Soil organic carbon sequestration and fertility response to newly-built terraces with organic manure and mineral fertilizer in a semi-arid environment

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**ABSTRACT**

Terraces are a popular and widely-distributed engineered agricultural landscape in mountainous regions. In this study, the effects of adding manure on soil organic C (SOC) sequestration, soil aggregate distribution, C/N ratio and activities of enzyme were evaluated in newly-built terraces over 7 growing seasons from 2004 to 2010 on the semi-arid Loess Plateau of China.

Experimental treatments including CK (control treatment with no fertilizer), NP (nitrogen and phosphorus), M (manure) and MNP (manure, nitrogen and phosphorus) were employed with a field pea–spring wheat–potato cropping system. SOC built up quickly in M and MNP treatments, while applying fertilizer alone (NP) was not effective in increasing soil C. The C sequestration rates are high in the early stages in manure treatments, and finally became zero as soil C reaches an equilibrium level. The simulation results showed that the maximum increase of SOC in newly-built terraces was 3.4 g kg⁻¹. Organic amendment significantly increased soil water stable macro-aggregates (> 0.25 mm). The largest aggregates (> 2 mm) in manure treatments have important implications for C sequestration, with 29.4% and 30.6% of total SOC in M and MNP, respectively. Application of fertilizer alone could not form the largest aggregates (> 2 mm) in the 7 years. SOC content was significantly higher in M and MNP than in CK and NP in all soil aggregate size classes. Manure treatments improved soil C/N ratio, while fertilizer treatment (NP) decreased soil C/N ratio. A significant sigmoid relationship was found between C/N ratio and cumulative inputs of SOC and TN in manure treatments, and a significant logistic relationship was found C/N ratio and cumulative TN inputs in NP treatment. After 7 years, fertilizer alone was as important as manure for improving activity of urease. Manure treatments improved activities of alkaline phosphatase and β-glucosidase compared with no manure treatments. The overall results show that adding manure is essential in improving soil fertility and accelerating the build-up of fertility in newly-built terraces in a semi-arid environment.

1. Introduction

Terraces are a crucial landscape engineering measure to decrease soil erosion, improve agricultural productivity, and maintain sustainable agriculture development under hillside agriculture in mountainous regions (Lü et al., 2009; Durán et al., 2011; Pietsch and Mabit, 2012; Arnáez et al., 2015). Terraces are popular and widely-distributed in countries such as Italy, France, Japan, China and in Southeast Asia (Cao et al., 2007). Terraced fields have also been used in America and a number of African countries (Dickey et al., 1997; Ali et al., 2008).

Soil erosion is a serious problem affecting crop productivity and farmers’ incomes in mountainous areas. Terraces as a conservation measure can control soil erosion and improve water conservation. Yang (2006) reported that terraces intercepted 92.4% of rainfall runoff and sediment. Reconﬁguring hillside ﬁelds into terraces is a primary management practice to ensure food and ecological security in marginal and ecologically-fragile hillside regions (Zhang et al., 2008; Bouchnak et al., 2009; Kovář et al., 2016). The semi-arid areas of China are mainly

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characterized by a hilly landscape, and its agricultural development level is relatively low. Creating new terraces is labor intensive, and initially crop yields are low. These factors restrict the development of new terraces. However, in the last 10 years, crop yields from terraces in semi-arid areas have greatly increased due to new technique of double ridges and furrows mulched with plastic film. The grain yield of maize has reached 6800 kg ha\(^{-1}\) in a region where the average annual precipitation is only 320 mm (Liu et al., 2009). It is clear that terraces have significant potential for further development in semi-arid areas.

