Evaluating the soil quality of newly created farmland in the hilly and gully region on the Loess Plateau, China

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Abstract: In order to better understand the quality of newly created farmland (NF) as well as slope and check-dam farmland (CF) soil quality, two typical traditional farmland areas within the hilly and gully region of Chinese Loess Plateau were selected as controls in this analysis. The results of this study initially reveal that pH values for slope farmland (SF) and CF were significantly lower ($P < 0.05$) than those for NF and that SF values were always greater than those of their CF counterparts. At the same time, cation exchange capacity (CEC) and soil organic matter (SOM) occurred in the following size-decreasing sequence, i.e., CF, SF, and NF. Data also show that long-term planting has resulted in increases in total nitrogen (N), available N, total phosphorus (P), available P, total potassium (K) and available K and has also enhanced concentrations of soil copper (Cu), zinc (Zn), iron (Fe), and manganese (Mg) as well as soil cadmium (Ca), lead (Pb), chromium (Cr), and mercury (Hg). These latter elements occur in the concentration sequence of SF > CF > NF. Overall, results indicate that long-term planting negatively impacts soil health because of the accumulation of toxic heavy metals. This means that farmland planted over longer timescales needs to lie fallow to enable it to rehabilitate while NF requires the addition of organic matter as well as rotational utilization in order to facilitate the development of green agriculture.

Keywords: Loess Plateau; land use; soil quality; heavy metals

1   Introduction

The Loess Plateau covers approximately 62.4×10^4 km^2 within China and comprises one of the most severe regions for soil erosion globally because of numerous gullies. The dominant form of agricultural farmland in this region is found on slopes less than 15°, encompassing 56.3% of the total on the plateau. A second abundant form of farmland is of a check-dam type, the most widespread structures used for controlling soil and water loss in this region, which encompass about 9% of the overall total. Check-dam farming is, however, responsible

for 20.5% of the total food production derived from the hilly and gully region (Chen *et al.*, 2015; Liu *et al*., 2018).

The Chinese government implemented the Grain for Green (GFG) project in 1999 in order to reduce soil erosion, the largest vegetation ecological restoration program put in place since the founding of the People's Republic of China in 1949. Vegetation coverage on the Loess Plateau has greatly increased from 31.6% in 1999 to 59.6% in 2013 (Wang *et al.*, 2011). Regional soil erosion has therefore been effectively reduced and annual sediment discharge into the Yellow River declined to 1.73 Gt in 2013, close to primordial agricultural period levels (Chen *et al*., 2015). This largest vegetation restoration program also resulted in a grain deficit in partial regions on the Loess Plateau because this area exceeded the 105% of the upper limited area set by the GFG program (2.36 million ha) in 2008. As a result, 4.83 million ha of cropland was converted to forest and grassland on the Loess Plateau between 2000 and 2008, which doubled the limitation area for the GFG Program (Tang *et al*., 1998; Lu *et al*., 2012).

