Do land use change and check-dam construction affect a real estimate of soil carbon and nitrogen stocks on the Loess Plateau of China?

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A R T I C L E   I N F O

Article history:
Received 2 September 2016
Received in revised form 20 January 2017
Accepted 29 January 2017

Keywords:
Land use change
Check-dam systems
Soil organic carbon
Total nitrogen
Enrichment ratios
Soil erosion

A B S T R A C T

Land use change and check-dam construction have been widely considered as the major measures to reduce soil and water loss. However, whether catchments behave as sources or sinks of soil carbon and nitrogen based on the combined performance of land use change and check-dam construction in sub-catchment systems are still poorly known. To quantitatively assess the effect of land use change and check-dam construction on soil organic carbon (SOC) and total soil nitrogen (TSN) stocks, and to explore the dominant factor influencing SOC and TSN sequestration potential, three sub-catchments controlled by check-dams were selected in the small catchment on the loess plateau of China. The SOC and TSN content and soil physio-chemical properties were analyzed under different land use types (farmland, grassland, shrubland, forestland, and check-dam land). Results clearly showed that the conversion from farmland to grassland and forestland induced an increase of SOC and TSN (1.32-fold C and 1.36-fold N increase in grassland and 1.24-fold C and 1.20-fold N increase in forestland, respectively). Comparing sediments to the corresponding source soil, the average enrichment ratios (ER) for SOC and TSN in sediments trapped behind check-dams were lower than 1 (0.56 ± 0.10 and 0.65 ± 0.12, respectively), and check-dam construction induced a net C and N loss (19.38% and 10.61%, respectively). The amount of SOC and TSN in three sub-catchments showed a significant positive correlation with the controlled watershed area (P < 0.05). High proportion of forestland and years after construction contributed positively to SOC and TSN stocks per unit area in check-dam (P < 0.05), indicating that the controlled watershed area, forestland fraction, and years after construction other than soil erosion were also the dominant influencing factors to affect carbon and nitrogen sequestration potential. The results indicated that, although erosion-induced soils and associated SOC and TSN were redistributed at the landscape scale, land use change and check-dam construction might still cause the catchment to behave as soil C and N sinks within the soil erosion subsystem since the 1990s.

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1. Introduction

The carbon (C) and nitrogen (N) cycles in terrestrial ecosystems have gained increasing attention over the past decades because of their oxides (i.e., CO2, N2O) contributing to the aggravation of global warming, air pollution, eutrophication, diversity decline and water quality deterioration (Mellilo and Morriseau, 2002; Fu et al., 2010; Chen et al., 2015). Soil erosion is a pivotal process influencing terrestrial C and N cycling (Lal, 2003; Ma et al., 2016a,b; Li et al., 2017). Quinton et al. (2010) have estimated that topsoil is laterally redistributed due to soil erosion at the rate of 28 Pg per year (1 Pg = 1015 g), leading to approximately 0.5 Pg yr−1 of soil carbon being mobilized globally. However, the role of C and N cycles induced by soil erosion is still a great controversy within the scientific community (Zhang et al., 2006), resulting from the discrepancy on whether soil erosion behaves as a source or a sink of soil carbon.

Abbreviations: SOC, soil organic carbon; TSN, total soil nitrogen; AG, artificial grass; RP, Robinia pseudoacacia; PS, Prunus sibirica; PD, Populus davidiana; FAL, fallow CD check-dam; BD, bulk density; SMC, soil moisture content.

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http://dx.doi.org/10.1016/j.ecoleng.2017.01.036
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and nitrogen (Lal, 2003; Boix-Fayos et al., 2009). Therefore, understanding the effect of soil erosion on the C balance in terrestrial ecosystems is of great importance for assessing the C flux between the soil and the atmosphere and will help a better understanding on the feedbacks within the global C cycle (Zhang et al., 2013b; Wei et al., 2014).

Land use change and check-dam construction, as the commonly used biological and engineering measures to control water and soil loss, have already significantly impacted the biogeochemical cycles of carbon and nitrogen in terrestrial ecosystems by changing soil properties, above- and below-ground biomass, and soil erosion (Guo and Gifford, 2002; Boix-Fayos et al., 2009; Li et al., 2012). Previous studies had demonstrated that the global estimate of SOC ranged from 684 to 724 Pg of C in the upper 30 cm, 1462–1548 Pg of C in the upper 100 cm, and 2376–2456 Pg of C in the upper 200 cm (Batjes, 1996). However, soils lost 40–90 Pg C globally through cultivation and disturbance, with current rates of C loss due to land use change of approximately 1.6 ± 0.8 Pg C yr−1 (Smith, 2008) and N2O emissions of 6.0 Tg yr−1 from natural soils and 4.2 Tg yr−1 from agricultural soils (Saikawa et al., 2014). Nevertheless, check-dam systems might retain massive SOC (42.3 million tons) with a high spatial variability, which was equal to approximately 1.48% of the SOC stored in the 0–40 cm soil layer across the whole Loess Plateau (Lü et al., 2012).