### 2.1. Description of study site

The Loess Plateau of China is characterized by an extremely hilly loess landscape and most steep sloping land (Liu et al., 2003). In this region, newly built terraces are generally over 10 m wide to make tillage operations easier. To build the terraces 10 m wide on steep sloping lands farmers generally excavate soil from the uphill (part A) and move it downhill (part B) (Fig. 1). This building pattern leads to a large amount of subsoil covering the surface of the terraces. Many studies focused on the effects of the terraces on rainwater harvesting and sediment reduction (Yang, 2006; Hsu and Zhi, 2013; Liu et al., 2014a,b). Newly-built terraces are characterized by low SOC content and infertile soils which limited the growth of crops (Shang et al., 2001; Xie et al., 2001). The application of fertilizer and manure is an important way to improve SOC and fertility. Although terrace farming is rapidly expanding in this region, especially in Gansu Province, with 3.33 × 10\(^6\) ha of terraces being built from 2009 to 2012 (Cui and Ma, 2016).

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### 2.2. Experimental design and field management

In May 2002, a field with 18% slope was terraced with an excavator according to the method shown in Fig. 1. In order to conduct more experiments in this newly-built terraces and the width of it was expanded to 20 m. The soil formation of the Chinese Loess Plateau mainly originates from the sediment at upper reaches of the Yellow River by winter wind (Nie et al., 2015), and the soil texture is relatively homogeneous. In this region, the soil texture has no obvious difference between mature terraces and newly-built terraces. The contents of silt (2–50 μm) account for 75–80% of the total soil particles and less than 1% of the clay (< 2 μm) (Liu et al., 2013a; Zhou et al., 2015). Based on the above information, the experiment design did not involve performing treatments on different levels of terraces. The experiment employed a randomized block design with three replications in the subsoil of newly-built terraces. Each plot was 6.5 m (length) × 4.5 m (width) separated by a buffer 1 m wide by 0.4 m high. The fertilizer regime commenced in August 2003 and comprised four treatments: (1) CK (control), no fertilizer or manure, (2) NP, (N applied as urea at the rate of 70 kg N ha\(^{-1}\) and P as superphosphate at the rate of 15.7 kg P ha\(^{-1}\)), (3) M (sheep manure applied at the rate of 20 t ha\(^{-1}\) from 2004 to 2006, 10 t ha\(^{-1}\) from 2007 to 2009, and 5 t ha\(^{-1}\) in 2010), and (4) MNP (sheep manure together with N and P at the same rates as above).

Generally, the manure was a mixture of sheep manure and some alfalfa residue. The composition of manure varied from year to year, but the average values (g kg\(^{-1}\)) were as follows: organic C, 150.0; total N, 10.0; total P, 0.84; mineral N (NH\(_4\)-N + NO\(_3\)-N), 0.09; and available P, 0.15. The fields were ploughed flat, and the fertilizers and manure were incorporated into the soil using spades each October from 2003 to 2009, and also before the crops were sown in 2010.

The crops were field pea (Pisum sativum L. cv. ‘Yannong 2’), spring wheat (Triticum aestivum L. cv. ‘Heshangtou’) and potato (Solanum tuberosum L. cv. ‘Xindaping 1’), grown in this sequence and repeated as necessary from 2004 to 2010. The seeding rate was 135 kg ha\(^{-1}\) for field pea, 180 kg ha\(^{-1}\) for spring wheat, and 300 kg ha\(^{-1}\) for potato (fresh tubers). The peas were not inoculated with rhizobium prior to planting. Field peas and spring wheat were row planted in furrows with 20 cm row spacing. The potato crop was planted with a row spacing of 60 cm in the flat plots. Field pea and spring wheat were grown from early April to early August and potato was grown from late April to late September. Precipitation data were measured using an automatic weather station (WS-STD1, England). 2004, 2006, 2008, and 2009 were dry years with precipitation between 195 and 254 mm; 2005 and 2010 were average years with 316 and 309 mm precipitation, respectively; and 2007 was a wet year, with 390 mm precipitation.

### 2.3. Sampling and measurements

All of the aboveground biomass of field pea and spring wheat was removed from plots, but roots were left in the soil. The potatoes were harvested by spade at about the 20 cm soil depth, and the aboveground biomass, main roots and tubers of it were all removed.

Before sowing in 2010, soil samples were collected from each plot from 0 to 20 cm depth (the roots of the crops mainly distributed in this soil layer) for determination of water-stable aggregates (WSA). Soil WSA distribution was determined according to Oades and Waters (1991).