Liu *et al*. (2015) analyzed the benefits of useful agricultural productivity to meet the food supply needs of an expanding population. In order to address this contradiction between population and farmland shortages, the Chinese government implemented a program entitled 'Filling gullies to create farmland on the Loess Plateau' within the city of Yan'an on the Loess Plateau hilly and gully region in Shaanxi Province. This area within northern China includes 12.68% of the Loess Plateau area. Around 800 million USD dollars were invested in this project which created 333 million hectares of farmland between 2013 and 2017 (He, 2015; Liu *et al*., 2015). This approach, filling gullies to create farmland, involves the removal of soil from surrounding hills and then using this to infill channels. The flat fields created within these channels are then used for cultivation and ultimately increase the area of farmland on the Loess Plateau.
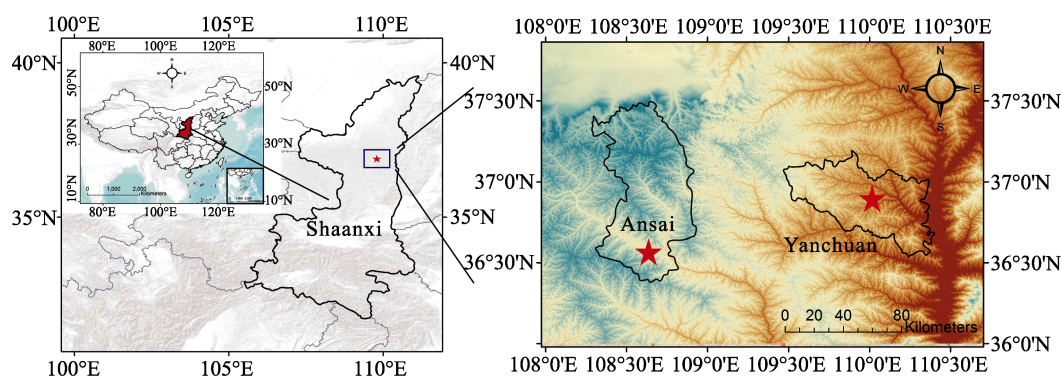
The completion of this gully filling project is one desirable outcome for regional sustainable development. It is clear that soil fertility plays a key role in both the growth of crops and their productivity. At the same time, however, little information is currently available about whether the fertility of new farmland will meet the needs for crop growth. In order to assess this outstanding question, a series of soil samples were collected from newly created (NF), slope (SF), and check-dam (CF) farmland and a range of physical and chemical parameters (i.e., pH, cation exchange capacity (CEC), organic matter content, concentrations of total nitrogen (N), available N, total phosphorus (P), available P, total potassium (K), and available K as well as heavy metals were measured in order to evaluate both the quality of NF and agricultural sustainability. Typical and primary farmland types (i.e., SF and CF lands) were selected as comparative samples.

2 Materials and methods

2.1 Study area and sample site

The soil samples evaluated in this study were collected from within the Liangjiahe (110°43'E, 36°50'N) and Nangou watersheds (109°17'E, 36°35'N), examples of typical hilly and gully regions on the Loess Plateau (Figure 1). These watersheds encompass the towns of Wen'anyi and Gaoqiao, respectively, within the city of Yan'an in Shaanxi Province. The av-

erage annual temperature in this region ranges between 8.5℃ and 9.5℃, accumulated temperature (greater than or equal to 10℃) ranges between 3100℃ and 3300℃, the frost-free period ranges between 162 days and 190 days, and average annual precipitation ranges between 520 mm and 550 mm, all indicating a warm-temperate, arid and semi-arid climate zone (Zhang *et al*., 2016). Almost 70% of regional precipitation is concentrated in summer months when there is a high probability of heavy rains, floods, and droughts (Zhou *et al*., 1997).

Figure 1　Maps showing the sample collection site. The five-pointed star denotes the sampling sites within Shaanxi Province, China.

Nine sample plots of 10 m × 10 m each were selected from NF, SF, and CF regions, respectively. Specifically, NF areas within the Liangjiahe and Nangou watersheds were created in 2015 and have subsequently not been cultivated, while CF areas were implemented in the 1970s, and SF areas have been cultivated for more than 40 years. Maize (*Zea mays L.*) and potato (*Solanum tuberosum L.*) are cultivated extensively in both SF and CF areas. A total of five sample points were selected in each case using the 'diagonal' method during winter 2017; plough layer soil was collected from the surface to a depth of 20 cm and was mixed evenly before approximately 1 kg of loess was placed in polythene bags and brought to the laboratory for analysis. The soil type within these sampling regions is Huangmian Soil (*Calcaric Cambisols*, FAO) developed from loess parent material.

2.2　Sample analysis

Composite soil samples were sieved through a 2 mm nylon griddle to completely remove sundries, pebbles, roots, and litter before being air dried at room temperature. Subsamples of less than 2 mm air-dried soil were again ground to pass through 0.149 mm, 0.25 mm, and 1.00 mm nylon sieves for further soil chemical analyses. The fraction less than 1.00 mm in size was used for soil pH as well as available N, P, K, and trace element analyses. The fraction less than 0.25 mm in size was then also used for soil organic matter as well as total N, P, K, and soil CEC capacity analyses, while the fraction less than 0.149 mm in size was used for total trace elements and heavy metal analyses.

