agriculture targeted towards C-neutrality in arid areas.

**Study area**

Xinjiang in northwest China (34.4°N–48.2°N, 73.7°E–96.3°E) has an area of 1.66 M km², accounting for one-sixth of the total area of China. Xinjiang falls within the hinterland of the Eurasian continent and is bordered by eight countries. The landforms of Xinjiang comprise alternating mountains and basins within desert and oasis ecosystems. Xinjiang is bounded by the Altai and Kunlun mountains to the north and south, respectively, whereas the Tianshan Mountains divide Xinjiang down the middle into the Tarim and Junggar basins to the south and north, respectively.

Xinjiang falls within an extra-tropical continental climate zone characterized by high potential evaporation and low precipitation. The average annual precipitation and temperature of Northern Xinjiang range between 100–500 mm and 4–8 °C, respectively, whereas drier and hotter conditions occur in Southern Xinjiang of 20–100 mm and 10–13 °C, respectively [34]. The mountains of Xinjiang act as the headwaters of many rivers, leading to the formation of oases on the edges of the basins and in the river valleys. These oases, accounting for 5–8% of the land area of Xinjiang, are the most important agricultural areas in China and are inhabited by more than 80% of the population in Xinjiang.

**Materials and methods**

**Land use/cover change data**

The present study used two types of LUCC data for Xinjiang. The first type of LUCC data consisted of annual areas of cropland, LCC, and CLO. Cropland areas for the periods 1975–2008, 2017, and 2018 were obtained from a series of Xinjiang Statistical Yearbooks. All the yearbooks were compiled by the Statistic Bureau of Xinjiang Uygur Autonomous Region. The total net increment in cropland area is accurate for the period 2009–2016 according to cropland land area in 2008 and 2017. Missing equivalent data for 2009–2015 were predicted based on increasing trends in cropland area, sown area and the ratios of cropland area to sown area in 2008 and 2017. The ratio of cropland area to sown area was between 1.03–1.18 after 2000. The present study obtained the annual area of LCC from yearbooks and Fan et al. [35]. However, yearbooks and Fan et al. [35] did not report data from 2008 to 2015. Missing data were estimated as:

\[ R_{Si} = \frac{(S_i - S_{i-1} + FS_i)}{1 - \frac{1}{r}} \]  \hspace{1cm} (1)

In Eq. (1), \( R_{Si} \) is the LCC area in the \( i^{th} \) year, \( S_i \) is the cropland area in the \( i^{th} \) year, \( FS_i \) is the cropland area converted to forest in the \( i^{th} \) year, and \( r \) is the ratio of LCC to cropland abandonment (taken to be 99.59 and 13.87 for 2005–2009 and 2010–2015, respectively [24]).

The area of CLO was obtained by subtracting the net increase in the area of cropland from the newly cleared area:

\[ CS_i = R_{Si} - (S_i - S_{i-1}) \]  \hspace{1cm} (2)
In Eq. (2), $CS_i$ is the area of CLO in the $i^{th}$ year.

The second type of LUCC data were obtained from land use/cover maps for 1975, 2005, and 2015. These maps were provided by the Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences, and were produced by visual interpretation of Landsat Multi Spectral Scanner (MSS), Thematic Mapper (TM), and Operational Land Imager (OLI) images for 1975, 2005, and 2015, respectively. The land use/cover types represented in the data included forest, grassland, shrubland, cropland, water, built-up land, and barren land. Two periods of data were used to generate a land cover transition matrix. This matrix was then used to define the types of LCC and CLO. Annual clearing and loss area for each land cover type were then estimated by multiplying the area ratio of the corresponding conversion type by the annual area [1]. Within this process, particular attention was paid to built-up land, which was assumed to cover 33.75% and 66.25% of pervious and impervious surfaces, respectively based on the median green coverage rate in built-up land from 2006 to 2015 (https://data.stats.gov.cn/easyquery.htm?cn=E0103).

