Soil fertility increases rapidly during the 6–10 yr following conversion of cropland to grassland in China’s Loess Plateau region
Qingyin Zhang and Ming’an Shao

**Abstract:** Change in land use causes changes in soil properties and soil fertility, with long-term effects on ecosystem and crop productivity. This study determined soil fertility along sequential conversion of cropland to grassland in China’s Loess Plateau. Soil samples were collected in 2015 at two sites in the semiarid region, following the conversion of cropland to grassland. Soil particle-size distribution, bulk density, pH, organic carbon (OC), total nitrogen (TN), total phosphorus (TP), available potassium, and available phosphorus were measured in this study. In addition, we analysed the changes of soil OC, TN, and TP, and evaluated soil fertility after the conversion from cropland to grassland. The establishment of grassland significantly increased soil OC, N, and P content, especially in the 0–10 cm soil layer. The highest change in soil OC, N, and P content occurred 6–10 yr after land conversion. The measured soil variables did not change significantly after 10 yr of land conversion. The overall increase in soil fertility after the land conversion was 13% at one site and 26% at the other site. The results suggested that establishing grassland could enhance soil fertility in the semiarid Loess Plateau region of China, and this enhancement is optimal 6–10 yr after the establishment of grassland.

**Key words:** soil property, cropland, grassland, soil fertility dynamics, Loess Plateau.

**Résumé :** Quand la vocation des terres change, ainsi en va-t-il des propriétés et de la fertilité du sol, avec les conséquences à long terme qu’on imagine pour l’écosystème et le rendement des cultures. Les auteurs ont déterminé la fertilité du sol lors de la conversion progressive d’une terre agricole en prairie sur le plateau de loess, en Chine. Pour cela, en 2015, ils ont prélevé des échantillons de sol à deux endroits de la région semi-aride auparavant cultivés, mais laissés en friche depuis. Ensuite, ils ont mesuré la répartition granulométrique des particules de sol, la masse volumique apparente, le pH, la concentration de carbone organique (CO) ainsi que celle de l’azote total (AT) et du phosphore total (PT), et la teneur en potassium et en phosphore disponibles. Enfin, les chercheurs ont analysé les variations de la teneur en CO, AT et PT, et évalué la fertilité du sol après le passage de l’état cultivé à l’état sauvage. La transformation en prairie augmente sensiblement la concentration de CO, de N et de P, surtout dans la couche supérieure de 0 à 10 cm du sol. La plus forte modification de la teneur en CO, en N et en P dans le sol survient 6 à 10 ans après le changement de vocation. Les variables du sol que les chercheurs ont mesurées ne changent plus de façon appreciable 10 ans après la conversion. Globalement, la conversion avait accru la fertilité du sol de 13 % à un site et de 26 % à l’autre. Ces résultats donnent à penser que le rétablissement de l’état prairial pourrait rendre le sol plus fertile dans la région semi-aride du plateau de loess chinois et que cette bonification atteint un pic 6 à 10 ans après la restauration de l’état sauvage. [Traduit par la Rédaction]

**Mots-clés :** propriétés du sol, terres agricoles, prairie, dynamique de la fertilité du sol, plateau de loess.

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**Introduction**

Semiarid regions are particularly sensitive to climate change and anthropogenic activity (Schlesinger et al. 1990; Reynolds et al. 2007). As the predominant ecosystem (Sala et al. 1997), grassland largely determines the use of soil resources in semiarid regions (Lafferty et al. 1999). Changes in land use can lead to changes in soil properties, including bulk density (BD) and pH, and then in organic carbon (OC), nitrogen (N), and phosphorus (P) content (Breuer et al. 2006; Bouwman et al. 2013). The conversion of agricultural lands to grassland not only increases soil nutrient but also decreases carbon dioxide (CO₂) flux into the atmosphere (Don et al. 2011; Harris et al. 2012). Studies show that changes in land use influence soil fertility by altering abiotic or biotic factors (Qiu et al. 2012; Deng et al. 2014; Wei et al. 2014; Askari and Holden 2015).