The Loess Plateau in China, characterized as mountainous with extremely complex topography and an annual average soil loss of 50–100 Mg ha−1, is considered as one of the most severely eroded areas in the world (Li et al., 2008; Zhao et al., 2013). To control soil and water loss effectively on the Loess Plateau, a series of ecological programmes were carried out in the last few decades, consisting of terracing, afforestation, natural rehabilitation, and check-dam construction (Zhao et al., 2013). Consequently, the magnitude and variability of the runoff and sediment discharge in the lower reaches of the Yellow River have apparently been decreased (Zhou et al., 2004; Zhao et al., 2013).

Check-dam systems in mountain streams have been widely considered as the major measure to control soil erosion and other environmental problems where afforestation methods alone were not successful due to the arid climate and barren soils (Zhou et al., 2004). Because of the transportation of sediment and runoff accompanied by the loss of nutrients (Liu and Xing, 2012), a real estimate of soil C and N by check-dam retention is of vital importance to accurately evaluate soil quality and biogeochemical cycles of carbon and nitrogen in terrestrial ecosystems. It is well known that changes in land use on SOC and TN sequestration have been thoroughly explored (Fu et al., 2010; Guo and Gifford, 2002; Boix-Fayos et al., 2009; Li et al., 2012; Aweke et al., 2014; Zhang et al., 2013a), but an integrated evaluation of the effectiveness and impacts of check-dams combined with afforestation and other land use changes on soil organic carbon and nitrogen stocks is lacking at the small catchment scale, especially when it involves the soil erosion subsystem (Boix-Fayos et al., 2009; Li et al., 2012).

Hence, we hypothesized that in a small watershed of the Loess Plateau: (1) land use change and check-dam construction will have a great influence on soil organic carbon and nitrogen stocks and (2) soil conditions and the main characteristic of sub-catchments will dominate carbon and nitrogen sequestration potential. As an extension of our previous studies, the objectives of the study are (1) to assess the combined performance of land use change (i.e., conversion from farmland to forest, shrubland and grassland) and check-dam construction on soil-eroded C and N stocks, and (2) to explore the dominant factors influencing C and N sequestration potential at the sub-catchment scale in the context of typical land use changes and check-dam construction in the loess gully and semi-arid conditions.

2. Materials and methods
2.1. Study region
The present study was conducted at the Qiaozigou watershed (2.45 km²) in the loess hilly–gully region of the Loess Plateau near Tianshui City, Gansu Province, China (105° 43′ E, 34° 36′ N). A pair of adjacent catchments (Qiaozigou East and Qiaozigou West) was developed within the Luoyugou watershed, which itself is within the Xihe River watershed in the Weihe river system (Fig. 1). The climate is semi-arid and continental, with a mean annual temperature of 10.7 °C and an average annual precipitation of 542.5 mm (Liu et al., 2017). The precipitation occurs in the form of intense, short-duration rainstorms between June and September, with large inter-annual and annual variations. The main soil type distributed is black cinnamonic soil, followed by rhogosol such as the loess black-brown soils (Zhou et al., 2012). The Qiaozigou East and Qiaozigou West watershed, which are located on the east side and west side of the Qiaozigou watershed, have similar soil and geomorphologic conditions (Fig. 1). In this catchment, the primary land use is cropland. Many of the original forests are remained, which are concentrated on the upper part of this catchment and only a few of grassland and abandoned land are found (Fig. 2). Since the implementation of the “Grain for Green” programme in 1999, lots of ecological programmes, including check-dam construction and the planting of
grasses (species like Medicago sativa), forests (e.g., like Robinia pseudoacacia and Populus davidiana), and shrubs (Ulmus spumilia and Prunus sibirica) in farmland, have been conducted in Qiaozi East to control soil erosion and other environmental problems. In comparison, the Qiaozi West Watershed is without management. By 2000, the vegetation coverage and the conservation area had covered 39.9% and 55.7% in Qiaozi East watershed, and 22 check-dams had been constructed in this area since the 1990s, with the average mixing depth of sediment deposited up to 2–3 m. In this study, check dam 15 (upper), 11 (middle), and 18 (lower) were chosen as the representative sites to study the combined performance of land use change and check dam construction on SOC and TSN stocks at the catchment scale (Fig. 2).