Soil pH values were determined using the potential method (i.e., soil:water ratio 1:2.5) (GB7859-1987), while organic matter content was determined via hot oxidation with potassium dichromate and sulfuric acid (Yeomans *et al.,* 1988). Soil total N and P contents were

determined using the Kjeldahl digestion procedure (Bremner *et al*., 1972) and molybdenum antimony blue colorimetry (Murphy *et al*., 1962), respectively, while total K was determined using the HF-HClO$_4$ digestion method (Jackson, 1969). The amount of available N was released and transformed to NH$_3$ using 1.07 M NaOH and FeSO$_4$ powder at 40°C for 24h, and then absorbed with 2% (w/v) H$_3$BO$_3$, and finally titrated with 0.005M H$_2$SO$_4$ (Lu, 2000). The amounts of available phosphorus and potassium were then determined by extracting samples with 0.5 M NaHCO$_3$ (pH = 8.5) at a solution:solid ratio of 20:1 for 30 minutes (Olsen *et al*., 1982) and 0.2 M cold HNO$_3$ at a solution:solid ratio of 20:1 for 30 minutes (Bao, 2002), respectively. Soil CEC was measured following soil treatment with NaOAc (pH = 8.2) and NH4OAc solutions (pH = 7.0) (Lu, 2000).

Values for available iron (Fe), manganese (Mn), zinc (Zn), and copper (Cu) in soils were determined using the diethylenetriaminepentaacetic acid (DTPA) micronutrient extraction method (Lindsay *et al*., 1978). In order to determine contents of total Fe, Mn, Zn, Cu, chromium (Cr), cadmium (Cd), lead (Pb), and mercury (Hg) in soils, samples were digested with a typical concentrated acid mixture (HCl-HNO$_3$-HF-HClO$_4$) (Zheng *et al*., 2016) and metal concentrations were analyzed using atomic absorption spectroscopy (AAS; ZEEnit 700 P, Analytik Jena, Germany). Concentrations of Fe, Cu, Zn, Mn, and Cr were measured using the AAS air acetylene flame method applying an electrically modulated deuterium-HCL background correction. Hydride-forming Hg elements were measured using the AAS HS55 Hydride System, while concentrations of Pb and Cd were measured using the AAS graphite furnace coupled with a MPE 60 graphite autosampler, applying two-field mode Zeeman effects background correction. All metal concentrations were tested three times in this study and expressed in micrograms per gram on a dry weight basis (mg·kg^{-1} dw).
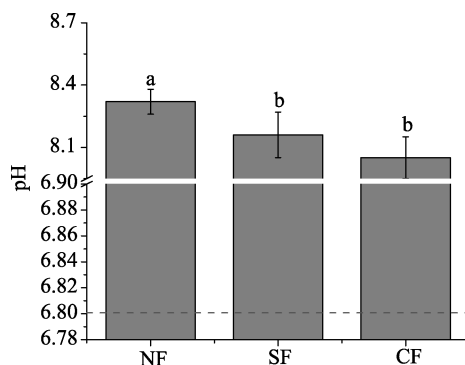
2.3　Statistical analysis

One-way analysis of variance was used to determine the effects of land use on soil quality indicators, while the least significant difference (LSD) method was applied for multiple comparisons. All statistical analyses were performed using the software SPSS 20.0 (IBM SPSS Statistics, IBM Corp., USA), and a significance level $P<0.05$ was applied unless stated otherwise.

3　Results
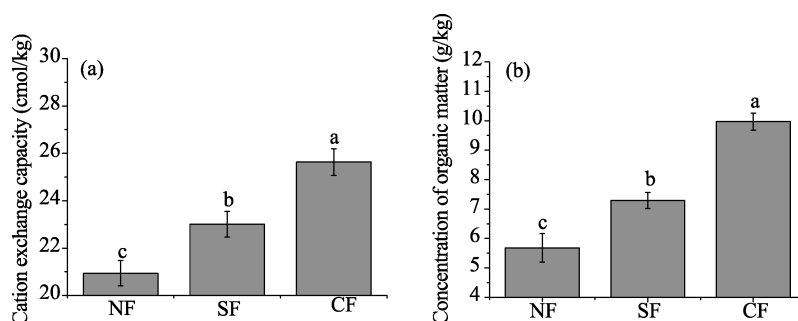
3.1　Soil pH, CEC, and organic matter

The results of this analysis reveal that different types of farmland are characterized by a range of pH values (Figure 2). Data show that pH values for loess were significantly higher than the national average values (pH ≈ 6.8) from a second soil survey (1979–1983), while compared with NF, pH values for SF and CF were significantly lower ($P < 0.05$) than those for

Figure 2　Comparisons between soil pH values in three loess types. Bars (means values ± SD from six independent experiments) with different letters are significantly different at the 0.05 level (n = 6) based on LSD multiple comparisons. The dotted line denotes soil pH background levels (1979-1983).