Cultivation and tillage of cropland could lower soil OC, N, and P stocks (Li et al. 2009) and favour the formation of micro-aggregates (Qiu et al. 2012; Wei et al. 2013). The loss of physical protection by aggregates decreases soil OC storage under long-term cultivation or tillage (Caravaca et al. 2004). Cultivation would also result in a change in the aggregate-size distribution and stability; and an important relationship among soil OC, microbial activity, and aggregate-size and stability has been reported previously (Raiiesi 2007; Li et al. 2009). Grassland is generally the natural regrowth in abandoned croplands and also the widely used vegetation in rehabilitation of degraded lands in semiarid and arid regions around the world (Breuer et al. 2006; Deng et al. 2014). Land use change can cause significant changes in the input and dynamics of soil OC (Raiiesi 2007). Martens et al. (2004) noted that soil OC increased at the rate of 0.62 Mg ha⁻¹ yr⁻¹ for croplands converted to grassland in Central America. In addition, Zhang et al. (2010) reported an average gain increase of 0.37 Mg C ha⁻¹ yr⁻¹ following the conversion of cropland to grassland in China. Guo and Gifford (2002) observed that global soil OC stocks could increase significantly (+19%) with the conversion of croplands to pasture. The discrepancies in these results were likely due to multiple factors, including climate, soil type, soil depth, spatial scale, and land-use management (Li et al. 2012). Thus, the need for sound knowledge on the effect of grassland systems following cropland conversion on soil physical and chemical properties and on soil fertility (Li et al. 2007; Wei et al. 2009, 2014) for sustainable grassland management practices.

Assessments of soil fertility at watershed scale could more clearly demonstrate the effect of land use change on soil quality (Karlen et al. 1998; Andrews et al. 2004). Potential soil fertility issues include rate of erosion, loss of organic matter, low crop productivity, or even chemical and heavy metal contamination (Doran and Parkin 1994; Karlen et al. 2003). As in other parts of the world, widespread land use change on the Loess Plateau, especially in the last century, has led to changes in soil fertility, crop productivity, and environmental sustainability (Xu et al. 2005; Li et al. 2007). Low soil fertility and severe flooding after land use change are among the most severe threats to the functions and services of ecosystems throughout the country (Raiiesi 2007; Khormali et al. 2009; Abbazadeh Afshar et al. 2010).

Currently, paired comparisons are used to detect differences in specific soil management practices (e.g., among different sites or land uses) and to develop correlations between the response of soil fertility to specific soil variables (Cambardella et al. 2004; Moorman et al. 2004). In this study, we used paired comparisons to detect changes in of land use and soil variables. We focused on the dynamics of main soil chemical properties and soil fertility following the conversion of cropland to grassland at two sites on the Loess Plateau where grassland, including legume (Medicago sativa L.), has been planted on adjacent croplands at different times. As the conversion from croplands to grasslands could change soil properties in the semiarid region, it was hypothesised that conversion of cropland to grassland increases soil OC, N, and P, and improve soil fertility at the two sites. The specific objectives of this study were to determine the dynamics of soil OC, N, and P contents and to evaluate soil fertility using paired cropland and grassland analysis.

**Materials and Methods**

**Study site**

This study area included Liudaogou watershed (38°49' N, 110°23'E) in Shenmu County (6.78 km²) and Donggaohuai village (35°15' N, 108°06'E) in Bin County (3.59 km²), Shaanxi Province, China (Fig. 1). Shenmu County has a semiarid continental climate, with mean annual precipitation of 437 mm and temperature of 8.1 °C. The precipitation is most intensive during the growing season from June to September, accounting for 70% of the annual precipitation. The Calcaric Regosol (FAO-UNESCO) soil originates from low fertility loess, with weak cohesion, high infiltration, low water retention, and highly erodible (Fu et al. 2010). The dominant native grass in Shenmu County is Stipa bungeana Trin., and the main crops include Setaria italica L. and Glycine max Merr. Since the late 1970s, the M. sativa (an N₂ fixer) crop has been widely cultivated on degraded slopes to prevent soil erosion. Bin County has a temperate semiarid climate, with mean annual precipitation of 579 mm, most of which falls as intense storm during the period from June to September. The mean annual temperature is 9.7 °C, and the soil is a Gleyic Phaeozems (FAO-UNESCO). The dominant native grass in Bin County is Themeda triandra Forsk. var. Japonica, and the main crops include Zea mays L. and Triticum aestivum L.
Field investigation and sampling