2.2. Data acquisition

The data were obtained from soil samples collected at eroding and depositional sites in three sub-catchments (upper, middle, and lower slope positions in the studied catchment), which were evenly distributed from upstream to downstream within the Qiaozi East catchment and have slightly different sizes and morphological characteristics (Table 1). Three duplicates were established for each of the soil samples, and location of each sampling site was also recorded in the field with a GPS. The samples were separately collected from 5 layers at the depth of 1 m, with 20 cm increments under each land-use type [Artificial grass (AG), Robinia pseudoacacia (RP), Prunus sibirica (PS), Populus davidiana (PD), Follow (FAL)] at eroding sites, and 10 layers at the depth of 2 m, with 20 cm increments in the sediment behind check-dams at depositional sites within the catchment area of each studied check-dam. Soil profiles with identical depth intervals of 100 cm (various land use types) and 200 cm (each check-dam) were dug to estimate the bulk density by using the soil cores (i.e., 100 cm³ volume stainless steel tubes). Prior to laboratory analysis, visible root residues and stones were removed manually from the soil samples. The samples were air-dried at room temperature, gently ground and passed through a 2-mm sieve to determine soil texture and pH. They were then passed through a 0.25 mm mesh to determine SOC and TSN. Soil pH was determined using HI 3221 pH metre with a soil–water ratio of 1:2.5 (Hanna Instruments Inc., USA). The soil bulk density (Mg m⁻³) of the different soil layers was measured by the volumetric ring method (Carter, 1993). Simultaneously, soil moisture content (SMC) was determined gravimetrically by oven drying the whole soil sample at 105 °C for 48 h to calculate the dry soil bulk density. The SOC and TSN contents were determined with the dichromate oxidation method (Nelson and Sommers, 1982) and the modified Kjeldahl method (Liu et al., 1996). Soil texture was analyzed using a Laser particle size analyser (Mastersizer 2000, Marlvern, Ltd., UK).

2.3. Data calculation

The SOC and TSN stocks (Mg ha⁻¹) were calculated using the following equations (Chen et al., 2007; Li et al., 2017):

\[
TSOC = \sum_{i=1}^{n} \text{SOC}_i \times B_i \times D_i \times 10^{-1}
\]

\[
TSN = \sum_{i=1}^{n} \text{TN}_i \times B_i \times D_i \times 10^{-1}
\]

where \( \text{SOC}_i \) is the SOC content on the ith layer (g kg⁻¹); \( \text{TN}_i \) is the TN content on the ith layer (g kg⁻¹); and \( B_i, D_i \) represent the bulk density (Mg m⁻³) and soil depth (m) of the ith layer, respectively.

The total SOC and TSN storage in each sub-catchment are calculated as follows:

\[
\text{SOC}_{T} = \sum_{i=1}^{n} \frac{\text{SOC}_{mi} \times S_i}{\sum_{i=1}^{n} S_i} \times S_r
\]

\[
\text{TSN}_{T} = \sum_{i=1}^{n} \frac{\text{TSN}_{mi} \times S_i}{\sum_{i=1}^{n} S_i} \times S_r
\]

where \( \text{SOC}_{T} (\text{TSN}_{T}) \) represents the total SOC (TSN) storage in the study area (kg); \( \text{SOC}_{mi} (\text{TSN}_{mi}) \) is SOC (TSN) mass per unit surface area in the ith class (kg m⁻²); \( S_i \) is the area of the ith class (m²); \( S_r \) is the reference area (m²); and \( n \) is the number of the classes.

2.4. Statistical analyses

All statistical tests were carried out using SPSS version 18.0 (SPSS Inc., Chicago, IL, USA). The soil physico-chemical properties (BD, pH, sand, silt, clay, SMC, SOC, TSN, and C:N ratio) were treated with a mean ± standard deviation and a coefficient of variation in all soil samples. Significant differences in SOC and TSN contents among different depths were evaluated at the 0.05 level using the least significant differences (LSD). Spearman analysis was also used to perform correlation among the soil physico-chemical variables, the characteristics of sub-catchments, and the SOC (TSN) content and stock.

3. Results

3.1. Changes in SOC and TSN following land use changes at eroding site

The SOC and TSN contents and stocks for different land use types were identified in the Qiaozi East catchment (Tables 2 and 3). The SOC content varied with soil depth and land use type. For all land uses, SOC and TSN were significantly greater in the 0–20 cm soil layer than those in the deep soil layer (20–100 cm). Among the land use types, the RP showed significantly greater SOC and TSN in the 0–60 cm soil layer compared with AG, PS, and PD. The average amounts of SOC and TSN stocks varied with land-use types in the 0–20 cm layers (16.2–26.7 Mg Ca ha⁻¹; 2.3–3.0 Mg N ha⁻¹, respectively) and in the 0–100 cm layers (58.6–83.6 Mg Ca ha⁻¹; 7.4–10.4 Mg N ha⁻¹, respectively). The SOC and TSN stocks were highest in the RP soils and lowest in the PS soils (26.7 ± 0.6 and 3.0 ± 0.3 Mg Ca ha⁻¹; 16.2 ± 1.4 and 2.4 ± 0.5 Mg N ha⁻¹, respectively) in the surface soil layer (0–20 cm). Compared with FAL, the stock of SOC (TSN) in the 0–20 cm soil layer showed a 1.32-fold (1.36-fold) increase in AG, a 1.54-fold (1.36-fold) increase in RP, a 0.93-fold (1.09-fold) increase in PS, and a 1.24-fold (1.14-fold) increase in PD, respectively. In general, the changes in SOC and TSN following the conversion of land use experienced a net gain after vegetation restoration.

