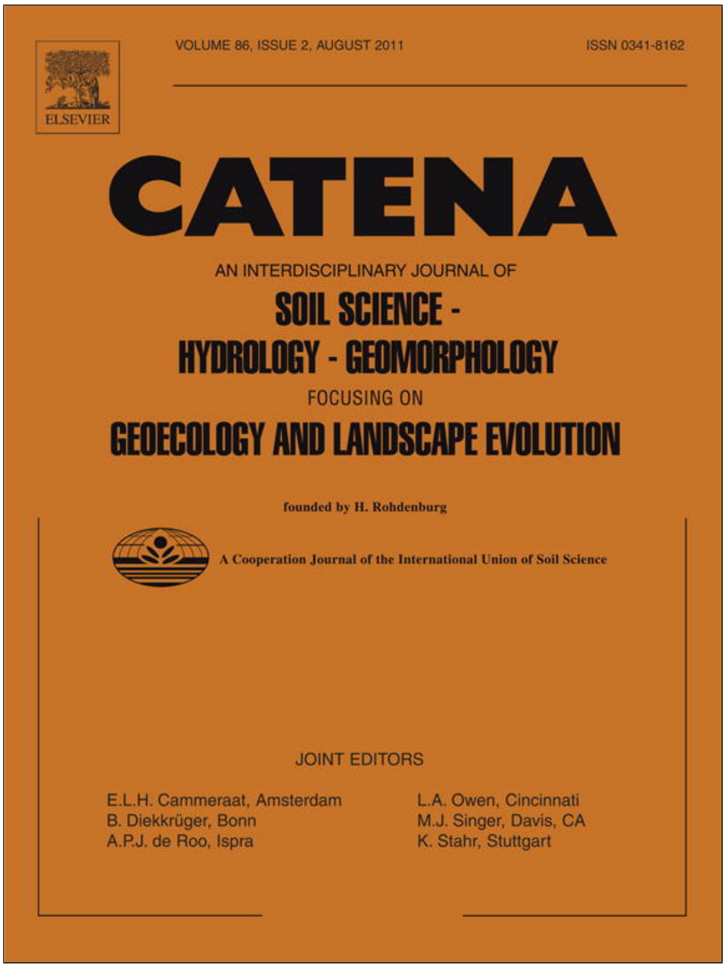
Provided for non-commercial research and education use.
Not for reproduction, distribution or commercial use.



VOLUME 86, ISSUE 2, AUGUST 2011 ISSN 0341-8162

ELSEVIER

CATENA

AN INTERDISCIPLINARY JOURNAL OF
SOIL SCIENCE -
HYDROLOGY - GEOMORPHOLOGY
FOCUSING ON
GEOECOLOGY AND LANDSCAPE EVOLUTION

founded by H. Rohdenburg

A Cooperation Journal of the International Union of Soil Science

JOINT EDITORS

E.L.H. Cammeraat, Amsterdam	L.A. Owen, Cincinnati
B. Diekkrüger, Bonn	M.J. Singer, Davis, CA
A.P.J. de Roo, Ispra	K. Stahr, Stuttgart

This article appeared in a journal published by Elsevier. The attached copy is furnished to the author for internal non-commercial research and education use, including for instruction at the authors institution and sharing with colleagues.

Other uses, including reproduction and distribution, or selling or licensing copies, or posting to personal, institutional or third party websites are prohibited.

In most cases authors are permitted to post their version of the article (e.g. in Word or Tex form) to their personal website or institutional repository. Authors requiring further information regarding Elsevier's archiving and manuscript policies are encouraged to visit:

http://www.elsevier.com/copyright

Author's personal copy

Catena 86 (2011) 110–116

Contents lists available at ScienceDirect

Catena

journal homepage: www.elsevier.com/locate/catena

Changes in soil properties across a chronosequence of vegetation restoration on the Loess Plateau of China