Soil samples were collected from two sites in the study area (Fig. 1). The Bin County site included three (6, 10, and 15 yr) and the Shenmu County site included four (6, 10, 15, and 20 yr) cropland and grassland (M. sativa) vegetation. The initial land use at the two sites before the conversion from cropland to grassland was fallow. Therefore, any increase in soil OC, N, and P under grassland was due mainly to land use change. Three plots were established for each land use type (10 m × 10 m grassland and 10 m × 10 m cropland), where soil samples were collected in October 2014. The ages of the plantations were obtained by interviewing local farmers who participated in previous official land use inventories in the selected watersheds. Every year, the aboveground biomass of the crops was harvested and removed. Both sites have a long history of chemical fertilizers application, with N applied as urea (90 kg N ha⁻¹ yr⁻¹) and P as super phosphate (33 kg P ha⁻¹ yr⁻¹). Therefore, we assumed that the physical and chemical properties of the soil were initially the same at each of the two sites at the time of conversion because of the same soil type and similar physiographic and slope conditions (Fu et al. 2010; Qiu et al. 2012; He et al. 2016).

In June 2015, millet was grown in Shenmu County and maize in Bin County where the samples were collected. Three replicate core samples were collected at the 0–10 and 10–20 cm soil layers in each plot for analysis of soil physical (including BD) and chemical properties using a ring of 5 cm in height and 5 cm in diameter. Visible roots and rock fragments were removed at sampling. A total of 168 samples (seven ages × two sites × three replicates × two soil layers × two samplings for BD and composite variables) were collected. As land use change mainly influences surface soil layer (Wei et al. 2009, 2013), soil samples were only collected from the top 20 cm soil layer.

Laboratory and data analyses

The collected soil samples were air-dried, ground, and passed through a 2 mm mesh for the measurement of the physical and chemical properties used to evaluate the soil fertility and to determine the effects of management intensity. Eight soil attributes were measured for each sample. (1) Particle-size distribution was determined using the pipette method (Gee and Or 2002) and classified based on the USDA soil classification system (Askari and Holden 2015). (2) Soil cores were oven-dried...
at 105 °C for 24 h within 1 d after sampling to determine BD by the dry-weight method. (3) pH was measured with a pH meter. (4) Soil OC concentrations were determined using the Walkley–Black method (Nelson and Sommers 1982). (5) Total N (TN) concentration was measured using the Kjeldahl method (Bremner and Mulvaney 1982). (6) Total P (TP) concentration was determined colorimetrically after wet digestion with sulphuric and perchloric acids (Olsen and Sommers 1982). (7) Also, available potassium (AK) concentration was determined colorimetrically with nitric acid (Zhou 1988). (8) Then, available P (AP) concentration was determined using the molybdenum-blue colorimetric method (Zhou 1988).

The eight indicators for the two study sites were used because they are easily influenced by soil fertility. In particular, soil pH is critical for plant growth, nutrient cycling, and biological activity. Soil OC affects several important soil functions, and as it well influences physical, chemical, and biological properties of soil. It prevents soil erosion, enhances soil nutrient/water storage and supply and thus soil fertility (Baldock and Nelson 2000). To better characterise the investigated soils, anthropogenic impact along with soil nutrient, soil BD, TN, TP, AK, and AP were also treated as indicators. Because soil and crop management practices have significant effect on these parameters, they were considered to be good indicators of soil fertility.

Calculations

The stocks of soil OC, N, and P in each soil layer (SOC\textsubscript{i}, SN\textsubscript{i}, and SP\textsubscript{i} in Mg ha\textsuperscript{-1}) were calculated as follow:

\[ \text{SOC}_{i} = \frac{D_{i} \times BD_{i} \times OC_{i}}{10} \]
\[ \text{SN}_{i} = \frac{D_{i} \times BD_{i} \times N_{i}}{10} \]
\[ \text{SP}_{i} = \frac{D_{i} \times BD_{i} \times P_{i}}{10} \]

where \( D_{i} \), \( BD_{i} \), \( OC_{i} \), \( N_{i} \), and \( P_{i} \) represent the thickness (cm), bulk density (g cm\textsuperscript{-3}), soil organic carbon (g kg\textsuperscript{-1}), total N (g kg\textsuperscript{-1}), and total P (g kg\textsuperscript{-1}), respectively, of the \( i \)th layer of soil.