3.2. SOC and TSN buried in sediments retained by check-dams at deposition site

The SOC and TSN buried in sediments deposited behind check-dams were shown at the different sampling depths (Fig. 3). The SOC content in sediments varied from 1.83 to 7.37 g kg⁻¹, with an average of 3.71 g kg⁻¹ and TSN content varied from 0.27 to 0.95 g kg⁻¹, with an average of 0.54 g kg⁻¹. For each check-dam, substantial differences in SOC and TSN depth variation were observed. Check-dam 11 showed a higher SOC and TSN depth compared to check-dams 15 and 18. The contents of SOC and TSN in sediments displayed a decreasing trend as soil depth increased, accompanied by a large fluctuation. The sediments retained by check-dams 11, 15 and 18 showed a low coefficient of variation of SOC (0.24, 0.23, and 0.25, respectively) and TSN (0.22, 0.22, and 0.18, respectively) depth. The SOC exhibited significantly negative correlation with BD and pH and a positive correlation with silt, SWC, and C:N ratio (Table 4). The relevance of TSN was similar to SOC depth in sediments retained by...
Table 1
Main characteristics of the three selected subcatchments for detailed soil C and N erosion studies.

<table>
<thead>
<tr>
<th>Check-dam (location)</th>
<th>Subcatchment area (ha)</th>
<th>Years after construction (a)</th>
<th>BD (Mg m⁻²)</th>
<th>pH</th>
<th>SMC (%)</th>
<th>Soil texture (%)</th>
<th>Land use (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15° (upper)</td>
<td>3.54</td>
<td>10</td>
<td>1.48 ± 0.03</td>
<td>8.29 ± 0.10</td>
<td>18.18 ± 0.84</td>
<td>24.24 ± 1.60</td>
<td>16.10% 24.29% 52.54% 1.13%</td>
</tr>
<tr>
<td>11° (middle)</td>
<td>0.29</td>
<td>23</td>
<td>1.49 ± 0.02</td>
<td>8.27 ± 0.07</td>
<td>19.20 ± 2.05</td>
<td>24.26 ± 1.02</td>
<td>68.85 ± 1.26 6.72 ± 0.57</td>
</tr>
<tr>
<td>18° (lower)</td>
<td>0.84</td>
<td>10</td>
<td>1.47 ± 0.04</td>
<td>8.20 ± 0.09</td>
<td>16.55 ± 2.83</td>
<td>28.91 ± 2.60</td>
<td>66.39 ± 1.71 4.66 ± 1.39 66.67% 11.90% 7.14% 3.57%</td>
</tr>
</tbody>
</table>

The values represent as mean values ± standard deviation. BD, soil bulk density; SMC, soil moisture content; DOC, dissolved organic carbon; forest, shrub, and grass represented forestland, shrubland, and grassland, respectively; 15°, 11°, 18° represented the serial number of check dam in different slope positions.

Table 2
Content and stock of soil organic carbon (SOC) at different soil depths for artificial grass (AG), Robinia pseudoacacia (RP), Prunus sibirica (PS), Populus davidiana (PD), and Fallow (FAL).