Soil retained in each sieve was oven-dried at 50 °C and weighed to compute the percentage of WSA (Nimmo and Perkins, 2002; Wilson et al., 2009). A portion of these oven-dry samples from each aggregate-size fraction was ground and sieved to obtain 0.15 mm fraction to determine total SOC concentration.
In each plot, three soil cores (diameter 8 cm, height 20 cm) were taken at randomly chosen locations in early August 2003, when the experiment was initiated, and each year thereafter at harvest. Non-decomposed sheep manure (i.e. some sheep manure did not completely decompose due to arid conditions in this region) and visible plant residues such as straw, chaff and larger roots were removed by hand. Samples were air-dried, ground, sieved (2 mm, 0.9 mm and 0.15 mm) and stored at room temperature until required. To determine microbial biomass C (MBC) and soil enzymes activities, samples were brought to the laboratory and stored at 4 °C for subsequent analysis (Abellán et al., 2011; Kotroczó et al., 2014).

SOC was determined using the HT1300-µm/C3100-analyzer (Jena, Germany). A KJ (Kjeldahl) Auto Analyzer (TECATOR Product, Sweden) was used to measure soil total nitrogen (TN) after digestion with salicylic acid-H2SO4. Total phosphorus (TP) was determined colorimetrically after digestion with perchloric acid. Available phosphorus (AP) was determined using the Olsen method (Olsen et al., 1954). Dried samples weighing 10 g each were added to 50 ml of 2 M KCl, shaken for 1 h, and analyzed with a FIAStar 5000 Analyzer (FOSS Tecator, Sweden) for nitrate nitrogen (NO3-N) and ammonium nitrogen (NH4-N). Soil MBC was determined using fumigation extraction and a KEC factor of 0.25 (Voroney et al., 1993) was assumed the difference between C extracted with 0.5 M K2SO4 through chloroform-fumigation and that from unfumigated samples. After extraction, MBC was measured by determining C mass in the filtrate with the multi N/C 3100 analyzer (Jena, Germany). β-glucosidase enzyme activity was determined according to Dick et al. (1996). Activities of urease and alkaline phosphatase activities were assayed as described by Tabatabai (1994).

The plant tissue samples of the potato tubers, aboveground biomass and roots were collected at maturity. The plant tissue samples of the spring wheat and field pea grains and their straw were collected at maturity. The sample plants were oven-dried for dry matter content at 60°C for 48 h, then ground and analyzed for total nutrient concentrations. The harvested plant material was ground using a Tekmar-10 pulverizer, and the total N was determined using a KJ (Kjeldahl) Auto Analyzer after digestion with salicylic acid-H2SO4 and total phosphorus using colorimetry after digestion with perchloric acid.

2.4. Statistics

The data were subjected to ANOVA using the software package SAS (SAS Institute, 1989). Comparisons were made using the method of least significant differences (LSD) at the probability level at \( P = 0.05 \). Proc CORR in SAS was used to examine correlation relationships between variables. Mean values are reported in the tables and figures.

3. Results

3.1. SOC storage and sequestration

A significant Logistic relationship was found between the increase of SOC and cumulative SOC inputs in manure treatments (Fig. 2). Simulation results (the function reaches a plateau) showed that the maximum increase of SOC in the newly-built terraces was 3.4 g kg⁻¹. Different fertilization treatments had a significant influence on both SOC storage and sequestration. Topsoil (0–20 cm) C storage was significantly higher in the manure applied treatments compared with the no manure treatments (Fig. 3A). By the end of the 2010 growing season, the SOC in CK, NP, M and MNP treatments was 104.8%, 107.1%, 252.0% and 244.0%, respectively, of the initial value measured in 2003.

3.2. Aggregates and SOC distribution in the aggregates

The percentage of macro-aggregates (> 0.25 mm) in the 0–20 cm soil layer was significantly affected by organic amendment (Table 1). Water-stable macro aggregate (> 0.25 mm) accounted for 34.4, 34.2, 52.2 and 53.8% of whole soil weight for fertilizer treatments CK, NP, M and MNP in the 0–20 cm soil layer, respectively. Different fertilizer practices influenced aggregate size distribution. After 6 years, the largest-sized class (> 2 mm) was observed in manure treatments, but not in the treatments without manure.