NF but for SF pH values were greater than those recorded for CF soils.

The data presented in Figure 3 highlight changes in CEC (Figure 3a) and organic matter content (Figure 3b) in the different farmland types. The CEC size sequence recovered in this analysis (from largest-to-smallest) was CF, SF, and NF; differences between these three types were statistically significant ($P < 0.05$) (Figure 3a). Indeed, compared with NF samples, long-term planting has resulted in an increase in soil organic matter concentration (Figure 3b). The organic matter order recovered here (from largest-to-smallest) was CF, SF, and NF; data show that the NF content is lower than values seen in nine grade standards from Shaanxi Province (less than 6.00 g·kg^{-1}) (Guo, 1992) and therefore extremely deficient and unfavorable for crop growth and development.
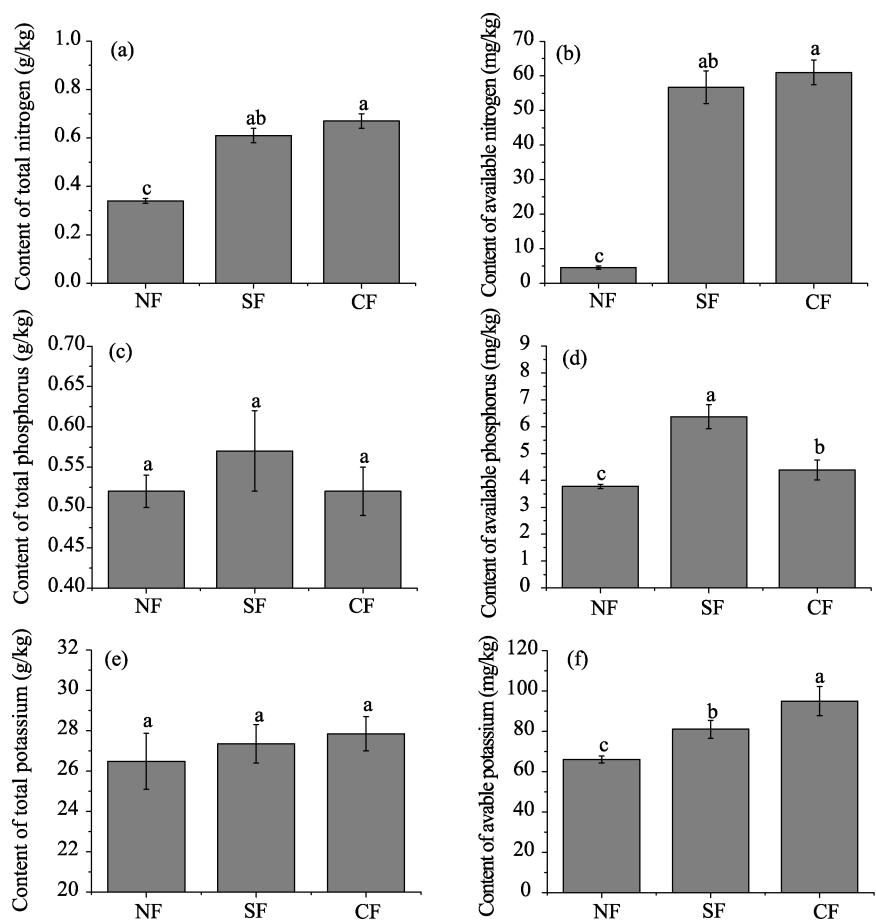