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Content (g kg⁻¹)</th>
<th>AG</th>
<th>RP</th>
<th>PS</th>
<th>PD</th>
<th>FAL (reference)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0–20</td>
<td></td>
<td>8.33 ± 0.10 a</td>
<td>11.24 ± 0.26 a</td>
<td>7.13 ± 0.06 a</td>
<td>9.36 ± 1.18 a</td>
<td>7.63 ± 0.92 a</td>
</tr>
<tr>
<td>20–40</td>
<td></td>
<td>4.98 ± 0.76 b</td>
<td>5.65 ± 0.83 b</td>
<td>4.55 ± 0.09 b</td>
<td>3.59 ± 0.13 b</td>
<td>4.25 ± 0.94 b</td>
</tr>
<tr>
<td>40–60</td>
<td></td>
<td>4.38 ± 0.42 b</td>
<td>4.51 ± 0.83 c</td>
<td>4.05 ± 0.07 b</td>
<td>2.86 ± 0.59 b</td>
<td>4.26 ± 0.32 b</td>
</tr>
<tr>
<td>60–80</td>
<td></td>
<td>4.14 ± 0.58 b</td>
<td>4.12 ± 0.43 c</td>
<td>3.83 ± 0.06 b</td>
<td>2.60 ± 0.49 b</td>
<td>3.45 ± 0.67 b</td>
</tr>
<tr>
<td>80–100</td>
<td></td>
<td>4.15 ± 1.62 b</td>
<td>4.06 ± 0.48 c</td>
<td>3.88 ± 0.08 b</td>
<td>3.40 ± 0.46 b</td>
<td>3.39 ± 0.55 b</td>
</tr>
<tr>
<td>Stock (Mg Ch⁻¹)</td>
<td></td>
<td>22.8 ± 2.8 a</td>
<td>26.7 ± 0.6 b</td>
<td>16.2 ± 1.4 a</td>
<td>21.4 ± 3.7 a</td>
<td>17.3 ± 2.4 a</td>
</tr>
<tr>
<td>0–100</td>
<td></td>
<td>77.2 ± 4.9 a</td>
<td>83.6 ± 7.8 a</td>
<td>64.9 ± 8.5 a</td>
<td>58.6 ± 10.8 a</td>
<td>76.0 ± 8.2 a</td>
</tr>
</tbody>
</table>

The values represent as mean values ± standard deviation, the different letters indicate significant difference among the depths means at P<0.05.

Table 3
Content and stock of total soil nitrogen (TSN) at different soil depths for artificial grass (AG), Robinia pseudoacacia (RP), Prunus sibirica (PS), Populus davidiana (PD), and Fallow (FAL).

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Content (g kg⁻¹)</th>
<th>AG</th>
<th>RP</th>
<th>PS</th>
<th>PD</th>
<th>FAL (reference)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0–20</td>
<td></td>
<td>1.02 ± 0.18 a</td>
<td>1.34 ± 0.13 a</td>
<td>0.99 ± 0.01 a</td>
<td>1.02 ± 0.15 a</td>
<td>0.99 ± 0.13 a</td>
</tr>
<tr>
<td>20–40</td>
<td></td>
<td>0.67 ± 0.14 b</td>
<td>0.73 ± 0.13 b</td>
<td>0.71 ± 0.01 b</td>
<td>0.49 ± 0.05 b</td>
<td>0.59 ± 0.12 b</td>
</tr>
<tr>
<td>40–60</td>
<td></td>
<td>0.58 ± 0.06 b</td>
<td>0.59 ± 0.14 bc</td>
<td>0.57 ± 0.01 bc</td>
<td>0.37 ± 0.07 b</td>
<td>0.55 ± 0.05 b</td>
</tr>
<tr>
<td>60–80</td>
<td></td>
<td>0.57 ± 0.05 b</td>
<td>0.55 ± 0.08 c</td>
<td>0.54 ± 0.01 bc</td>
<td>0.41 ± 0.05 b</td>
<td>0.49 ± 0.10 b</td>
</tr>
<tr>
<td>80–100</td>
<td></td>
<td>0.56 ± 0.15 b</td>
<td>0.52 ± 0.06 c</td>
<td>0.55 ± 0.01 c</td>
<td>0.42 ± 0.04 b</td>
<td>0.45 ± 0.09 b</td>
</tr>
<tr>
<td>Stock (Mg N ha⁻¹)</td>
<td></td>
<td>3.0 ± 0.8</td>
<td>3.0 ± 0.3</td>
<td>2.4 ± 0.5</td>
<td>2.5 ± 0.2</td>
<td>2.2 ± 0.4</td>
</tr>
<tr>
<td>0–100</td>
<td></td>
<td>10.4 ± 1.1</td>
<td>10.4 ± 1.4</td>
<td>7.4 ± 1.3</td>
<td>9.3 ± 1.0</td>
<td>9.5 ± 1.2</td>
</tr>
</tbody>
</table>

The values represent as mean values ± standard deviation. The different letters indicate significant difference among the depths means at P<0.05.

Fig. 3. The SOC and TSN contents at different soil depth intervals in sediments retained by check-dam. The error bars represent the standard deviation of the mean (n = 3).

Check-dams, indicating that soil property was a major influencing factor on soil C and N sequestration.