### Vegetation and soil organic carbon density

Information on vegetation carbon density (VCD) and soil organic carbon density (SOCD) were obtained from a dataset provided by Xu et al. [36]. This information was updated using field data obtained from the literature (see Appendix references). The growth stages of forest were divided into the categories of young, middle-aged, and mature forest according to the regulations for age-class and age-group divisions of main tree species (LY/T 2908–2017) published by the National Forestry and Grassland Administration. Grassland was divided into categories of desert steppe, typical steppe, and mountain steppe [22]. The mean VCD and SOCD at a depth of 1 m (Table 1) were calculated using 722 samples (see Appendix Tables S1 and S2) during which the impact of built-up land on C stocks was considered. Since the pervious surfaces were equally divided between forest and grassland [22], the VCD of pervious surface was calculated as the mean of those of mature deciduous broadleaf forest and grassland (Table 1).

#### Vegetation carbon oxidation rate

LCC was the major disturbance to land use/cover in the study area since the biomass of the preceding ecosystem was cleared during the process. During calculation of the C flux during LCC, a proportion of the ecosystem biomass was removed from the site and included in the estimates of C flux to the atmosphere. The remaining biomass was assumed to remain on-site, with biomass residues considered to form part of soil organic C. Removed biomass was allocated into three C pools with different retention times according to availabilities [38]: (1) immediately released C; (2) short-lived C; and (3) long-lived C. The present study identified the main uses of removed biomass based on investigations in the Manas River Basin, Ili River Basin, and Altay Region in Xinjiang from July to October 2011, including firewood, farm tools, and wood for furniture and building. Almost all firewood was depleted within 1 year, whereas C remained in farm tools and industrial wood over periods of 5 and 15 years, respectively. Table 2 shows the average proportions of apportionment

### Table 1. Carbon (C) density of different land cover types (Unit: kg C m$^{-2}$) for Xinjiang, China.

| Ecosystem type          | Vegetation C density | Soil organic C density |
|-------------------------|----------------------|------------------------|
|                         | Samples | Mean | SE | Samples | Mean | SE |
| Forest                  |         |      |    |         |      |    |
| Deciduous Broadleaf Forest |       |      |    |         |      |    |
| Young Forest (≤ 10 a)   | 33      | 2.13 | 0.14 | /       | /     | /  |
| Middle-Aged Forest (11–20 a) | 4  | 2.70 | 0.30 | /       | /     | /  |
| Mature Forest (21–30 a) | 24      | 5.85 | 0.35 | /       | /     | /  |
| Overall                 | 61      | 3.63 | 0.32 | 5       | 7.03  | 2.79|
| Coniferous Forest       |         |      |    |         |      |    |
| Young Forest (≤40 a)    | 4       | 2.26 | 1.29 | /       | /     | /  |
| Middle-Aged Forest (41–100 a) | 38 | 8.41 | 0.62 | /       | /     | /  |
| Mature Forest (≥ 101 a) | 85      | 15.71| 0.77 | /       | /     | /  |
| Overall                 | 127     | 13.10| 0.65 | 30      | 35.62 | 2.91|
| Grassland               |         |      |    |         |      |    |
| Desert Steppe           | 44      | 0.33 | 0.03 | 64      | 4.37 | 0.40 |
| Typical Steppe          | 24      | 0.48 | 0.04 | 32      | 7.99 | 0.79 |
| Mountain Steppe         | 53      | 0.62 | 0.05 | 43      | 18.19| 1.24 |
| Overall                 | 121     | 0.49 | 0.03 | 139     | 9.48 | 0.69 |
| Built-up land           |         |      |    |         |      |    |
| Impervious Surface      | /       | 0    | 0   | /       | 5.74*| 0.39*|
| Pervious Surface        | /       | 3.17*| 0.39*| 8       | 6.69*| 0.75*|
| Shrubland               | 130     | 0.32 | 0.03 | 14      | 4.37 | 0.51 |
| Barren land             | 9       | 0.08 | 0.03 | 8       | 2.93 | 0.34 |
| Cropland                | 16      | 0.75 | 0.05 | 62      | 6.23 | 0.39 |

*Density of soil organic C derived from Yan et al. [37], SE: standard error.