Feng Jiao, Zhong-Ming Wen, Shao-Shan An *

Institute of Soil and Water Conservation, Northwest A&F University, Yangling, Shaanxi, 712100, China
Institute of Soil and Water Conservation, Chinese Academy of Science and Ministry of Water Resource, Yangling, Shaanxi, 712100, China

ARTICLE INFO

Article history:
Received 24 June 2010
Received in revised form 26 February 2011
Accepted 1 March 2011

Keywords:
Soil property
Vegetation restoration
Soil bulk density
Soil organic carbon
Land use
Loess Plateau

ABSTRACT

Soil fertility is important for vegetation growth and productivity. The relationship between vegetation and soil fertility is important for both scientific and practical reasons. However, the effects of soil fertility on vegetation development and succession are poorly documented on the Loess Plateau. In this study, we compared soil properties of the Yanhe Watershed in northern Shaanxi across five different land uses (shrubland, farmland, natural grassland, woodland and artificial grassland) and a chronosequence of soils undergoing restoration for 5, 10, 15, 20, 25, 30, 35, 40 and 45 years. We found that revegetation had a positive effect on soil bulk density decrease, total porosity and capillary porosity increase in the surface soil layers but not in the subsurface layer. Additionally, soil organic matter, total nitrogen, available nitrogen and available potassium were greater at shrubland and woodland sites compared with other land uses. Total phosphorus and available phosphorus were greater at farmland sites. Results of the study indicate that revegetation on eroded soil can produce important increases in soil fertility on older plantations and in areas with natural succession.

© 2011 Elsevier B.V. All rights reserved.

1. Introduction

Past erosion in the Loess Plateau of China has been severe. As a consequence, the plateau's soils are now thin and nutrient poor (Li and Shao, 2003a,b). Additionally, overexploitation of the remaining vegetation further exacerbates land degradation and reduces soil nutrients and the supply of fuel and fodder in this area (Zha and Tang, 2003). Generally, soil structure degradation results in a reduction of total porosity and pore continuity (Dias and Northcliff, 1985), thereby reducing both soil aeration and water transport capabilities (Berger and Hager, 2000). This process yields barren soils that inhibit further plant growth (Wang et al., 2002). Hence, understanding declines in soil fertility is important for vegetation restoration, especially when converting agricultural land to reforested plantations or grassland. Additionally, there is need to understand natural vegetation recovery and its importance in soil rehabilitation on the plateau because very little natural vegetation exists. Better understanding of these processes will help guide current restoration of vegetation in western China.

Soil recovery during secondary vegetation succession has been recently studied (Chang et al., 1999; Lovich and Bainbridge, 1999; Wang et al., 2002). This attention on recovery shifts the focus from the examination of the soil properties of reclaimed lands in the postdeforestation process (Zheng and Zhang, 2002) to the contribution of revegetation or natural vegetation recovery (Zhang et al., 2004). Different vegetation types can be found within a short distance from a disturbed area simply because of changes in soil fertility levels (Harrington, 1991). In many ecosystems, especially in semiarid climates, vegetation productivity may be limited by nutrient availability (Aaron et al., 2001; Aerts and Chapin, 2000). In general, biomass and soil nutrients change substantially with plant age, and nutrient limitation is common during plant growth (Anderson and Ingram, 1989; Shao et al., 1996).

Human activities have greatly influenced the ecosystems on the Loess Plateau. Over the past century, population growth has resulted in fragmentation and degradation of the environment (Fu et al., 2000). To withstand further deterioration of the natural ecosystems, the Chinese government has launched a series of nationwide conservation projects focusing on the recovery of damaged ecosystems. One of the most pressing tasks involves the recovery of the vegetation because of its crucial role in the development of sustainable agriculture.

Although the study of degradation usually focuses on anthropogenic influences, the study of recovery is more important because it provides recommendations for eco-environmental reconstruction or rehabilitation. Recent research has addressed the influence of vegetation recovery on soil properties (An et al., 2009; Fu et al., 2003; Stolte et al., 2003). However, changes in soil properties during long-term vegetation recovery on the Loess Plateau still require thorough study. Research investigating changes in soil properties is necessary to understand the ecological consequences of vegetation recovery (Paniagua et al., 1999). In the semiarid area of the plateau,

---

* Corresponding author at: 26 Xinong Rd., Yangling, Shaanxi P, 712100, China. Tel.: +86 29 87016263.
E-mail address: shan@ms.iswc.ac.cn (S.-S. An).