To reduce data redundancy and to determine the most appropriate indicators of soil fertility, we used principal component analysis (PCA) and correlation analysis (Liu et al. 2012). The weighted loadings for each component were used to select the indicators. The 10% of the highest weighted loading was used as threshold for the selection. Correlation analysis was used to identify and eliminate the available variables, and the remaining independent indicators were used for developing the soil fertility (Askari and Holden 2015). Then, soil texture (sand, silt, and clay contents), pH, BD, OC, TN, TP, AK, and AP indicators were used to evaluate the soil fertility under grassland and cropland managements (Liu et al. 2012; Askari and Holden 2014). To determine the changes in soil fertility following the conversion of cropland to grassland, we calculated the values of soil fertility using the linear and nonlinear scoring functions to normalise the indicators (Hussain et al. 1999). For linear scoring, a “sigmoidal” function was used for the 0–20 cm soil layer (Xu 2003):

\[ \mu(x) = \begin{cases} 1 & x \geq x_0 \\ \frac{x}{x_0} & x < x_0 \end{cases} \]

where \( \mu(x) \) is the member score between 0 and 1; \( x \) is the value of measurement; \( x_0 \) is the upper limit of the soil variable; and OC, N, P, AP, and AK belong to this class (Xu 2003).

For nonlinear scoring, the “midpoint optimum” function was used for the 0–20 cm soil layer (Xu 2003):

\[ \mu(x) = \begin{cases} 1 & b_2 \geq x \geq b_1 \\ \frac{x - a_1}{b_1 - a_1} & a_1 < x < b_1 \\ \frac{x - a_2}{b_2 - a_2} & a_2 < x < b_2 \\ 0 & x \leq a_1 \text{ or } x \geq a_2 \end{cases} \]

where \( a_1 \) and \( a_2 \) are the upper and lower limits of the critical soil variable, respectively; \( b_1 \) and \( b_2 \) are the upper and lower limits of suitable soil variable, respectively; and pH, BD, and texture belong to this class (Xu 2003).

The values of soil fertility in the 0–20 cm soil layer were calculated using the principle of weighted additive method, with a mathematical model of Liu et al. (2012):

\[ FI_j = \sum_{i=1}^{n} W_j \times \mu_{ji} = 1, 2, 3 \ldots, n; \quad j = 1, 2, 3 \ldots, m \]

where \( FI_j \) is the \( i \)th (soil sample) value of the soil fertility evaluation; \( W_j \) is the \( j \)th weight value of the indicator, calculated using PCA. The greater the \( W_j \), the more the contribution to soil fertility. Then, \( \mu_{ji} \) is the degree of membership of soil fertility evaluation indicator; \( m \) is the number of soil fertility indicators, \( n = 14 \) (seven ages × two sites).

Kappa analysis was used to measure the statistical classification accuracy (significant difference) by evaluating the inter-raster agreement or arrangement between two inter-commentator (categorical) qualitative elements (Cohen 1968). The resultant Kappa coefficient, always less than or equal to 1, explained the agreement between the indices and the indicators. In this study, the Kappa analysis was done on a five-soil grade scale (Liu et al. 2012) — grade I (0.8–1.0, very high), grade II (0.6–0.8, high), grade III (0.4–0.6, moderate), grade IV (0.2–0.4, low), and grade V (0.0–0.2, very low).

Statistical analyses

A two-way analysis of variance was conducted for the datasets from each site to separately identify the differences among land uses (cropland and grassland),
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Characterisation and temporal trends of the main nutrients in the 0–10 and 10–20 cm soil layers under grassland compared with adjacent cropland in Bin and Shenmu County sites (mean ± standard error, unless otherwise stated) (Tables 1 and 2).

The conversion from cropland to grassland significantly increased soil OC, but this effect varied with soil depth and duration after conversion (Tables 1 and 2). The trends of increase were similar for both soil depths and were most rapid during 6–10 yr after planting grass. Specifically, soil OC content in the 0–10 cm soil layer increased by 2.03 and 1.3 g kg\(^{-1}\) (\(p < 0.05\)) during 6–10 yr after planting grass, respectively, in Bin and Shenmu Counties. Soil OC content in the 10–20 cm soil layer increased by 0.49 and 0.47 g kg\(^{-1}\) (\(p < 0.05\)) during 6–10 yr after planting grass in Bin and Shenmu Counties, respectively. Soil OC did not change significantly after 10 yr of land conversion at the two sites. Comparison of the two soil layers suggested that soil OC increase was higher in the 0–10 cm soil layer than in the 10–20 cm soil layer after land conversion.