*Mean vegetation carbon density (VCD) of mature deciduous broadleaf forest and grassland.
of biomass and the associated durations required for C depletion after cropland clearing in Xinjiang.

### The carbon bookkeeping model

The present study used the Carbon Bookkeeping Model, a widely used statistical method, to identify the contributions of LCC and CLO to C stocks in the region [1, 4, 16, 39]. This model tracks the flux of C held in vegetation, soil, wood products removed from sites, and wood residues left on-site as a direct consequence of human activities [13, 39]. The model does not directly consider the C flux in ecosystems due to effects of environmental change (e.g. the concentration of CO₂ in the atmosphere, changes in climate, and N deposition) and due to factors not directly related to land use change [10, 13, 40].

The change in C density within the first few years after LUCC is a result of litter decay, vegetation recovery after artificial disturbance, and changes to soil organic C. These processes contributing to the losses or gains in C after disturbance were expressed as the VCD and SOCD response curves [1, 41]. Changes to C following disturbance and growth were obtained from published field investigations and included those in biomass and soil organic matter [13, 33]. The localized Carbon Bookkeeping Model was used to calculate the annual change in C resulting from LCC and CLO in Xinjiang. The present study derived the C density values of grassland and forest from the desert steppe and broadleaved deciduous forest, respectively since most of the croplands were converted from grey desert soil [42].

The Carbon Bookkeeping Model described the contributions of both LCC and CLO to regional C stocks. The annual per hectare changes in vegetation and soil following land-use changes were defined in the model (Table 3). The present study analyzed the annual area of LCC and CLO as well as the response curves of C density for corresponding LUCC types (Table 3). Finally, the annual changes in vegetation and soil organic C stocks were accumulated and the contributions of LCC and CLO to regional C stocks in the study area were estimated.

1. **The response of VCD and SOCD to LCC**

   The oxidation rates of litter biomass and removed biomass associated with LCC were obtained from survey data (Table 2). The model assumed the times required for SOCD to reach stability after the clearing of forest, shrubland, grassland, barren land, and built-up land to be 15 years [1], 20 years [33, 43], 20 years [43], 40 years [40], and 20 years, respectively. SOCD of forest, shrubland, grassland, barren land, and built-up land was assumed to experience the majority of change (80%) within the first 7 years [33], 10 years [33, 43], 10 years [33, 43], 20 years [33, 40], and 10 years, respectively (Table 3), whereas change stabilized in the later period.

2. **The response of VCD and SOCD to CLO**

   The times required for the recovery of biomass of forest, shrub, grassland, barren land, and built-up land were 25 years [44], 10 years [1, 33], 10 years [33, 43], 1 year, and 25 years, respectively (Table 3). The biomass values of young, middle-aged, and mature forests were considered for afforestation (broadleaved deciduous forest). The times required for C density to reach the average values of different stages were then estimated according to the stand age of most samples (Table 3). Within estimating the changes in SOCD, a constant rate of change was assumed after CLO and the times required for SOCD to a reach steady-state after the conversion of cropland to the forest, shrubland, grassland, barren land, and built-up land were taken to be 20 years, 30 years, 30 years, 40 years, and

### Table 2. Apportionment of carbon (C) and associated durations for C depleted after land clearing for cropland (LCC) in Xinjiang.

|          | Apportionment of vegetation C after land clearing for cropland | Proportion of vegetation C apportionment (%) | Duration required for C depletion (a) |
|----------|-----------------------------------------------------------------|---------------------------------------------|---------------------------------------|
| Forest   | Dead vegetation left in the soil                                | 17                                          | /                                     |
|          | Wood                                                             | 35                                          | 15                                    |
|          | Firewood                                                         | 42                                          | 1                                     |
|          | Farm tools                                                       | 6                                           | 5                                     |
| Shrubland| Dead vegetation left in the soil                                | 22                                          | /                                     |
|          | On-site burning                                                 | 13                                          | 1                                     |
|          | Firewood                                                         | 60                                          | 1                                     |
|          | Farm tools                                                       | 5                                           | 5                                     |
| Grassland| Dead vegetation left in the soil                                | 49                                          | /                                     |
|          | On-site burning                                                 | 42                                          | 1                                     |
|          | Firewood                                                         | 9                                           | 1                                     |