Figure 3   Comparisons between concentrations of soil CEC (a) and organic matter (b) in three types of loess soils. Bars (means values ± SD from three independent experiments for CEC or six independent experiments for organic matter) with different letters are significantly different at the 0.05 level based on LSD multiple comparisons.
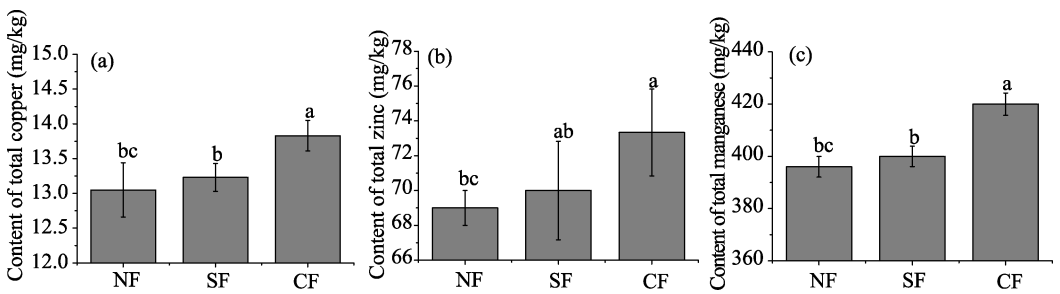
3.2   Soil macro elements

The data presented in Figure 4 illustrates changes in macroelement content within different types of farmland. Results show that compared with NF values, long-term planting has resulted in increases in total (Figure 4a) and available N (Figure 4b) as well as total (Figure 4c) and available P (Figure 4d), and total (Figure 4e) and available K (Figure 4f) concentrations. The order of change recovered in concentrations of total and available N as well as total and available K (from largest-to-smallest) were CF, SF, and NF, while concentrations of total (greater than 0.6 g·mg^{-1}) and available N (greater than 30 g·mg^{-1}) were all below basic six grade criteria for national nutrient levels on NF. These data show that NF soils within this study are unhealthy even though these regions are characterized by abundant potassium, at higher levels than those required by loess criteria (i.e., greater than 6 mg·kg^{-1} for total and greater than 50 mg·kg^{-1} for available K, respectively) (Guo, 1992). The concentration order of change for total and available P (from largest-to-smallest) was SF, CF, and NF; total and available P concentrations did not, however, attain necessary loess criteria in any sample (i.e., greater than 0.6 mg·kg^{-1} and greater than 5 mg·kg^{-1}, respectively) (Guo, 1992).

3.3   Soil microelements

The data presented in Figures 5 and 6 show changes in microelement contents given different patterns of soil utilization. These results reveal that compared with NF (Figure 5),
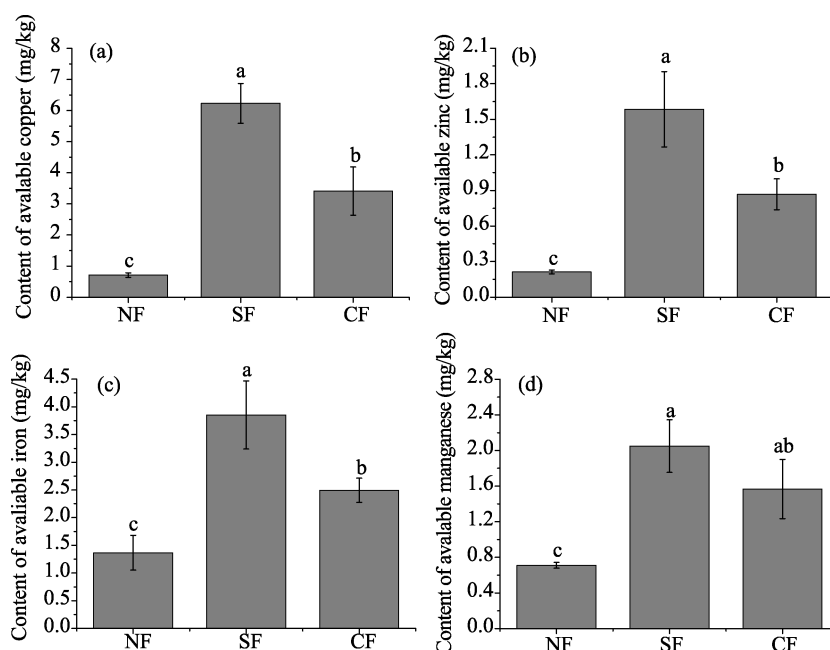
Figure 4 Comparisons between concentrations of total N (a), available N (b), total P (c), available P (d), total K (e) and available K (f) in three loess types. Bars (mean values ± SD from six independent experiments) with different letters are significantly different at the 0.05 level (n = 6) based on LSD multiple comparisons.