0341-8162/$ – see front matter © 2011 Elsevier B.V. All rights reserved.
doi:10.1016/j.catena.2011.03.001

Author's personal copy

vegetation recovery is consistently nutrient limited. Few studies have addressed this issue. Studies of long-term changes in soil properties under natural revegetation regimes on the plateau are particularly needed (Chang et al., 1999). To rehabilitate eroded lands and improve the regional environment, some successful measures have been implemented throughout the Loess Plateau. Large areas of natural grassland on degraded land were reestablished to help hold soil and water to ensure improvement in the local ecosystem by natural succession after the cessation of grazing. The objective of the present study is to identify changes in soil properties associated with five different land uses, namely, shrubland, natural grassland, artificial grassland, farmland and woodland, and changes in soil properties following different intervals of planting for restoration. We hypothesized that local soil properties are largely a consequence of plant growth during secondary succession. The vegetation chronosequence of the grassland was also investigated to examine how soil properties change over time during restoration.

2. Materials and methods

2.1. Description of the study area

The study area was located in Yanhe Watershed of the Loess Plateau (36°23′–37°17′ N, 108°45′–110°28′ E) in northern Shaanxi Province. The area is 287 km in length. Of the total area (7687 km^2), 90% is hilly, 3% consists of villages, rivers, and lakes, and only 7% is considered suitable for intensive agriculture. Climate in the study area is semi-subarid with heavy seasonal rainfall and periodic flooding followed by drought. Average annual rainfall at the study site is 497 mm (1970–2000, CV 22%) with distinct wet and dry seasons. The rainy season is July to October, with August rainfall amounting to 23% of the annual total. Annual reference evapotranspiration is approximately 1000 mm. Most of the area lies at 900–1500 m altitude. The area's topography is characterized by cliffs and very steep slopes (40%). The topography, soil type, soil and land use patterns of Yanhe Watershed are typical of the Loess Plateau. The study area is composed of forest-steppe and temperate grassland. Typical vegetation includes *Bothriochloa ischaemun, Stipa bungeana, Artemisia sacrorum, A. giraldii Pamp,* and *Lespedeza davurica* (Li and Shao, 2003a,b).

2.2. Study approach and sampling design

Geographic characteristics of the sites are described in Appendix A. Soil samples were collected in August 2006 at 3 different depths: 0–20, 20–40 and 40–60 cm. For each type of land use, an area of 10 m × 10 m was selected at each site. Three 10 m × 3 m subplots were divided into five replicates for sampling. We used a soil sampling auger with a diameter of about 3 cm. An S-shaped soil sampling pattern was used in each subplot. Several 3 cm core samples were taken from each plot and mixed to form a pooled sample of about 1 kg. They were then air-dried and passed through a 2 mm sieve for soil analysis.

International standard methods adopted and published by the Institute of Soil Science, Chinese Academy of Sciences (1978) were used to analyze soil samples. Soil organic matter (SOM) was determined by oxidation with potassium dichromate in a heated oil bath. Total nitrogen (N_t) was measured by the semimicro Kjeldahl method. Available nitrogen (N_{avi}) was measured using the alkali diffusion method. Total phosphorus (P_t) was digested with perchloric acid and sulfuric acid and then measured by colorimetry. Total potassium (K_t) was digested with hydrofluoric acid and perchloric acid. Available phosphorus (P_{avi}) was extracted with sodium bicarbonate and measured with colorimetry. Available potassium (K_{avi}) in soil was extracted with ammonium acetate.