The enrichment ratios (ER) for SOC and TSN contents, bulk density and texture variables in the 0–20 cm soil layer are shown in Table 5. The ER varied between 0.45 and 0.73, with an average of 0.56 ± 0.10 for SOC content and between 0.49 and 0.78, with an average of 0.65 ± 0.12 for TSN content. The sediments were slightly enriched in clay and silt particles (1.84 ± 0.43 and 1.01 ± 0.02, respectively). No significant correlations were found between the ER for SOC or TSN and soil texture variables in the surface soil layer (P > 0.05, n = 3). Check-dam 11 showed a higher enrichment ratio of SOC and TSN than that of check-dams 15 and 18, and the lowest enrichment ratios for SOC (0.73) and the highest for BD (1.12) were also found in check-dam 11 (Table 5).
Table 4
Pearson correlation coefficients between SOC (TSN) content and physico-chemical variables at the deposition site.

<table>
<thead>
<tr>
<th></th>
<th>BD</th>
<th>pH</th>
<th>Clay</th>
<th>Silt</th>
<th>Sand</th>
<th>SMC</th>
<th>C/N ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>SOC content</td>
<td>−0.834</td>
<td>−0.845</td>
<td>−0.710</td>
<td>0.780</td>
<td>0.549</td>
<td>0.774</td>
<td>0.779</td>
</tr>
<tr>
<td>TSN content</td>
<td>−0.792</td>
<td>−0.889</td>
<td>−0.675</td>
<td>0.728</td>
<td>0.500</td>
<td>0.694</td>
<td>0.798</td>
</tr>
</tbody>
</table>

SOC, soil organic carbon; TSN, total soil nitrogen; BD, bulk density; SWC, soil moisture content.

Correlation is significant at the 0.05 level (2-tailed).

Correlation is significant at the 0.01 level (2-tailed).

The stock of SOC (TSN) in sediments retained by check-dams in the superficial soil layer (0–20 cm) were 21.1 ± 2.3 Mg Ch⁻¹ (2.7 ± 0.3 Mg N ha⁻¹) in check-dam 11, 10.2 ± 0.6 Mg Ch⁻¹ (1.5 ± 0.1 Mg N ha⁻¹) in check-dam 15, and 11.7 ± 0.3 Mg Ch⁻¹ (1.7 ± 0.1 Mg N ha⁻¹), respectively. Compared with PAL, the stock of SOC (TSN) buried in sediments deposited behind check-dams represented a gain of 22.0% (22.72%) in check-dam 11, a decrease of 41.04% (31.82%) in check-dam 15, and losses of 39.09% (22.73%) in check-dam 18 (Table 6).

In general, although construction of check-dam systems might intercept massive sediment and retain a high proportion of the carbon and nitrogen behind check-dams, it experienced a net loss of carbon and nitrogen compared with the corresponding source soil at the sub-catchment scale.

3.3. SOC and TSN stores at the sub-catchment scale

The SOC and TSN stores at the 100 cm depth of each sub-catchment were estimated, such as 2.60 × 10⁴ and 0.32 × 10⁴ kg in check-dam 11, 26.28 × 10⁴ and 3.45 × 10⁴ kg in check-dam 15, and 5.4 × 10⁴ and 0.65 × 10⁴ kg in check-dam 18, respectively (Table 6). The average SOC and TSN stocks per unit area in check-dam 11 were highest in the entire soil layer (8.95 kg m⁻² and 1.10 kg m⁻², respectively), followed by that in check-dam 15 (7.42 kg m⁻² and 0.97 kg m⁻², respectively) and check-dam 18 (6.43 kg m⁻² and 0.78 kg m⁻², respectively) (Table 6).

From a correlation analysis, the amount of SOC and TSN in the studied catchment showed a significant positive correlation with the controlled watershed area (P < 0.05). High fraction of forest-land and years after construction contributed positively to SOC and TSN stocks per unit area in the check-dams (P < 0.05). The results indicated that controlled watershed area, forestland fraction, and years after construction other than soil erosion were also the dominant influencing factors to affect carbon and nitrogen sequestration potential.

4. Discussion

4.1. Soil C and N changes after land use change and check-dam construction

Land use change and check-dam construction might have a large impact on carbon or nitrogen sequestration potential in the loess hilly-gully region since 1995. The conversion of arable land to grassland and forestland had experienced a net gain in SOC and TSN. This result was consistent with previous studies (Chen et al., 2007; Fu et al., 2010; Zhang et al., 2013a). The conversion of arable land to grassland or forestland will contribute to more C and N gain from above-ground litter and roots and less soil C and N loss from erosion after grass and forest planting (Post and Kwon, 2000; Quinton et al., 2010). Previous studies indicated that the changes in land uses mainly had an influence on soil carbon and nitrogen storage by enhancing physical protection through either intra-aggregate or organic mineral complexes (Post and Kwon, 2000), changing the intensity of soil erosion to transport the soil and water loss along with associated C and N loss (Quinton et al., 2010; Ma et al., 2016a), altering the input rates of organic matter (Li et al., 2017), and the decomposition of organic matter inputs that increase in light fraction organic carbon (Cambardella and Elliott, 1992; Ma et al., 2016b). In this study region, forests, shrubland and dense grassland provided the best protection from erosion. Moreover, the magnitude of soil and water showed a significantly decreased trend and plant cover density obviously increased after afforestation (Zhou et al., 2012).