Soil OC stock in the 0–20 cm soil layer increased by 2.22 and 1.86 Mg ha\(^{-1}\) (\(p < 0.05\)) during 6–10 yr after planting grass in Bin and Shenmu Counties (Figs. 2a–2d), respectively. However, soil OC did not change significantly after 10 yr of land conversion at the two sites.

Soil N and P dynamics

The conversion from cropland to grassland significantly increased TN and TP content in the soil, but this effect varied with soil depth and the duration after conversion (Tables 1 and 2). Soil TN and TP in the 0–10 cm soil layer increased, respectively, by 0.24 and 0.13 g kg\(^{-1}\) in Bin County and 0.16 and 0.06 g kg\(^{-1}\) in Shenmu County (\(p < 0.05\)) 6–10 yr after planting grass but not in the 10–20 cm soil layer. Soil TN and TP did not change significantly after 10 yr of land conversion at the two sites. Comparison of the two soil layers indicated that soil TN and TP increase was higher in the 0–10 cm soil layer than in the 10–20 cm soil layer after land conversion.

Soil TN and TP stocks also significantly increased after the conversion of cropland to grassland (Figs. 2b, 2c, 2e, and 2f). Soil TN and TP in the 0–20 cm soil layer increased, respectively, by 0.21 and 0.08 Mg ha\(^{-1}\) in Bin County and by 0.22 and 0.05 Mg ha\(^{-1}\) in Shenmu County 6–10 yr after planting grass. Soil TN and TP stock did not change significantly after 10 yr of land conversion at the two sites.

### Results

#### Soil OC dynamics

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### Note:

Different lowercase letters indicate significant differences between land use within each duration after land conversion and different uppercase letters indicate significant differences between duration after land conversion within each land use (\(p < 0.05\)). OC, soil organic carbon; TN, soil total nitrogen; TP, soil total phosphorus.

<table>
<thead>
<tr>
<th>Layer (cm)</th>
<th>Site</th>
<th>Nutrient</th>
<th>Grasland (g kg(^{-1}))</th>
<th>Cropland (g kg(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>0–10</td>
<td>Bin</td>
<td>OC</td>
<td>8.47 ± 0.51a</td>
<td>10.0 ± 0.51a</td>
</tr>
<tr>
<td></td>
<td></td>
<td>TN</td>
<td>0.87 ± 0.11a</td>
<td>1.11 ± 0.11a</td>
</tr>
<tr>
<td></td>
<td>Shenmu</td>
<td>OC</td>
<td>5.34 ± 0.08a</td>
<td>6.01 ± 0.08a</td>
</tr>
<tr>
<td></td>
<td></td>
<td>TN</td>
<td>0.44 ± 0.08a</td>
<td>0.50 ± 0.08a</td>
</tr>
</tbody>
</table>

### Table 1: Characterisation and temporal trends of the main nutrients in the 0–10 and 10–20 cm soil layers under grassland compared with adjacent cropland in Bin and Shenmu County sites (mean ± standard error, n = 3).

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Soil fertility dynamics

The results of commonality and weight indicator screening for soil fertility using PCA are summarised in Table 3. Soil fertility significantly increased ($p < 0.01$) with increasing soil OC, N, and P contents (Fig. 3). The values used to evaluate soil fertility under grassland and cropland before and after conversion (6, 10, 15, and 20 yr) at both sites are shown in Table 4. Soil fertility increased with increasing time after conversion but remained stable without conversion (i.e., under cropland). Soil fertility was highest 15 yr after land conversion in Bin County (0.77, grade II) and highest 20 yr after conversion in Shenmu County (0.58, grade III). Soil fertility increased by 13% and 26% after conversion from cropland to grassland in Bin (15 yr) and Shenmu (20 yr) Counties, respectively. The highest changes in soil fertility was 6–10 yr after land conversion. Soil fertility was relatively stable after 10 yr of land conversion at the two sites.

Discussion

Land conversion and soil OC, N, and P

The conversion of cropland to grassland in the study significantly increased soil OC, N, and P contents at both investigated sites, supporting the hypothesis that land conversion increases soil nutrient content. This is consistent with previous studies on soil nutrient following the conversion of croplands to grasslands in semiarid areas (Bronson et al. 2004; Breuer et al. 2006; Deng et al. 2014). There are several main reasons for the higher soil nutrient after conversion from cropland to grassland.