In situ slope angle and direction were determined using a pocket compass (DQY-1, China). Altitude, longitude and latitude were determined using a portable GPS. After removal of the litter and the humus layer, bulk density was measured using three intact soil cores from the surface layer (0–20 cm) and the subsurface layers (20–40 cm and 40–60 cm). Bulk density was determined by oven-drying the cores at 105–110 °C. Total soil porosity was calculated using Eq. (1) based on measured bulk density and assuming a soil particle density of 2.65 g cm^{-3}. Soil capillary porosity was subsequently calculated with Eq. (2) using bulk density and soil capillary water capacity data (Huang, 2003).

$$P_t = (1 - B_d / d_s) \times 100 \tag{1}$$

Where P_t is the total soil porosity (%); B_d is the soil bulk density (g cm^{-3}); d_s is the soil density (g cm^{-3}).

$$P_c = W_c \times B_d / V \times 100 \tag{2}$$

Where P_c is the soil capillary porosity (%); W_c is the soil capillary water content (%); V is the volume of soil core (cm^3).

A common approach in soil rehabilitation studies investigating vegetative cover is to monitor plant and soil changes along a vegetative chronosequence developed on similar soils under similar climatic conditions (Bhojvaid and Timmer, 1998). This chronological approach has been used widely in applied ecosystem research (Fang and Peng, 1997) and is considered retrospective research because existing conditions are compared with known original conditions and treatments. We used this approach here because nearby vegetation communities were established 5, 10, 15, 20, 25, 30, 35, 40 and 45 years ago on eroded soils with similar properties. These vegetation communities provide a time gradient of grass occupancy on similar sites. Rates of change in soil properties can be estimated by comparing sites of different ages. Nine sites (5, 10, 15, 20, 25, 30, 35, 40 and 45 years of age) that have undergone light livestock grazing in recent years were found at adjacent locations in the study area. Five sites were sampled within each series. Five nearby, nonvegetated sites (farmland) were used as controls for the chronosequence. The geographic characteristics of the sites are described in Appendix B.

2.3. Data analysis

Soil samples were compared among successional stages using analysis of variance (ANOVA). Correlations among soil variables were tested using SPSS, version 11.0. The LSD test (at $p<0.05$) was used to compare means of soil variables when the results of ANOVA were significant at $p<0.05$.

3. Results

3.1. Bulk density and total porosity under different land uses

Only in the 0–20 cm layer was soil bulk density associated with the different land uses. Shrubland soils had greater bulk density (1.35 mg m^{-3}) compared with other soils. The artificial grassland had the lowest bulk density value (1.24 mg m^{-3}) at the 10–20 cm soil depth, whereas the cultivated land had greatest bulk density values at either depth (Table 1). Bulk density was similar in the pasture and forest soils for the topsoil at 0–10 cm but was different at a soil depth of 10–20 cm. Bulk density differed significantly across soil depths in the pasture.

Total porosity and capillary porosity, like soil bulk density, changed in the 0–20 cm layer but not in the 20–40 cm layer under different land uses. Total porosity in the surface layer was greatest (53%) for artificial grassland and lowest (49.2%) for shrubland

Author's personal copy

Table 1
Successional series and plant communities.

Restoration years	Number of samples	Slope (°)	Community types	Soil type
5	5	21, 26, 13, 29, 8	*Artemisia scoparia, Leymus scalinus, Lespedeza davurica*	Typic loessi orthic primosols
10	5	24, 27, 29, 28, 6	*Leymus scalinus, Lespedeza davurica, Stipa bungeana*	Typic loessi orthic primosols
15	5	20, 26, 24, 25, 5	*Stipa bungeana, Lespedeza davurica, Artemisia*	Typic loessi orthic primosols
20	5	5,35,28,25,5	*Artemisia, Lespedeza davurica, Bothtiochloa ischaemun*	Typic loessi orthic primosols
25	5	24, 27, 24, 35, 30	*Bothtiochloa ischaemun, Stipa grandis,Lespedeza davurica*	Typic loessi orthic primosols
30	5	27, 28, 20, 21, 35	*Bothtiochloa ischaemun, Stipa grandis,Lespedeza davurica*	Typic loessi orthic primosols
35	5	30, 29, 37, 20, 30	*Bothtiochloa ischaemun, Lespedeza davurica, Artemisia sacrorum*	Typic loessi orthic primosols
40	5	25, 19, 20, 8, 17	*Bothtiochloa ischaemun, Lespedeza davurica, Stipa grandis*	Typic loessi orthic primosols
45	5	22, 25, 5, 25, 27	*Stipa bungeana, Sophora viciifolia, Ziziphus jujuba Mill. var. spin*	Typic loessi orthic primosols