Different fertilizer practices affected the distribution of SOC concentration in aggregates (Fig. 4), ranging from 2.8 to 35.0 g kg⁻¹ for manure treatments, and 1.7 to 5.6 g kg⁻¹ for no manure treatments. SOC content was significantly higher in M and MNP than in CK and NP in all soil aggregate size classes. SOC concentration decreased gradually with decreasing aggregate size in all treatments. A power function explained 99% of variability between SOC concentration and aggregate size in manure treatments.

The largest size class (> 2 mm) contained the largest C pool in manure treatments, with 29.4% and 30.6% of total SOC in M and MNP, respectively, while the smallest size class (< 0.16 mm) contained the largest C pool in no manure treatments, with 34.8% and 33.3% of total SOC in CK and NP respectively (Table 1). The SOC of macro-aggregates (> 0.25 mm) occupied 45.0%, 44.5%, 73.3% and 74.3% of total SOC in CK, NP, M and MNP, respectively.

3.3. Soil N, P and ratio of SOC to TN (C/N)

A significant logistic relationship was found between the increase of TN and cumulative TN inputs in the manure treatments, and a significant linear relationship was found in the TN content and cumulative TN inputs in the NP treatment (Fig. 5). The simulation results (the function reaches a plateau) showed that the maximum increase of TN in the newly-built terraces was 0.28 g kg⁻¹. Different fertilization treatments had a significant influence on both TN storage and sequestration. By the end of the 2010 growing season, TN in CK, NP, M and MNP treatments was 111.3%, 120.3%, 225.8% and 217.1%, respectively, of the initial value measured in 2003 (Fig. 5B). At harvest 2010, TP content was significantly higher in NP, M and MNP than in CK (Fig. 3C), and TP in CK, NP, M and MNP treatments was 99.7%, 107.5%, 109.2% and 112.2%, respectively, of the initial value measured in 2003.
During the 7 years of the study, mineral N (MN) was the highest in MNP and the lowest in CK (Fig. 6A). There were no differences in mineral N between MNP and NP in year one, but over the next 6 years it was higher in MNP than in any other treatment. Soil available P (AP) and the ratio of available P to total soil P (AP/TP ratio) in MNP increased rapidly with time, with both significantly higher in MNP than in any other treatment for the 7 years (Figs. 6B and 7).

At harvest 2010, C/N ratio was significantly higher in M and MNP than in CK and NP (Fig. 3D), and C/N ratio in CK, NP, M and MNP treatments was 93.7%, 88.9%, 112.0% and 111.3%, respectively, of the initial value measured in 2003. A significant sigmoid relationship was found between the C/N ratio and cumulative SOC and TN inputs in the manure treatments (Figs. 8 and 9), and a significant logistic relationship was found in the C/N ratio and cumulative TN inputs in the NP treatment (Fig. 9).

The total input of TN (fertilizer plus manure) over the 7-year period varied greatly among the treatments (Table 2): it was the highest in the MNP (1440 kg ha\(^{-1}\)), followed by M (950 kg ha\(^{-1}\)), NP (490 kg ha\(^{-1}\)), and CK (0 kg ha\(^{-1}\)). Over the same period, the total output of TN was 537.0 kg ha\(^{-1}\) in MNP, 331.6 kg ha\(^{-1}\) in NP, 286.7 kg ha\(^{-1}\) in M, and 154.4 kg ha\(^{-1}\) in CK. The input of TP also varied greatly among the treatments (Table 2): it was the highest in the MNP (189.7 kg ha\(^{-1}\)), followed by NP (109.9 kg ha\(^{-1}\)), M (79.8 kg ha\(^{-1}\)), and CK (0 kg ha\(^{-1}\)). The output of TP was 33.1 kg ha\(^{-1}\) in MNP, 20.4 kg ha\(^{-1}\) in NP, 18.1 kg ha\(^{-1}\) in M, and 8.6 kg ha\(^{-1}\) in CK from the first experimental year to the last.