Check-dam construction resulted in losses of SOC and TSN compared with the corresponding source soil at the sub-catchment scale. Although the sediments were slightly enriched in clay and silt particles (ER > 1), the enrichment ratios for the SOC and STN contents at the deposition zone were less than 1. The results were in disagreement with previous studies which reported that ER for the SOC content was more than 1 in small watersheds, referring to recently exported sediments due to water erosion (Owens et al., 2002; Rhoton et al., 2006). The difference may be attributed to C and N oxidation, even at a low rate, which has probably occurred during the erosion and deposition process or during the period after check-dam construction (Boix-Fayos et al., 2009). Moreover, sediments trapped behind check-dams might originate from the superficial soil horizons through sheet and rill erosion but also from deeper

Table 5
Average enrichment ratios of some measured variables in sediments at the sub-catchment (0–20 cm).

<table>
<thead>
<tr>
<th>Sub-catchments</th>
<th>BD (Mg m⁻³)</th>
<th>SOC (g kg⁻¹)</th>
<th>TSN (g kg⁻¹)</th>
<th>Clay (%)</th>
<th>Silt (%)</th>
<th>Sand (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Check-dam 11</td>
<td>1.12 ± 0.11</td>
<td>0.73 ± 0.13</td>
<td>0.78 ± 0.16</td>
<td>1.03 ± 0.00</td>
<td>1.01 ± 0.01</td>
<td>0.83 ± 0.06</td>
</tr>
<tr>
<td>Check-dam 15</td>
<td>1.10 ± 0.08</td>
<td>0.45 ± 0.10</td>
<td>0.49 ± 0.08</td>
<td>2.13 ± 0.15</td>
<td>0.99 ± 0.03</td>
<td>0.61 ± 0.03</td>
</tr>
<tr>
<td>Check-dam 18</td>
<td>1.04 ± 0.10</td>
<td>0.49 ± 0.08</td>
<td>0.67 ± 0.13</td>
<td>2.36 ± 1.15</td>
<td>1.03 ± 0.03</td>
<td>0.19 ± 0.14</td>
</tr>
<tr>
<td>Average</td>
<td>1.09 ± 0.10</td>
<td>0.56 ± 0.10</td>
<td>0.65 ± 0.12</td>
<td>1.84 ± 0.43</td>
<td>1.01 ± 0.02</td>
<td>0.54 ± 0.08</td>
</tr>
</tbody>
</table>

SOC, soil organic carbon; TSN, total soil nitrogen; BD, bulk density. Values are represented as mean ± standard deviations (n = 3).

Table 6
SOC and TSN stores and stocks of 100 cm and 20 cm depth respectively at each sub-catchment scale.

<table>
<thead>
<tr>
<th>Sub-catchments</th>
<th>Check-dam 11</th>
<th>Check-dam 15</th>
<th>Check-dam 18</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SOC</td>
<td>TSN</td>
<td>SOC</td>
</tr>
<tr>
<td>Stocks per unit area (kg m⁻²)</td>
<td>8.95</td>
<td>1.10</td>
<td>7.42</td>
</tr>
<tr>
<td>Total SOC storage (10⁴ kg)</td>
<td>2.60</td>
<td>0.32</td>
<td>26.28</td>
</tr>
<tr>
<td>Stocks (Mg ha⁻¹)</td>
<td>21.1 ± 2.3</td>
<td>2.7 ± 0.3</td>
<td>10.2 ± 0.6</td>
</tr>
<tr>
<td>The proportion in comparison with PAL</td>
<td>22.0% (+)</td>
<td>22.72% (+)</td>
<td>41.04% (−)</td>
</tr>
</tbody>
</table>

SOC, soil organic carbon; TSN, total soil nitrogen. Values are represented as mean ± standard deviations (n = 3). The plus and minus sign in bracket represent gain and loss, respectively.
soil layers with poor C and N contents removed by gully erosion (Boix-Fayos et al., 2009). It was also verified by Hargeweyn et al. (2008) who reported a low enrichment ratio of organic C (0.93) in sediments of small catchment for similar environmental conditions and scales.