The model assumed the times required for SOCD to reach stability after the clearing of forest, shrubland, grassland, barren land, and built-up land to be 15 years [1], 20 years [33, 43], 20 years [43], 40 years [40], and 20 years, respectively. SOCD of forest, shrubland, grassland, barren land, and built-up land was assumed to experience the majority of change (80%) within the first 7 years [33], 10 years [33, 43], 10 years [33, 43], 20 years [33, 40], and 10 years, respectively (Table 3), whereas change stabilized in the later period.
30 years, respectively [1,33,40,43] (Table 3 and Figure 1).

Results

Characteristics of cropland change

Xinjiang Province experienced a significant expansion in cropland area by 2.03 Mha from 1975 to 2015. The changes in cropland between 1975 and 2015 can be divided into two stages (Figure 2): (1) the period of 1975–2004; and (2) the period of 2005–2015. The cropland area increased slightly with fluctuations during the first period (1975–2004) during which ~1.75 Mha of land was cleared for cropland and 1.53 Mha area of cropland was lost. During most years, the intensity of clearing exceeded that of CLO. Nonetheless, the area of cropland decreased continuously from 1980 to 1986 by a total of 0.15 Mha. The cropland area subsequently recovered and increased due to the increase in the clearing. As a result, the cropland area increased in 2004 by 0.22 Mha compared to that in 1975 to 3.36 Mha.

During the second period (2005–2015), large-scale LCC activities resulted in substantial increases in cropland area. The expansion of cropland area was also facilitated by improvements to agricultural technologies, such as water-saving irrigation technology and the construction of water conservancy facilities [24, 27]. The statistical data indicated that cropland area reached 5.18 Mha in 2015, a significant increase of 1.81 Mha compared to that in 2004. There was a considerable increase in the area of cropland cleared of 2.34 Mha. The maximum annual cleared area of 0.39 Mha occurred in 2008, accounting for 16.73% of the total between 2005 and 2015. In contrast to the considerable increase in LCC, the annual CLO was less and more stable, ranging between 0.04–0.06 Mha\(\text{a}^{-1}\) with a mean of 0.05 Mha\(\text{a}^{-1}\).

LCC maps based on Landsat images indicated the types of LCC and CLO during different periods (Figure 3). Grassland was the major source of land for LCC, particularly during 1975–2005, and accounted for 92.67% of all LCC. Barren land was the next highest contributor to land for LCC, with its contribution increasing by 10.10% during the second period compared to that in the first period.

Table 3. Parameters of the Carbon Bookkeeping Model within its application to Xinjiang, China.