**Fig. 3.** Soil organic carbon (SOC), total N (TN), total P (TP) and ratios of SOC to TN (C/N) in the 0–20 cm soil layer in the various treatments before the experiment in August 2003 and at harvest in August 2010. 2003: reference soil (taken before experiment). CK: no fertilizer or manure; NP: N applied as urea at the rate of 70 kg N ha\(^{-1}\) and P as superphosphate at the rate of 15.7 kg P ha\(^{-1}\); M: sheep manure applied at the rate of 20 t ha\(^{-1}\) from 2004 to 2006, 10 t ha\(^{-1}\) from 2007 to 2009, and 5 t ha\(^{-1}\) in 2010; MNP: sheep manure together with N and P at the same rates as above. Different letters indicates significant differences at P \(\leq\) 0.05.

Table 1

<table>
<thead>
<tr>
<th>SWASC</th>
<th>Treatments</th>
<th>Macro-aggregates (&gt; 0.25 mm)</th>
<th></th>
<th>Micro-aggregates (&lt; 0.25 mm)</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>&gt; 2 mm</td>
<td>1–2 mm</td>
<td>0.5–1 mm</td>
<td>0.25–0.5 mm</td>
<td>Sum</td>
<td>0.106–0.25 mm</td>
</tr>
<tr>
<td>CK</td>
<td>0b</td>
<td>4.0b</td>
<td>5.8b</td>
<td>24.6b</td>
<td>34.4b</td>
<td>25.0a</td>
<td>40.6a</td>
</tr>
<tr>
<td>NP</td>
<td>0b</td>
<td>4.0b</td>
<td>5.8b</td>
<td>24.6b</td>
<td>34.4b</td>
<td>25.0a</td>
<td>40.6a</td>
</tr>
<tr>
<td>M</td>
<td>4.6a</td>
<td>7.1a</td>
<td>10.0a</td>
<td>30.5a</td>
<td>52.2a</td>
<td>18.5b</td>
<td>29.3b</td>
</tr>
<tr>
<td>MNP</td>
<td>4.7a</td>
<td>6.0a</td>
<td>11.0a</td>
<td>32.1a</td>
<td>53.8a</td>
<td>17.0b</td>
<td>29.2b</td>
</tr>
<tr>
<td>CR</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>CK</td>
<td>0b</td>
<td>11.1a</td>
<td>8.9a</td>
<td>25.0a</td>
<td>45.0b</td>
<td>20.2a</td>
<td>34.8a</td>
</tr>
<tr>
<td>NP</td>
<td>0b</td>
<td>8.8b</td>
<td>7.6a</td>
<td>28.1a</td>
<td>44.5b</td>
<td>22.2a</td>
<td>33.3a</td>
</tr>
<tr>
<td>M</td>
<td>29.4a</td>
<td>10.3a</td>
<td>10.4a</td>
<td>23.2b</td>
<td>73.3a</td>
<td>11.6b</td>
<td>15.1b</td>
</tr>
<tr>
<td>MNP</td>
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<td>9.0b</td>
<td>10.7a</td>
<td>24.0b</td>
<td>74.3a</td>
<td>10.4b</td>
<td>15.3b</td>
</tr>
</tbody>
</table>

CK: no fertilizer or manure; NP: N applied as urea at the rate of 70 kg N ha\(^{-1}\) and P as superphosphate at the rate of 15.7 kg P ha\(^{-1}\); M: sheep manure applied at the rate of 20 t ha\(^{-1}\) from 2004 to 2006, 10 t ha\(^{-1}\) from 2007 to 2009, and 5 t ha\(^{-1}\) in 2010; MNP: sheep manure together with N and P at the same rates as above. Values within a column followed by the same letters do not differ significantly at P \(\leq\) 0.05.
3.4. Soil enzymes activities

All soil enzyme activities responded to different amendments, but the response differed between enzymes and treatments (Fig. 10). Urease activity was significantly lower in CK than in NP, M and MNP in August 2010 (Fig. 10A). Urease activity in August 2010 significantly increased in NP, M and MNP, but significantly decreased in CK compared to initial values in August 2003. Activities of alkaline phosphatase and β-glucosidase were significantly higher in manure treatments than in no manure treatments in August 2010 (Fig. 10B). Alkaline phosphatase activity significantly increased in manure treatments, with no significant change in no manure treatments compared to initial values in August 2003. β-glucosidase activity was significantly higher in all treatments compared to initial values in August 2003 (Fig. 10C). Significant positive correlations were observed between soil enzyme activities and SOC, TN, TP, MBC, MN and AP (Table 3).