First, restoration of grassland following abandonment of cropland is a form of establishment of live vegetation with the ecological characteristics necessary to facilitate soil OC and N accumulation (McLauchlan et al. 2006). For example, *M. sativa* is a legume plant with the ability to fix N into the soil and therefore could support soils with OC and N enrichment (He et al. 2016). The biomass of extensive fine roots of *M. sativa* can also importantly

### Table 2. Analysis of variance of soil organic carbon and nutrient content for land use (L) and duration after land conversion (A).

<table>
<thead>
<tr>
<th>Location</th>
<th>Layer (cm)</th>
<th>Main factor</th>
<th>OC</th>
<th>TN</th>
<th>TP</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>$F$</td>
<td>$P$</td>
<td>$F$</td>
</tr>
<tr>
<td>Bin</td>
<td>0–10</td>
<td>Land use</td>
<td>27.3</td>
<td>0.000</td>
<td>21.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Age</td>
<td>2.29</td>
<td>0.144</td>
<td>0.76</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Land use × age</td>
<td>2.29</td>
<td>0.144</td>
<td>2.46</td>
</tr>
<tr>
<td></td>
<td>10–20</td>
<td>Land use</td>
<td>19.8</td>
<td>0.001</td>
<td>5.90</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Age</td>
<td>0.62</td>
<td>0.553</td>
<td>0.23</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Land use × age</td>
<td>0.64</td>
<td>0.543</td>
<td>0.98</td>
</tr>
<tr>
<td>Shenmu</td>
<td>0–10</td>
<td>Land use</td>
<td>122.2</td>
<td>0.000</td>
<td>106.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Age</td>
<td>15.4</td>
<td>0.000</td>
<td>30.68</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Land use × age</td>
<td>0.21</td>
<td>0.885</td>
<td>2.10</td>
</tr>
<tr>
<td></td>
<td>10–20</td>
<td>Land use</td>
<td>0.51</td>
<td>0.487</td>
<td>3.87</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Age</td>
<td>1.02</td>
<td>0.181</td>
<td>3.29</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Land use × age</td>
<td>0.44</td>
<td>0.725</td>
<td>0.20</td>
</tr>
</tbody>
</table>

**Note:** OC, soil organic carbon; TN, soil total nitrogen; and TP, soil total phosphorus.

### Table 3. Results of principal component analysis (PCA) indicating the properties of the tested indicators used to characterise soil fertility under cropland and grassland in the Bin and the Shenmu counties study areas.

<table>
<thead>
<tr>
<th>PCs parameters</th>
<th>PC1</th>
<th>PC2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eigenvalue</td>
<td>7.38</td>
<td>1.50</td>
</tr>
<tr>
<td>Variance (%)</td>
<td>73.76</td>
<td>15.03</td>
</tr>
<tr>
<td>Cumulative (%)</td>
<td>73.76</td>
<td>88.79</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Indicators</th>
<th>Eigenvector</th>
<th>Communalities</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand</td>
<td>0.882</td>
<td>0.189</td>
<td>0.813</td>
</tr>
<tr>
<td>Silt</td>
<td>0.923</td>
<td>0.166</td>
<td>0.879</td>
</tr>
<tr>
<td>Clay</td>
<td>0.899</td>
<td>0.291</td>
<td>0.893</td>
</tr>
<tr>
<td>pH</td>
<td>−0.939</td>
<td>0.055</td>
<td>0.886</td>
</tr>
<tr>
<td>BD</td>
<td>−0.726</td>
<td>0.527</td>
<td>0.805</td>
</tr>
<tr>
<td>OC</td>
<td>0.809</td>
<td>0.570</td>
<td>0.979</td>
</tr>
<tr>
<td>TN</td>
<td>0.840</td>
<td>0.527</td>
<td>0.983</td>
</tr>
<tr>
<td>TP</td>
<td>0.944</td>
<td>−0.189</td>
<td>0.926</td>
</tr>
<tr>
<td>AP</td>
<td>0.738</td>
<td>−0.609</td>
<td>0.915</td>
</tr>
<tr>
<td>AK</td>
<td>0.857</td>
<td>0.254</td>
<td>0.799</td>
</tr>
</tbody>
</table>

**Note:** BD, bulk density; OC, organic carbon; TN, total nitrogen; TP, total phosphorus; AP, available phosphorus; and AK, available potassium.

### Table 4. Integrated evaluation grades of soil fertility under cropland and grassland vegetation for the sites in Bin and Shenmu Counties.