|                          | Forest | Shrubland | Grassland | Barren land | Pervious surface | Impervious surface |
|--------------------------|--------|-----------|-----------|-------------|------------------|-------------------|
| Vegetation carbon (C) density of undisturbed ecosystems (Mg/ha) | 58.50  | 3.24      | 3.31      | 0.80        | 31.7             | /                 |
| Vegetation C density of crops (Mg/ha)                            | 7.54   | 7.54      | 7.54      | 7.54        | 7.54             | 7.54              |
| Vegetation C density of the recovering ecosystem for different growth stages (Mg/ha) | 21.31  | /         | /         | /           | /                | /                 |
| Young                    | 27.047 | /         | /         | /           | /                | /                 |
| Middle-aged              | 58.50  | 3.24      | 3.31      | 0.80        | 31.7             | /                 |
| The time required for the recovering ecosystem to reach a growth stage (a) | 10     | /         | /         | /           | /                | /                 |
| Young                    | 15     | /         | /         | /           | /                | /                 |
| Middle-aged              | 25     | 10        | 10        | 1           | 25               | /                 |
| Soil organic C density of undisturbed ecosystems (Mg/ha)          | 70.29  | 43.74     | 43.69     | 29.25       | 86.9             | 57.4              |
| Soil organic C density of recovered ecosystems (Mg/ha)            | 70.29  | 43.74     | 43.69     | 29.25       | 86.9             | 57.4              |
| Fraction of C in dead vegetation left in soil at time of clearing (%) | 0.17   | 0.22      | 0.49      | 0.49        | 0.18             | /                 |
| The fraction of C in vegetation assigned to different decay pools after clearing (%) | 0.42   | 0.13      | 0.51      | 0.51        | 0.43             | /                 |
| 1 (a)                    | 0.06   | 0.65      | /         | /           | 0.06             | /                 |
| 15 (a)                   | 0.35   | /         | /         | /           | 0.33             | /                 |
| Soil organic C density experiencing initial rapid change following clearing (Mg/ha) | 7.97   | 18.58     | 18.63     | 33.14       | 24.58            | 4.92              |
| Stable soil organic C density of the cultivated system (Mg/ha)    | 62.32  | 62.32     | 62.32     | 62.32       | 62.32            | 62.32             |
| The time required for initial rapid change in soil organic C following clearing (a) | 7      | 10        | 10        | 20          | 10               | 10                |
| Time required for C in soil to reach the maximum/minimum value during cultivation (a) | 15     | 20        | 20        | 40          | 20               | 20                |
| The time required for soil organic C density to reach recovery level in an abandoned system (a) | 20     | 30        | 30        | 40          | 30               | 30                |

30 years, respectively [1,33,40,43] (Table 3 and Figure 1).
proportion of cropland converted to built-up land decreased to 34.38% of CLO area in second period. The rate of cropland converted to the forest significantly exceeded 17% during the first period but decreased to 1.80% in the second period. However, the proportion of cropland converted to barren land increased by 2.37% during the second period.

**Contribution of cropland expansion to regional carbon stocks**

Cropland expansion in Xinjiang Province between 1975 and 2015 resulted in a C sink of up to 94.24 Tg C. LCC provided the dominant contribution to annual C sequestration before 1986, following which the positive effect of CLO began to emerge (Figure 4). Although LCC and CLO both contributed to C sequestration, they continued to show significant differences in the C transfer pattern.

LCC contributed to a net increase in regional C stocks of 71.50 Tg C (17.48 Mg C ha\(^{-1}\)). Soil organic C played a more important role than vegetation in regional C dynamics, accounting for 67.01% of the variation (Figure 4, Table 4). A comparison of the different types of clearing showed that C sequestration was enhanced by clearing of grassland, barren land, and shrubland, whereas the clearing of forest and built-up land resulted in releases of C (Figure 5). Grassland clearing through LCC had the most profound effect, increasing regional C stocks by 62.03 Tg C and accounting for 85.53% of C sequestered. The increases in C stocks resulting from the clearing of barren land and shrubland were 10.17 Tg C and 0.33 Tg C, respectively. Moreover, part of the increase in C stocks counteracted C emissions, whereas emissions resulting from the clearing of forest and built-up land were 0.98 Tg C and 0.04 Tg C, respectively.

C sequestration under CLO was 22.74 Tg C (11.07 Mg C ha\(^{-1}\)) and the increases in the C stocks of vegetation and soil were 20.96 Tg C (10.02 Mg C ha\(^{-1}\)) and 1.78 Tg C (0.87 Mg C ha\(^{-1}\)), respectively. There were negative annual increases in the C stock of vegetation during some years prior to 1985. However, the C stocks of vegetation began to increase due to rapid increases in forest biomass and woodland in built-up land (Figures 4 and 5). In contrast, C stocks within soil organic matter decreased from 2010 at a rate of 0.21 Mg C ha\(^{-1}\).