4. Discussion

4.1. SOC, soil aggregate-size distribution and C concentration in aggregates

SOC plays an important role in the pool of soil nutrients and their availability (Zhao et al., 2009; Zhou et al., 2012; Li et al., 2017). Increase of SOC by adding manure improved porosity, infiltration and water-holding capability of soil (Karami et al., 2012; Liu et al., 2013a). In the present experiment, SOC in MNP and M increased rapidly, and...
similar results have been reported from other long-term experiments (Wu et al., 2004; Ding et al., 2012). In order to improve soil nutrient availability and water-holding capability in newly-built terraces, SOC needs to be built up quickly, and chemical fertilizers had less effects on C-sequestration compared to manure amendment. In this study, we found that the C sequestration rates are high in the early stages in manure treatments, and then decrease with consequent increases of soil C pool and finally became zero as soil C reaches an equilibrium level. In this region, the SOC are very low in the farmland. The SOC ranged from 7.0 to 11.5 g kg$^{-1}$ in the terraces for farming history over 100 years (Liu et al., 2009, 2013b, 2015). After 7 years, the SOC can reach 5.5 g kg$^{-1}$ in the manure treatments, and the results are acceptable.

Our results indicated that WSA > 0.25 mm significantly increased following application of manure. Results of similar field trials showed that long-term manure application promoted formation of soil macro-aggregates and increased aggregate stability (Lee et al., 2009; Lobe et al., 2011). It indicates that applied manure has positive effects on soil aggregation in newly-built terraces.

The importance of SOC content for aggregate formation is well known (Blanco-Canqui and Lal, 2007; Karami et al., 2012). In our study, macro- and micro-aggregation was significantly improved by application of manure, and SOC concentration in manure treatments explained the variability in aggregate properties by as much as 99%. In this study, large water stable aggregates (> 2 mm) were only observed in manure treatments. These large aggregates contained the largest C pool in manure treatments, and suggested their importance for C sequestration in newly-built terraces.

### Table 2

<table>
<thead>
<tr>
<th>Treatments</th>
<th>N input (kg ha$^{-1}$)</th>
<th>N output (kg ha$^{-1}$)</th>
<th>Residual N (kg ha$^{-1}$)</th>
<th>P input (kg ha$^{-1}$)</th>
<th>P output (kg ha$^{-1}$)</th>
<th>Residual P (kg ha$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CK</td>
<td>0.0</td>
<td>154.4</td>
<td>-154.4</td>
<td>0.0</td>
<td>8.6</td>
<td>-8.6</td>
</tr>
<tr>
<td>NP</td>
<td>490.0</td>
<td>331.6</td>
<td>158.4</td>
<td>109.9</td>
<td>20.4</td>
<td>895.5</td>
</tr>
<tr>
<td>M</td>
<td>950.0</td>
<td>286.7</td>
<td>663.3</td>
<td>79.8</td>
<td>18.1</td>
<td>617.0</td>
</tr>
<tr>
<td>MNP</td>
<td>1440.0</td>
<td>537.0</td>
<td>903.0</td>
<td>189.7</td>
<td>33.1</td>
<td>156.6</td>
</tr>
</tbody>
</table>

CK: no fertilizer or manure; NP: N applied as urea at the rate of 70 kg N ha$^{-1}$ and P as superphosphate at the rate of 15.7 kg P ha$^{-1}$; M: sheep manure applied at the rate of 20 t ha$^{-1}$ from 2004 to 2006, 10 t ha$^{-1}$ from 2007 to 2009, and 5 t ha$^{-1}$ in 2010; MNP: sheep manure together with N and P at the same rates as above.