<table>
<thead>
<tr>
<th>Location</th>
<th>Land use</th>
<th>6 yr</th>
<th>10 yr</th>
<th>15 yr</th>
<th>20 yr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bin County</td>
<td>Grassland</td>
<td>0.64 II</td>
<td>0.75 II</td>
<td>0.77 II</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>Cropland</td>
<td>0.66 II</td>
<td>0.64 II</td>
<td>0.68 II</td>
<td>—</td>
</tr>
<tr>
<td>Shenmu</td>
<td>Grassland</td>
<td>0.45 III</td>
<td>0.55 III</td>
<td>0.56 III</td>
<td>0.58 III</td>
</tr>
<tr>
<td></td>
<td>Cropland</td>
<td>0.41 III</td>
<td>0.43 III</td>
<td>0.41 III</td>
<td>0.46 III</td>
</tr>
</tbody>
</table>

**Note:** —, no data.
Fig. 2. Effects of land conversion from cropland to grassland on the stocks of (a and d) organic carbon, (b and e) total nitrogen, and (c and f) total phosphorus in the 0–20 cm soil layer in Bin and Shenmu Counties. *, denotes significant treatment differences at each age of plantation based on pairwise comparisons ($p < 0.05$). **, denotes significant treatment differences at each age of plantation based on pairwise comparisons ($p < 0.01$).

contribute to soil OC and N store in grassland soils (Guo and Gifford 2002). Deep-rooting native vegetation in dryland could favour the uptake of N at deep soil profile and concurrently replenish nutrient content in surface soils by releasing N during decomposition (Breuer et al. 2006; Fu et al. 2010).

Second, the long-term removal of crop residues reduces organic matter input into the soil coupled with sparse vegetation cover at harvest loosens the surface soil and reduces soil OC content in the top soil of cultivated lands. This difference in soil OC, N, and P contents is explained in terms of tillage, which destroys soil macro-aggregates and induces mineralization of released organic matter (Post and Kwon 2000; Six et al. 2000). Tillage and cultivation disrupt soil macro-aggregates, decreasing the physical protection of OC, and creating a more oxidative soil environment that results in lower soil nutrients (Wei et al. 2013). In addition, low aggregate stability in cultivated soils resulting from frequent soil disturbance via intensive tillage could affect soil C and N accumulation. This is because the physical protection provided by organic matter is lost, and the resulting unstable aggregates enhance organic matter mineralization, leading to significant soil OC and N loss (Wei et al. 2013).
Third, other factors could cause soil nutrient loss, soil organic matter decomposition, and litter loss (by high winds) in croplands. However, perennial species such as *M. sativa* can capture more plant residue (both above-ground and belowground) and thereby reduces loss of soil organic matter (He et al. 2016).

As in many other studies (Houghton et al. 1991; Davidson and Ackerman 1993), soil OC, N and P stocks, and soil fertility increased rapidly within 6–10 yr after the conversion of cropland to grassland (Fig. 2). However, Vesterdal et al. (2002) noted that the establishment of grasslands on croplands had no effect on soil OC after 30 yr. Soil OC content in the 0–5 cm soil layer was significantly higher after 10 yr of grass restoration on abandoned sloping croplands on the Loess Plateau (He et al. 2016). Soil OC content decreased in the initial 5 yr of the “Grain-for-Green” programme for the restoration of sloping croplands with grassland (Zhang et al. 2010). Soil OC could be influenced by multiple factors, including climate, grass species, soil texture, and soil depth (Li et al. 2012). These results indicate the importance of considering multiple conditions when predicting soil OC, N, P concentrations and stocks, and soil fertility due to the conversion of cropland to grassland.

Soil OC, N, and P contents were higher in Bin County than in Shenmu County, probably because of their distribution in the soil (von Lutzow et al. 2007; Beheshti et al. 2012). The average silt and clay fractions in the 0–10 cm soil layer in the study area was higher in Bin County (51%) than Shenmu County (27%), corresponding with the higher OC, N, and P in Bin County. Correspondingly, Beheshti et al. (2012) observed that soil OC and N content in surface soil layers was higher in silt and clay fractions than in sand fraction. In addition, soil OC decomposes more quickly in sandy soils, leading to rapid loss in this soil type (Hofstede et al. 2002). A further important parameter responsible for the differences in soil OC, N, and P is climate, including precipitation. The amount of precipitation controls both aboveground and belowground net primary productivity and thus organic matter input into the soil (Wiesmeier et al. 2013). In this study, the higher mean annual precipitation in the Bin County (~600 mm) than Shenmu County (~400 mm) was the most likely cause of the higher soil nutrient in Bin County. Miller et al. (2004) also showed that soil OC and N increased with increasing mean annual precipitation. In addition, environmental factors such as drought, intensive rainfall, and high winds can cause soil erosion, resulting in the depletion of soil nutrient on sloping landscapes as in Shenmu County (Fu et al. 2010).