(Table 1). This result was in contrast to the bulk density changes. Capillary porosity in the surface layer was greatest (19.4%) for shrubland and lowest (17.9%) for artificial grassland (Table 1), in agreement with the results for bulk density. The ratios of capillary porosity to total porosity were similar at the 0–20 and 20–40 cm depths (Table 2).

3.2. Soil nutrient values for different land uses

In the 0–20 cm layer, N_{avi} was highest in farmland, followed by SOM, K_{avi}, P_{avi}, N_t and P_t (Fig. 1). SOM was highest in natural grassland, followed by N_{avi}, N_t, P_{avi}, K_{avi} and P_t (Fig. 1). Compared with the results from farmland and natural grassland, K_{avi} was highest in artificial grassland, N_{avi} and P_{avi} were highest in forest land, and P_t was highest in shrubland soil (Fig. 1).

All soil nutrients within the same type of land use decreased from the 0–20 cm layer to the 20–40 cm layer (Fig. 1). Overall, SOM, N_t, N_{hydro} and K_{avail} declined from the 0–20 cm layer to the 20–40 cm layer (Fig. 1), whereas other parameters, such as P_t and P_{avi}, did not (Fig. 1). Thus, the proportion of macropore space in the soil decreased with soil depth.

3.3. Bulk density and soil nutrient in different restoration years

On average, soil bulk density, total porosity and capillary porosity for the natural grassland were not influenced by vegetational succession over 45 years of restoration (Table 2). Following 5 to 45 years of restoration, SOM, N_t, N_{avi}, P_{avi} and K_{avi} were greater in the 0–20 cm layer ($p<0.05$). N_{avi} and P_{avi} were significantly different in the 20–40 cm layer at $p<0.05$, whereas SOM, N_t, P_t, and K_{avi} were not (Fig. 2). These parameters declined ($p<0.05$) from 5 to 15 years of restoration but then increased ($p<0.05$) from restoration years 15 through 20. Significant decreases ($p<0.05$) were found for 20 and 25 years of restoration, and significant increases ($p<0.05$) were reported for years 25 through 45 (Fig. 2).

4. Discussion

4.1. Effect of land uses on soil properties

Estimation of soil properties under different land use systems is helpful in determining the vulnerability of land degradation. This information is important for countries in arid areas with high susceptibility to desertification (Giertz et al., 2006). Tillage causes changes in soil structure that vary with tillage intensity and soil depth. Surface layer changes in soil structure in intensive systems are much more pronounced than in nonintensive systems, but these changes are not statistically different from the soil properties in uncultivated areas. Although bulk density in freshly tilled farmland was very low due to frequent tillage and low long-term input of organic matter, the soil structure in farmlands is usually unstable and can easily be negatively influenced over time (Li and Shao, 2003a,b). This difference might result from compaction of the topsoil (0–10 cm) owing to overgrazing of the pastures. In this study, the loss of SOM resulting from the conversion of the pasture into cultivated fields may have produced a greater bulk density in the cultivated soils (Table 1). In addition, following conversion from pasture to cultivation, a decline in soil aggregation resulted in increased bulk density. This process may be worsened by the continuous use of machinery for either conversion or cultivation.