Fig. 9. The ratios of soil organic C (SOC) to total N (C/N) in M and MNP treatments in the 0–20 cm soil layer response to cumulative N inputs. NP: N applied as urea at the rate of 70 kg N ha$^{-1}$ and P as superphosphate at the rate of 15.7 kg P ha$^{-1}$; M: sheep manure applied at the rate of 20 t ha$^{-1}$ from 2004 to 2006, 10 t ha$^{-1}$ from 2007 to 2009, and 5 t ha$^{-1}$ in 2010; MNP: sheep manure together with N and P at the same rates as above.

GLU: β-Glucosidase activity; PAL: alkaline phosphatase; UR: urease; SOC: soil organic C; TN: total N; TP: total P; MBC: microbial biomass C; MN: mineral N; AP: available P.

4.2. Soil N, P, and ratio of SOC to TN (C/N)

Soil TN increased rapidly in MNP and M but not in CK and NP. This difference may be attributed partly to the slow release of N from manure due to the low soil microbial activities, resulting in smaller losses of N. In this region, TP is about the same as that recorded in the present experiment in all treatments, which suggests that newly-built terraces have no shortage of soil total P.

Microbial biomass carbon (MBC) is an important fraction of soil organic matter, and it is a general indicator of soil microbial activity (Wick et al., 1998). In this study, a significant positive correlation was found between MBC and SOC, and between MBC and TN (Fig. 11A and B), indicating that MBC contents could be higher with the increase of SOC and TN content in newly-built terraces. Mandal et al. (2007) showed that MBC is positively correlated with MN during crop development. The present study showed MBC was positively correlated with MN (Fig. 11C). MN in MNP was higher than in any other treatment from the second year, probably because of enhanced activity of several enzymes induced by microbial biomass (Mandal et al., 2007). In the

phosphate bound P) in the Loess Plateau of China (Wang et al., 2005). significant lower than 11.Li et al. (2003) found a positive feedback ratio decreased significantly. Wu et al. (2004) reported that chemical Decomposing manure can produce diifferent organic acids, which react with Al3+, Fe3+ and Ca2+, and improves phosphorus availability (Wang, 1992). Thus, it is not the lack of P reserves in soil but activation of P from residual P sources in soil that is pivotal in making the newly-built terraces more productive. The P added through fertilizers is mostly in the less available form of Ca8-P (octo-calcium phosphate bound P) in the Loess Plateau of China (Wang et al., 2005).

The ratio of SOC and TN (C/N) is a reliable indicator of the ability of soil microorganisms to assimilate and mineralize Chen (1990) and Huang (2000) reported that a C/N ratio of 6–11 enhanced the mineralization of soil organic N and significantly increased MBC; soil organic matter also decomposed more quickly when the C/N ratio was significantly lower than 11. Li et al. (2003) found a positive feedback loop between SOC content and C/N when the C/N ratio ranged from 6 to 11 in a similar agro-ecosystem characterized by mulch in typical Loess soils: mulching and applying chemical fertilizers lowered the C/N ratio, which, in turn, accelerated the decomposition of SOC, lowering the ratio even further. Therefore, in semi-arid regions, increasing the SOC and C/N ratio is effective in improving soil quality and reducing N loss. In the present study, the C/N ratio increased rapidly in MNP and M, probably because of the high C/N ratio (generally about 15) of the manure. The simulation results (the function reaches a plateau) showed that the maximum C/N ratio can reach 12.0 in the manure treatments in newly-built terraces, which could limit the mineralization of soil nitrogen, thereby conserving soil nitrogen and SOC. In the NP, the C/N ratio decreased significantly. Wu et al. (2004) reported that chemical fertilizers may hasten the decomposition of soil organic matter. Application of nitrogenous fertilizers was another reason for the lower C/N ratio in NP whereas in CK the ratio did not change significantly.