As shown in Figure 4 and Table 4, C stocks particularly in vegetation increased due to afforestation and the expansion of built-up area, while conversion of cropland to grassland, shrubland, and

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Figure 1. A map of Xinjiang, China showing the spatial distribution of major land use/cover types.
barren land caused carbon emission. The quantities of carbon released were $-22.28$ Tg C, $-7.12$ Tg C, $5.77$ Tg C, $0.03$ Tg C, and $0.86$ Tg C, respectively. Overall, the trend of annual increase in C stock through CLO was similar to that for the conversion of cropland to forest. This result could be attributed to the C density of vegetation and soil in forest far exceeding that in cropland ($\sim 58.93$ Mg ha$^{-1}$), although area of afforestation accounted for approximately $17.17\%$ and $1.80\%$ of CLO area during the first and second periods, respectively. Additionally, the releases of C resulting from the conversion of cropland to grassland, barren land, and shrubland were neutralized by the expansion of built-up land.

**Discussion**

**Driving forces of cropland expansion**

During the entire study period, cropland expansion was characterized by the development of oasis agriculture in Xinjiang. The significant differences in cropland expansion among the various stages could be attributed to agricultural policies and the improvements in agricultural technology. The expansion of agriculture generally resulted from...
Shifts in governmental policy between 1975–2005 [30]. The end of the cultural revolution in 1976 prompted a short-term recovery in cropland area. During the period of reform and opening up subsequent to 1978, the government of China implemented the household contract responsibility system. Nevertheless, the separation of ownership and usage rights of collective land was completed in 1987 [28]. The positive role of agricultural system reform was not significant during the period.

Table 4. Cumulative vegetation carbon (VC), soil organic carbon (SOC), and total carbon (TOTC) flux density (Mg C ha⁻¹) resulting from land clearing for cropland (LCC) and cropland loss (CLO) in Xinjiang, China. Positive values represent carbon sequestration, whereas negative values represent carbon emissions.

| Area (M ha) | LCC/CLO | LCC (Mg C ha⁻¹) | CLO (Mg C ha⁻¹) | LCC&A CLO TOTC (Mg C ha⁻¹) |
|------------|---------|----------------|----------------|---------------------------|
| 1975–2004  | 1.75/1.53 | 5.91           | 12.28          | 6.80/1.24 13.46          |
| 2005–2015  | 2.34/0.53 | 5.66           | 11.29          | 20.00/-0.21 17.47        |
| 1975–2015  | 4.09/2.06 | 5.77           | 11.71          | 15.20/0.87 15.33        |

Figure 4. Changes in the contributions of land clearing for cropland (LCC) and cropland loss (CLO) to vegetation carbon (VC) stock, soil organic carbon (SOC) stock, and total carbon (TOTC) stock in Xinjiang, China during 1975–2015.

Figure 5. Contributions of land clearing for cropland (LCC) and cropland loss (CLO) among different land cover types to total carbon (TOTC) stocks in Xinjiang, China from 1975 to 2015. B→C: built-up land to cropland; B→C: barren land to cropland; G→C: grassland to cropland; F→C: forest to cropland; S→C: shrubland to cropland; C→B’: cropland to built-up land; C→B: cropland to barren land; C→G: cropland to grassland; C→F: cropland to forest; C→S: cropland to shrubland.
of policy adjustment. Cropland area showed a continual decrease from 1980 to 1986 due to the expansion of built-up land, ecological construction, and the abandonment of unsuitable cropland [26, 27]. However, the significant increase in cropland area since 1987 attributed to restoration and the deepening of reform was driven by economic development, population growth, and improvements in irrigation technology. Consequently, the area of cropland of 3.36 M ha in 2004 exceeded that in 1975 and 1986 by factors of 1.06 and 1.10, respectively.

The rapid increase in cropland area occurred at an annual mean clearing area of 0.21 Mha a⁻¹ after 2005, the highest growth rate since the "Great Leap Forward". This remarkable growth rate could be attributed to three factors. Firstly, the large-scale water-saving drip irrigation under mulch technology not only increased crop production but also significantly improved water use efficiency [27, 28, 45]. Secondly, the government of China increased the attractiveness of agriculture by abolishing agricultural taxes and introducing direct agricultural subsidies in 2006. Lastly, many people have immigrated to Xinjiang due to the adoption of a Western development strategy since the late 1990s [46].