Human activities and natural disasters may directly affect soil nutrient decomposition and loss (Jonasson and Michelsen, 1996; Xu, 1992). After vegetation implantation, soil nutrients usually increase (Zhang et al., 2004). In our results, SOM, Nt, N_{avi}, and K_{avi} were greater in shrublands and woodlands compared with other land uses, whereas P_t and P_{avi} were greater in farmland soils. After farmland returned to forest, SOM increased 49%, compared with an 18% increase following return to natural grassland. N_{avi} increased 37% and 5%, N_{avi} increased 68% and 31%, and K_{avi} increased 42% and 16%, respectively. Most research shows that abandoned land is associated with an increase in availability of soil nutrients.

Despite its degradation by grazing, grass can also maintain soil nutrients. However, because of overgrazing, a low amount of biomass

Table 2
Means and coefficients of variation of bulk density and total porosity for different land uses.

Item	Soil layer (cm)	Farmland	Artificial grassland	Natural grassland	Woodland	Shrubland	Sig. of ANOVA
Bulk density (mg m^{-3})	0–20	1.28^{abc} (0.05)	1.24^{c} (0.02)	1.27^{bc} (0.09)	1.32^{ab} (0.05)	1.35^{a} (0.05)	0.025
	20–40	1.35 (0.04)	1.34 (0.07)	1.34 (0.05)	1.32 (0.03)	1.37 (0.05)	0.535
Total porosity (TP, %)	0–20	51.7^{abc} (0.04)	53.2^{a} (0.02)	52.1^{ab} (0.08)	50.1^{bc} (0.05)	49.2^{c} (0.05)	0.028
	20–40	49.2 (0.04)	49.3 (0.07)	49.6 (0.05)	50.2 (0.03)	48.4 (0.05)	0.522
Capillary porosity (CP, %)	0–20	18.5^{abc} (0.05)	17.9^{c} (0.02)	18.3^{bc} (0.09)	19.1^{ab} (0.05)	19.4^{a} (0.05)	0.027
	20–40	19.4 (0.04)	19.4 (0.07)	19.2 (0.05)	19.0 (0.03)	19.7 (0.05)	0.501
CP/TP (%)	0–20	35.8^{abc} (0.09)	33.6^{c} (0.05)	35.5^{bc} (0.17)	38.2^{ab} (0.10)	39.7^{a} (0.10)	0.028
	20–40	39.5 (0.07)	39.6 (0.15)	38.9 (0.10)	37.9 (0.05)	40.9 (0.10)	0.516

Means with the same letter in the same row are not significantly different at the 0.05 level (LSD).
Quantities in parentheses are coefficients of variation.