Figure 5 Comparisons between contents of total Cu (a), Zn (b), and Mn (c) in three loess types. Bars (mean values ± SD from three independent experiments) with different letters are significantly different at the 0.05 level (n = 3) based on LSD multiple comparisons.

concentrations of total Cu (Figure 5a), Zn (Figure 5b), and Mg (Figure 5c) have all been enhanced by long-term planting ($P > 0.05$), an order of change from largest-to-smallest of CF, SF, and NF. It is also the case that NF long-term planting has enhanced concentrations of soil available Cu ($P < 0.05$), Zn ($P < 0.05$), Fe ($P < 0.05$), and Mg ($P < 0.05$) even though

Figure 6   Comparisons between contents of soil available Cu (a), Zn (b), Fe (c), and Mn (d) in three loess types. Bars (mean values ± SD from three independent experiments) with different letters are significantly different at the 0.05 level (n = 3) based on LSD multiple comparisons.

values for these parameters were significantly lower in CF cases than in SF ($P < 0.05$), with the exception of the latter element. Available Fe and Mg contents in all farmland types did not attain levels required by loess criteria, greater than 5.0 mg·kg^{-1} and greater than 10 mg·kg^{-1}, respectively. Values for available Zn content also did not reach the necessary level, greater than 1.0 mg·kg^{-1}, with the exception of the SF case (Guo, 1992).
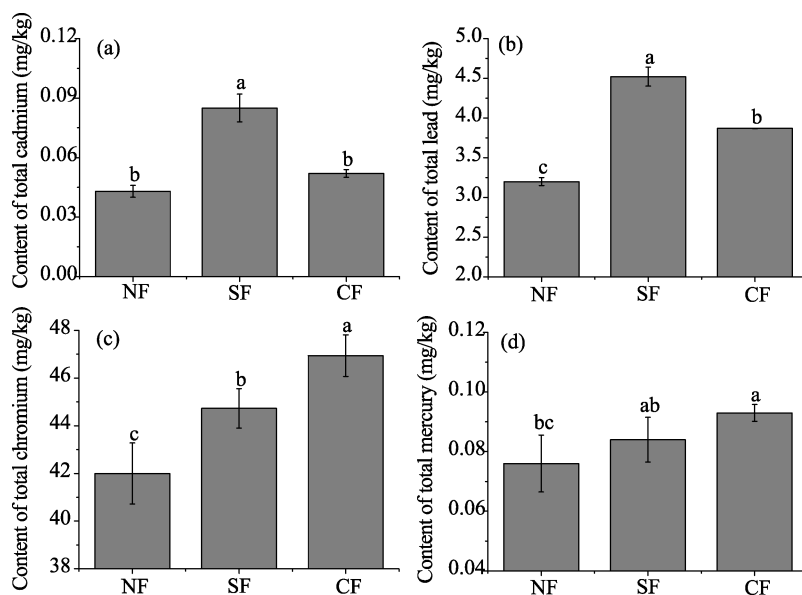
3.4   Soil toxic elements

The data presented in Figure 7 highlight trends in concentrations of soil Cd (Figure 7a) as well as total Pb (Figure 7b), Cr (Figure 7c), and Hg (Figure 7d) in different farmland types. Although long-term planting has increased the concentrations of all these toxic elements in soil, the effects of different farmland types are significantly different with respect to Cd and Pb concentrations, in sequence from largest-to-smallest SF, CF, and NF. The concentration order for Cr and Hg from largest-to-smallest was CF, SF, and NF. Data show that Hg concentrations in all farmland types exceeded the safe background value of 0.06 mg·kg^{-1} (Xue, 1986).

4   Discussion

4.1   Loess pH values

The physicochemical and biological properties of soils have always been influenced by pH values. Indeed, soil pH is well known to play a significant role in fertility formation and evolution (Brady *et al*., 1999; Aciego *et al*., 2008). Previous research performed as part of

Figure 7 Comparisons between concentrations of total Cd (a), Pb (b), Cr (c), and Hg (d) in three loess types. Bars (mean values ± SD from three independent experiments) with different letters are significantly different at the 0.05 level (n = 3) on the basis of LSD multiple comparisons.

the second soil survey (1979–1983) has shown that loess pH values for NF, SF and CF lands all tend to be significantly higher than the national average (pH ≈ 6.8), being 22%, 20%, and 18%, respectively. It is also the case that long-term planting acts to significantly decrease loess pH values but there is nevertheless an insignificant difference between SF and CF lands in this analysis. In terms of plant growth, NF lands require amelioration via acidic comprehensive fertility because a neutral pH is advantageous to both crop growth and development; a range between pH 5.5 and pH 6.5 has been shown to be best for potato and tomato growth (Islam et al., 1980).