**Effect of cropland expansion on carbon stocks in the arid area**

LUCC has a significant impact on C stocks. The effect was established at different transfer directions and scales, as well as the carbon density of land-use types [6, 17]. Over the last decades, Xinjiang has experienced large-scale expansion in oasis agriculture, that was mainly based on the clearing of the desert ecosystems (e.g. desert steppe) restricted by natural conditions, whose carbon densities were considerably lower than those of cropland [31, 42]. Clearing of water-stressed desert ecosystems increases C sequestration, particularly that associated with soil organic matter. This C sequestration is increased by sufficient irrigation, fertilization, return of crop residues, and other management measures [32, 47]. The results of the present study showed that LCC increased C stocks by 71.50 Tg C. A higher average total C (TOTC) density increased rate of 1.54 Mg C ha⁻¹ a⁻¹, and was found to have occurred during 2005–2015. The lowest TOTC of 0.61 Mg C ha⁻¹ a⁻¹ was similar to the C sink (0.8 ± 1.6 Mg C ha⁻¹ a⁻¹) of the African savannah [48]. In contrast, the release of C resulting from deforestation for cropland was 39.83 Mg C ha⁻¹ during 1975–2015. This release in C was much lower than that of tropical, temperate, and boreal forests, which ranged from 135 Mg C ha⁻¹ to 150.75 Mg C ha⁻¹ [49]. This difference can be likely attributed to the low VCD of woodland (58.50 ± 5.47 Mg C ha⁻¹) in the arid region.

Macro policies and economic development of China have resulted in the main drivers of persistent CLO being ecological protection, expansion of construction land, and cropland abandonment [26]. The ecological protection measure of returning cropland to the forest has been shown to have significantly increased C absorption (22.28 Tg C) from 1975 to 2015 and having accounted for ~46.97% of afforestation in Xinjiang since 1961 [1]. Previous studies that relied on untested assumptions and lower SOCD of the impervious surface tended to underestimate the C storage of built-up land [50]. Recent studies have indicated the SOCD of pervious and impervious surfaces in the northern Tianshan urban cluster to be 86.9 ± 7.5 Mg ha⁻¹ and 57.4 ± 3.9 Mg ha⁻¹, respectively [37]. The VCD (10.70 Mg ha⁻¹) and SOCD (67.34 Mg ha⁻¹) of built-up land derived from pervious and impervious surfaces as well as area weights exceeded those of cropland. The results of the present study showed that the expansion of built-up land into cropland increased the regional C stock to ~7.12 Tg C. Overall, the change in cropland significantly enhanced regional C stocks (94.24 Tg C) by 2015, with the proportion of contribution to total regional C stock of 1.4% [22]. The results of the present study also showed a remarkable sequestration potential of 34.02 Tg C over the next 40 years, mainly since some time will be needed to reach a new C density balance after disturbance.

Maintaining a persistent increase in C stock within intensely managed ecosystems (e.g. cropland and planted forest) relies on sustainable management strategies to guide human activity [8, 51]. Although the application of drip irrigation technology improves water use efficiency and relieves local water shortages, actual water consumption by agriculture has exceeded the availability of water resources, thereby threatening the desert ecosystem around oases [27, 28]. Consequently, soil salinization resulting from drip irrigation and the overuse of chemical fertilizer is not conducive to C sequestration and agriculture development [51, 52]. Therefore, there is a need to reduce the demand in cropland area and to focus on
improving cropland management methods, such as methods for application of fertilizers and the crushing of straw before returning. These efforts can promote increases in C stock and cropland productivity in the arid area of China [3, 27, 29].