4.3. Soil enzyme activities

Soil enzymes are important components for biochemical functioning of soils as they are the driving force in nutrient cycling, and commonly suggested as indicators in detecting changes or disturbances in the soil ecosystem (Islam et al., 2011; Wallentius et al., 2011; Piotrowska and Wilczewski, 2012; Dong et al., 2016). Newly-built terraces are characterized by low SOC, N and P contents which limits the growth of crops (Xie et al., 2001; Yang, 2006; Liu et al., 2013a). The decomposition of organic matter and transformation of N and P are mainly achieved by gluco-sidease, urease and phosphatase (Kotrocó et al., 2014; Zhang et al., 2016).

In the present study, the β-glucosidase and alkaline phosphatase activities were low in the control and NP fertilizer treatments and increased significantly with manure treatments. β-glucosidase is one of the most important glycosidases in soils because it catalyses the hydrolysis of carbohydrates with β-1-glucoside-bonds, such as cellobiose. The application of manure significantly enhanced the activities of β-glucosidase (Wang et al., 2017), and a significant positive correlation was also observed between β-glucosidase and SOC (Table 3). In the newly-built terraces, applying fertilizer alone (NP) was not effective for SOC sequestration in a semi-arid environment, and adding manure was essential for improving the activity of β-glucosidase. The phosphatases are a broad group of enzymes that hydrolyze esters and anhydrides of phosphoric acid. Liu et al. (2010) reported that alkaline phosphatase activity was low in the control and N fertilizer only treatments and increased significantly with manure and optimum NP application; the increase in alkaline phosphatase activity over the years with the application of inorganic nutrients was attributed to greater input of root biomass due to better crop productivity. In our study, the failure of fertilization to enhance phosphatase activity was likely due to the low input of crop residue and P adsorption or precipitation with soil minerals, which decreases its availability (Zibilske et al., 2002). Urease catalyses the hydrolysis of urea to CO2 and NH3. Dick et al. (1998) showed that urease activity decreased with long-term addition of inorganic N. It was hypothesized the enzymatic reaction (NH4+) suppressed urease synthesis. In the present study, activity of urease was significantly higher in MNP followed NP and M treatments. The result is not in accordance with reports of Dick et al. (1998), and may be due to the different soil types. In this region, the soil belongs to calcareous–alkaline soils (Liu et al., 2013a,b), and Li and Liu (1993) reported that the amount of NH3 volatilization was positively correlated with the pH in calcareous soil. In this study, the soil NH4+ content was low in all treatments during the entire period due to the high soil pH (Fig. 12). Low NH4+ content can promote the synthesis of urease. Liu et al. (2010) reported that organic manure application increased urease

Fig. 11. Relationship between soil microbial biomass C (MBC) and organic C (SOC), total N (TN), mineral N (MN) and available P (AP) in the 0–20 cm soil layer over the experimental period.

![Figure 11](image-url)
activity. Significant positive correlation was also observed between SOC and urease activity in our study.

5. Conclusion

The simulation results showed that in the newly-built terraces the maximum increase of SOC was 3.4 g kg⁻¹ and the TN was 0.28 g kg⁻¹. SOC and TN built up quickly in manure application plots, which were not achieved by applying fertilizer alone. Soil WSA > 0.25 mm was significantly increased by application of manure. The largest size aggregates (> 2 mm) have important implications for C sequestration. Application of fertilizer alone could not form the largest aggregates (> 2 mm). Manure application significantly increased SOC content in all soil aggregate size classes compared to no manure treatments. Manure treatments improved soil C/N ratio, while fertilizer treatment (NP) decreased soil C/N ratio. Manure treatments significantly increased activities of alkaline phosphatase and β-glucosidase compared with no manure treatments. Significant positive correlations were observed between all tested enzyme activities and SOC, TN, TP, AP, MBC and MN. The overall results show that adding manure is essential in improving soil fertility and accelerating the build-up of fertility in newly-built terraces in a semi-arid environment. The soil AP is very deficient in newly-built terraces, and it is necessary to apply more P fertilizer to them.

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References


Fig. 12. Soil NH₄⁺ content in the 0–20 cm soil layer in various treatments over the experimental period. 2003: reference soil (taken before experiment). Error bars are LSD at P ≤ 0.05.