4.2   Loess organic matter

The quality and fertility of soils can be characterized on the basis of numerous basic chemical parameters, including CEC, organic matter, and total N. The first of these variables, CEC, is an indicator of soil quality and fertility; thus, a higher CEC concentration equates to better soil quality and fertility (Brady et al., 2002). The results of this analysis show that different farmland types have significantly different effects on CEC capacity ($P < 0.05$) (Figure 2a); results reveal a CEC size sequence from largest-to-smallest of CF, SF, and NF. The data suggest that the fertility of CF lands is better than that of their SF counterparts, while NF areas are the worst of the three loess types.

Organic matter content is the dominant index for assessing soil quality in agricultural practice (Bellamy et al., 2005). Long-term cultivation has resulted in an increase in the concentration of soil organic matter (Wang et al., 2015), from largest-to-smallest CF, SF, and NF. Soil CEC is closely correlated with pH values and SOM content (Caravaca et al., 1999; Von Oheimb et al., 2008); results show that CEC is negatively related to soil pH values (r = −0.579) and positively related to SOM (r = 0.737), consistent with previous research (Qiu et

al., 2010). Results show that soil organic matter content does not reach the necessary nine grade standard within Shaanxi Province (greater than 6.00 g·kg^{-1}) (Guo, 1992) for NF lands and is therefore extremely deficient and unfavorable for the growth and development of crops. Appropriate amounts of organic matter must therefore be added to NF lands and pH values must be decreased in order to increase both CEC capacity and soil quality.

4.3 Loess macroelements

Chemical elements play very important roles in plant growth and development. At the same time, however, different elements perform varied physiological functions within plant life-cycles and can be classified as either macroelements (e.g., N, P, and K), medium elements, (e.g., Ca, Mg, and S), or trace elements (e.g., Fe, Mn, Cu, Zn, Mo, and Cl) according to vital growth requirements (Kalavrouziotis *et al*., 2008; Li *et al*., 2010).

N retention and supply are thought to be influenced by soil organic matter (Brubaker *et al*., 1993). This element is the key raw material for amino acids and also performs a very important function in soil fertility. The results of this study show that the concentration of total N was insignificantly higher ($P < 0.05$) in both SF and CF lands compared to NF lands. Available N is directly absorbed by crops and influences both growth and yield (Macdonald *et al*., 2009); data show that this element occurs at significantly higher levels in both SF and CF lands compared to NF areas. It is also the case that fertility in SF and CF cases tends to be higher in terms of soil organic matter and N when compared to NF situations. This result implies that NF lands require a supply of both soil organic matter and N.

The element P is an important nutrient necessary for both plant growth and development. However, although soil contains a large proportion of total P, just a relatively small component is immediately available to plants (Richardson *et al*., 2009); this means that ensuring a suitable volume of this element in soils is critical for both crop growth and agricultural productivity. The results of this study also reveal that the concentration change order of total and available phosphorus was SF, CF, and NF (from largest-to-smallest) but that total phosphorus concentration did not reach the required loess criterion level in all cases (greater than 0.6 mg·kg^{-1}). As this was also the case for available phosphorus concentrations (greater than 5 mg·kg^{-1}) (Guo, 1992) it is clear that deficiencies decrease crop yields as available P is almost universally required to maintain production (Sundara *et al*., 2002). The results of this analysis therefore suggest that phosphorus fertilization should be carried out to improve crop yields on NF lands.

The element K is also key for plant growth and development; the presence of this metal enhances saccharide transport ratios and photosynthesis in natural ecosystems (Tripler *et al*., 2006), while the presence of soil available K trapped between interlayers of clay minerals is an important resource for plant growth in many soils (Mengel *et al*., 1993). The results of this analysis demonstrate that long-term planting enhances concentrations of both total and available K; indeed, available contents of this metal equaled (or exceeded) loess criteria in all cases (greater than 50 mg·kg^{-1}) (Guo, 1992). It is therefore clear that NF lands do not require the addition of this element.