**Land conversion and soil fertility**

The eight soil properties measured in this study have also been used in other studies as potential indicators for soil fertility (Lima et al. 2013; Askari and Holden 2015). Soil texture is the most fundamental physical property used in qualitative analysis of soil (Schoenholtz et al. 2000), and it is regarded as one of the most effective soil fertility indicators (Li et al. 2013). We, therefore, used soil texture as one of the fixed soil properties, although we excluded it from PCA (Askari and Holden 2015). Although the linear approach is simple and practical (Masto et al. 2008), the nonlinear method could represent the functions of the system in soil fertility evaluation (Sinha et al. 2009). The “sigmoidal” indicators (including soil OC, N, P, AP, and AK) along with the “midpoint optimal” indicators (including BD and pH) are also extensively used as indicators for soil nutrient availability, soil fertility, plant growth, and crop productivity (Liu et al. 2012). The method used in this study was mathematically biased, providing the required flexible to determine the indices with ready understanding of soil fertility evaluation (Askari and Holden 2014).
The framework used for indexing soil fertility under semiarid conditions, particularly the nonlinear and weighted integration framework, was responsive to the difference in soil fertility and therefore suitable for determining the effect of management intensity on soil fertility (Askari and Holden 2014). The approach was more practical than statistical measure of soil fertility as in the general indicator of soil quality (Velasquez et al. 2007). As statistical factors have no inherent meaning, their interpretations based on variable scores could be misleading (Rossi et al. 2009). In general, the value of the indices mostly suggested good to moderate soil fertility in the studied area.

Our results showed that soil fertility increased by 13% and 26% after the conversion of cropland to grassland in Bin County (15 yr) and Shenmu County (20 yr), respectively (Table 4). This supported our hypothesis that the conversion of cropland into grassland could improve soil fertility. Wei et al. (2009) concluded that the content of soil OC was lower in the northern than in the southern region of the Loess Plateau, which underscored the fact that soil fertility was positively correlated with soil OC content (Fig. 3). Soil fertility was higher in grassland than in cropland, consistent with the findings by Xu et al. (2005). Intensification of cropland management is associated with low soil OC and N contents, decreasing soil fertility, and crop productivity (Askari and Holden 2014).

Soil fertility was higher in Bin County than in Shenmu County (Table 3), very likely driven by “soil class” (Breuer et al. 2006) and climatic conditions such as precipitation. In Wyoming, USA, Robles and Burke (1998) noted that soil fertility in a pair of sites with croplands and grasslands was the same because of the same “soil class” and slow recovery of former grasslands, concluding that recovery under natural grassland conditions was a long-term process. The higher precipitation was another factor for the higher soil fertility in Bin County. Microbial decomposition of soil organic matter (a major contributor to soil fertility) largely depends on soil moisture condition (Wiesmeier et al. 2013). Therefore, it was concluded that change in soil fertility was not only driven by land conversion but also by differences in “soil class” and climatic conditions such as precipitation.

**Conclusions**

A detailed land use history on the conversion from cropland to grassland for the period of 1994–2014 was used to determine soil fertility in Bin and Shenmu Counties in China’s Loess Plateau region. The results of this study showed that the conversion of cropland to grassland improved soil OC, N, and P, thereby enhancing soil fertility at both sites, especially in the 0–10 cm soil layer. The variation in the amounts of soil OC, N, and P could be due to variations in soil conditions such as parental material. Improvement in soil fertility could continue increase age of restored grassland, with significant implications for land management in the semiarid area. Therefore, grasslands can be the ideal vegetation type for optimal sequestration of soil OC, N, and P in the two counties in the Loess Plateau. Soil OC, N and P contents, and soil fertility increased rapidly in first 6–10 yr after the conversion of cropland to grassland, then reached a new equilibrium after 10 yr. Changes in soil fertility were driven not only by land conversion but also by differences in soil classes and climatic conditions such as precipitation.

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**References**