The sediments trapped behind check dams differ from natural sediments, because they have a fast deposition rate, with tens of meters of sediment within a few decades (Chen et al., 2016a). The source of sediment and associated with organic carbon typically being stored in check dams have been identified by using geochemistry and biomarkers as the fingerprint properties (Chen et al., 2016a;b; McCorkle et al., 2016; Liu et al., 2017), indicating that O-horizon in forestland and cropland will be the main contribution source of sedimentary organic carbon. The mineralization of soil organic carbon during the transportation and deposition process may also result in the losses of the SOC (Nie et al., 2017). In our study, the good soil condition (higher pH and SWC) at the deposition zone would contribute to the activity of microorganisms, and lots of labile organic carbon could be mineralized easily (Huang et al., 2013, 2014; Li et al., 2015). All these factors resulted in a lower ER and stores of SOC and TSN at the deposition site relative to the eroding site.

4.2. Factors affecting SOC and TSN stores

Land use types were one of the main influencing factors that affected soil C and N sequestration (Boix-Fayos et al., 2009; Nie et al., 2017). In our study, the conversion of arable land to forest, grassland, and shrubland changed soil C and N stocks with different variations. Farmland was converted to forestland and grassland to increase SOC and TSN stocks, but it resulted in a SOC and TSN reduction from farmland to shrubland since the implement of the “Grain for Green” programme. The results were not completely consistent with previous studies in the Loess Plateau of China (Owens et al., 2002). The reasons may be attributed to the greater reduction in the intensity of soil erosion in this region owing to the increasing ability of plant cover on runoff interception, sediment trapping and soil loss in grassland and forestland compared with shrubland (Chen et al., 2007; Fu et al., 2010). Moreover, a higher vegetation coverage density was also found in grassland and forestland during soil sampling process.

From correlation analysis, controlled watershed area, three land use characteristics (grassland fraction, deposition zone area, and forestland fraction) and years after construction tended to have a great influence on carbon and nitrogen retention by check-dams (Tables 1 and 5). The amount of SOC and TSN in the studied catchment showed a significantly positive correlation with the controlled watershed area ($P<0.05$). A high fraction of forestland and years after construction contributed positively to SOC and TSN stocks per unit area in check-dams ($P<0.05$). Forestland showed higher SOC and TSN contents in the 0–60 cm soil layer in comparison with the other classes. It seems reasonable to attribute to these differences to net primary productivity of plant and soil conditions (Feng et al., 2013). Plantation of Robinia pseudoacacia with nitrogen-fixation plants induced an increase in soil N and C and more aboveground biomass returned into soil compared with other plants (Fu et al., 2010).

Moreover, soil conditions also affected the rate of vegetation growth and rate of decomposition of soil organic matter (Guo and Gifford, 2002). Soil properties, such as bulk density, soil water content and pH with high values in check-dam 11 indicated that good soil conditions were in favour of soil C and N accumulation. Check-dams retained C and N elements in sediments behind the check-dam to avoid C and N, as well as their oxides release to larger channels and the emission to atmosphere during the erosion and deposition process (Lü et al., 2012). Although C and N loss occurred during soil erosion, new C and N input into soil from plants on the hillslope after vegetation recovery will contribute to compensate the C and N loss.

In general, land use changes and check-dam construction might have a great impact on carbon and nitrogen sequestration potential in the small catchment, and the result indicated the catchment to behave as soil C and N sinks with the soil erosion subsystem since the 1990s. The carbon and nitrogen retention effect of land use changes and check-dam construction should be considered comprehensively for appraising their potential impacts on global carbon or nitrogen cycling.

5. Conclusions

The combined performance of land use change and check-dam construction on SOC and TSN stocks indicated that the catchments might act as C and N sinks within the soil erosion cycle with the implementation of the “Grain for Green” programme since 1999. SOC and TSN contents mainly centralized in the superficial soil layer (0–20 cm). Soil C and N in topsoils were removed from the slope and buried in check-dams or gullies. The mineralization of soil organic matter led to the loss of C and N during transportation and deposition process, which resulted in the ER for SOC and TSN in sediments trapped behind the check-dam lower than 1. Soil C and N were also replaced due to land use change (i.e., the conversion from farmland to grassland and forestland) with higher contents of soil C and N. The SOC and TSN stocks exhibited significant correlation with soil variables and subcatchment characteristics, indicating that the main characteristics of sub-catchment and soil conditions were also one of the dominate factors influencing carbon or nitrogen sequestration potential.

The application of hydrological control works (i.e., afforestation and check dam construction) should be considered as a whole when comparing the relationships between soil erosion and C and N cycling. However, the meaning of C and N sinks due to land use change and the interception of eroded sediments in a wider C and N balance remains uncertain, taking into account an important C and N output as soil respiration.

Acknowledgements

Financial support for this study came from the National Natural Science Foundation of China (41271294) and the ‘Hundred-talent Project’ of the Chinese Academy of Sciences. The authors are very grateful to the anonymous reviewers and the responsible editor of the journal for valuable comments and suggestions to improve this manuscript.

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