4.4 Loess microelements

Trace micronutrient elements in field crops (e.g., Fe, Mn, Cu and Zn) are essential for

growth and development although concentrations at one in a thousand levels are required (Zou *et al.,* 2008). Earlier research has estimated (Sillanpää, 1982, 1990) that agricultural soils globally are 49% deficient in Zn, 14% deficient in Cu, 10% deficient in Mn, and 3% deficient in Fe. The results of this analysis also suggest that concentrations of total Cu (Figure 5a), Zn (Figure 5b), and Mn (Figure 5c) have been enhanced by long-term planting ($P >$ 0.05), from largest-to-smallest change in the order CF, SF, and NF. This result implies that NF lands require the addition of reasonable levels of supplementary trace micronutrients.

Availability in this context can be defined as the quantity of a soil nutrient that is accessible to plant roots over a useful time period such as one growing season (White *et al.*, 1999). Crop roots can also absorb micronutrients directly from soils in solution, which results in a decrease in the total pool available. Previous research has shown that available concentrations of Fe, Mn, Cu, and Zn are related to plant growth responses to micronutrients (White *et al*., 1999); this means that deficiencies in available micronutrients can lead to physiological sickness. Long-term planting enhances the concentrations of soil available Cu ($P < 0.05$), Zn ($P < 0.05$), Fe ($P < 0.05$), and Mn ($P < 0.05$). However, available contents of Fe and Mn in all farmland types assessed here did not attain necessary loess criteria values greater than 5.0 mg·kg^{-1} and greater than 10 mg·kg^{-1}, respectively. This was also the case for available Zn (criterion greater than 1.0 mg·kg^{-1}), with the exception of SF lands (Guo, 1992). It is therefore clear that NF lands will require the addition of fertilizer or micronutrient supplements for plant growth because of low Fe, Mn, Cu, and Zn levels.

4.5   Non-essential loess elements

The pollution of soils with heavy metals has become a severe problem in many parts of the world (Facchinelli *et al.*, 2001; Solgi *et al.*, 2012). As a direct result of rapid socioeconomic development over recent decades, soil pollution by heavy metals has become both serious and widespread in China because of the overuse of chemical fertilizers (Chen *et al*., 1999; Wang *et al*., 2001). Although some heavy metals are present in soils, additional contributions also come from anthropogenic activities including agriculture, urbanization, industrialization, and mining (Facchinelli *et al*., 2001). This kind of pollution not only degrades soil quality and results in a decrease in crop growth, but threatens human health via the food chain (Wang *et al*., 2001; Nabulo *et al*., 2010; Dong *et al*., 2011). The elements Pb, Cd, Cr, and Hg are the most toxic, while the main sources of heavy metals in soil are from various agrochemicals, fertilizers, pesticides, and atmospheric deposition (Berthelsen *et al*., 1995; Gray *et al*., 2003; Huang *et al*., 2007). They influence crop growth and damage soil ecosystem health. Although concentrations of Pb, Cd, Cr, and Hg do not reach ecological risk levels in any of the land types studied here, Cd concentrations did exceed criteria in all cases (less than, or equal to, 1 mg·kg^{-1}) (Xue, 1986). The results of this analysis are therefore particularly relevant to SF and CF lands, while NF areas appear to be the most suitable for green agriculture.

5   Conclusions

The results of this study show that different farmland types encompass different nutrient levels in the context of loess physicochemical parameters. In the first place, NF lands tend to have higher pH values which should be decreased artificially, while the soil organic matter

content of these areas is lower than the nine grade standard in Shaanxi Province (less than 6.00 g·kg^{-1}). These lands are therefore extremely deficient and unfavorable for crop growth and development. The data show that concentrations of total (greater than 0.6 g·mg^{-1}) and available N (greater than 30 g·mg^{-1}) fall below the basic line of six grade criteria for national nutrient levels in NF lands while at the same time this farmland contains abundant K. Total P concentrations do not attain loess criteria values in all soil samples (greater than 0.6 mg·kg^{-1}) as is also the case for available concentrations of this element (greater than 5 mg·kg^{-1}). The data also show that NF lands do tend to lack some useful microelements but contain some toxic components. The results of this study suggest that NF lands are currently unhealthy and require increases in fertility for effective agricultural practice. Results indicate that long-term planting is a risk to soil health because of the accumulation of toxic heavy metals. Long-term planting therefore also requires fallow and rehabilitation to ensure food security.

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