Uncertainties

The present study aimed to improve the accuracy of model estimation by using annual-scale data reflecting changes in farmland area based on coupling statistical data and LULC maps [53], localized C density parameters derived from published literature, and considering the time lag effect of cropland changes on regional C stock [54]. The estimation of C sequestration of LCC of 14.47 Tg C in Xinjiang from 1980 to 1995 is consistent with that of Zhang et al. [55] of 12 Tg C. In addition, mean annual C sequestration resulting from cropland expansion of 3.74 Tg C a\(^{-1}\) from 2006 to 2015, accounted for 6% of carbon sequestration (58 Tg C a\(^{-1}\)) resulting from LUCC in China during the corresponding period [13]. Nonetheless, some uncertainties may persist in the results of the present study. For example, some spatial heterogeneity exists in the C density of the ecosystem. Previous studies mainly focused on the northern part of Xinjiang thus fewer samples were available in southern Xinjiang. The present study was unable to reduce the uncertainty resulting from this spatial bias [56]. Secondly, C sequestration through grassland clearing for cropland may have been overestimated in the present study. This is because of desert steppe with a lower C density was considered the main type of clearing grassland for cropland. In addition, the model used in the present study considered the time lag effect of preceding period. These resulted in the estimate of C sequestration of 32.52 Tg C in the present study exceeding that by Zhang et al. [55] of 15 Tg C during 1995 to 2010 by a factor of 2. Thirdly, although previous studies have found that the clearing of desert land increased C density in the arid region [29, 31, 32, 42], less attention has been paid to the changes in deep SOCD over a long temporal scale [32, 43]. This may have increased the uncertainty in understanding the response curve of C density on C stock. Therefore, further research on changes in C density during LUCC is essential. Lastly, the present study did not estimate the contribution of C transfer between cropland and water on regional C stock due to limited and inconsistent data for changes in C density [4, 57, 58]. These uncertainties can be addressed by improving understanding of the mechanism of LUCC effects on C density in the future. This increase in understanding is very important for ecosystem management and optimization of land use structures to mitigate rising CO\(_2\) concentrations in dryland areas.

Conclusions

Xinjiang Province experienced large-scale LCC and CLO from 1975 to 2015 of 4.09 Mha and 2.06 Mha, respectively. The area of cropland in Xinjiang in 2015 exceeded that in 1975 by a factor of 1.65. The rapid expansion in cropland, particularly after 2005, was mainly driven by improvements in agricultural technology and favorable agricultural policies. The expansion of cropland was mainly due to the clearing of grassland (desert steppe) and barren land. Furthermore, the main drivers of CLO were conversion of cropland to grassland, expansion of built-up land, and afforestation.

The expansion of cropland in Xinjiang resulted in the C sequestration of 94.24 Tg C (15.33 Mg C ha\(^{-1}\)). The clearing of grassland, shrubland and barren land played positive and important roles in increasing regional C stock, with TOTC sequestered of 72.52 Tg C. The clearing of forest and built-up land for cropland resulted in the release of 1.03 Tg C to the atmosphere, The average increase in C sequestration was 17.48 Mg C ha\(^{-1}\). Meanwhile, conversion of cropland to forest and built-up land increased C stock by 29.40 Tg C (11.07 Mg C ha\(^{-1}\)). The conversion of cropland to grassland and bare land was the main driver of the release of 6.66 Tg C to the atmosphere, accounting for \(~86.63\%\) of all C released by changes in cropland. Overall, reasonable and sustainable agricultural practices can promote social development as well as increase the C sequestration potential of arid areas in the future.

Disclosure statement

No potential competing interest was reported by the authors.

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Data availability statement

The green coverage rates in built-up land data were derived from the following resources available in the public domain: https://data.stats.gov.cn/easyquery.htm?cn=E0103; “A dataset of carbon density in Chinese terrestrial ecosystems (2010s)” are openly available in [Science Data Bank] at http://doi.org/10.11922/sciencedb.603, reference number [36]. The “vegetation carbon oxidation rate” and “VCD and SOCD of major land use/cover types” are available within the article and its supplementary materials, respectively. Annual areas of cropland change and land use/cover maps for 1975, 2005, and 2015 are available from the corresponding author, [G. Luo], upon reasonable request.

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