Author's personal copy

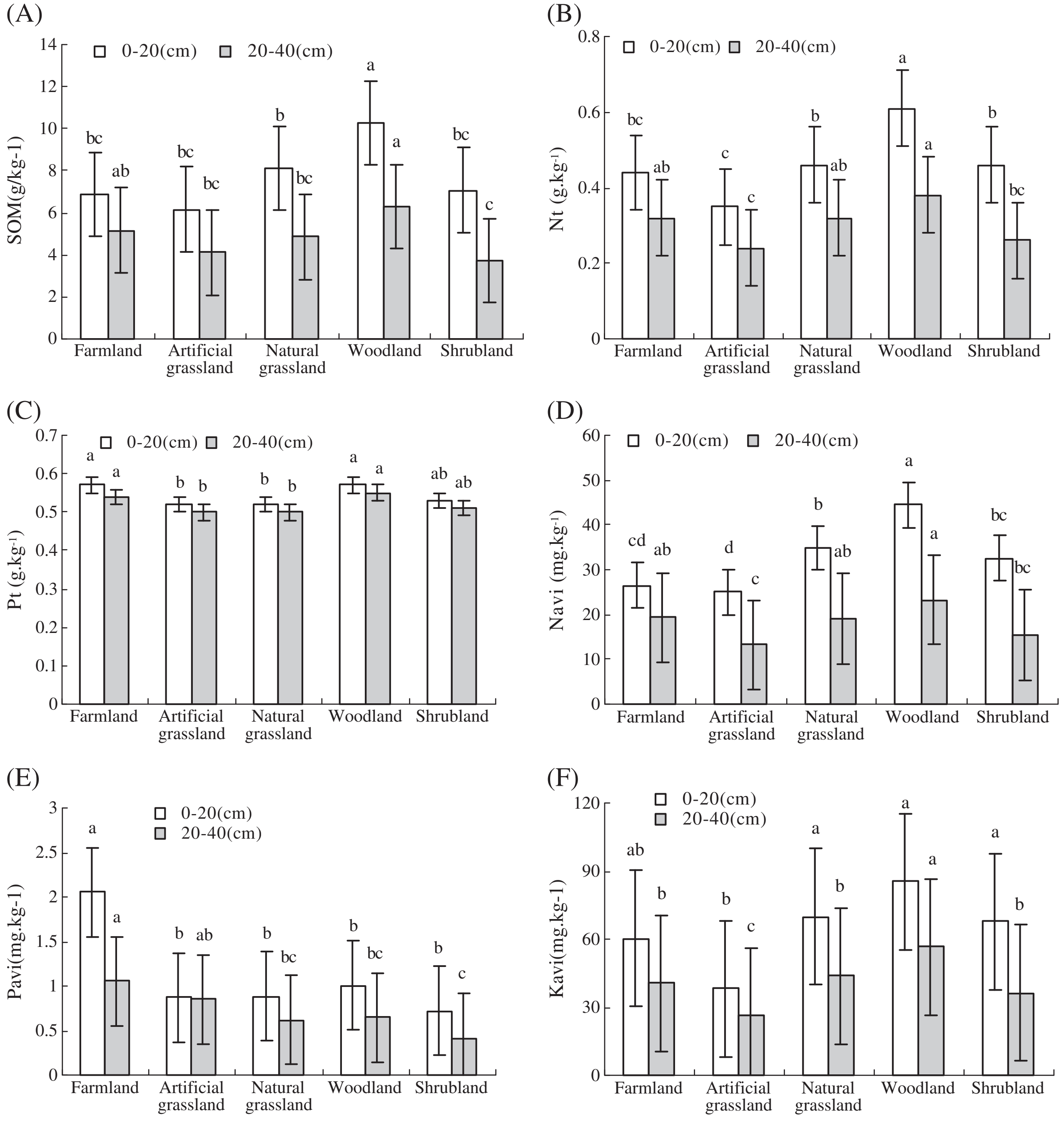


Fig. 1. Means and standard deviations of soil organic matter (SOM) (A), total nitrogen (N_t) (B), total phosphorus (P_t) (C), available nitrogen (N_{avi}) (D), available phosphorus (P_{avi}) (E) and available potassium (K_{avi}) (F) at different revegetation sites. Means with the same letter in the different row are not significantly different at the 0.05 level (LSD).

is returned to the soil each year, and roots occupy shallow soil layers. In the area studied, artificial grassland mainly consists of *A. adsurgen* or alfalfa. These crops are used for stock feeding. Because farmers harvest *A. adsurgen* or alfalfa 3 to 4 times per year, soil nutrients in the artificial grassland are depleted. Soil nutrients in farmland soils varied according to each site's individual characteristics, such as topography. Thus, a majority (52%) of the terraced farmland was found to be high in nutrients.

4.2. Effect of restoration time on soil properties

On the Loess Plateau, water erosion can be reversed through the implementation of conservation measures, including measures that involve active planting of vegetation (Zhao at al., 2000). Actively planting vegetation provides important protection against soil erosion by water in the Loess Plateau. Here, we show that the establishment and development of vegetation succession on eroded soil result in important changes in soil nutrients, as was also found in the Ansai County of Shaanxi Province in northwestern China (Wang et al., 2003). The results of this study are important for a number of reasons. First, vegetation restoration offers an important safeguard against soil erosion, although it may consume soil nutrients in the beginning stages of restoration of farmland soils (Chen et al., 2005). Second, vegetation succession results in changes in soil nutrients in the eroded soils and a gradual restoration of soil nutrients (Jiao at al., 2005). Third, surface soils recover soil nutrients to a greater extent than

Author's personal copy

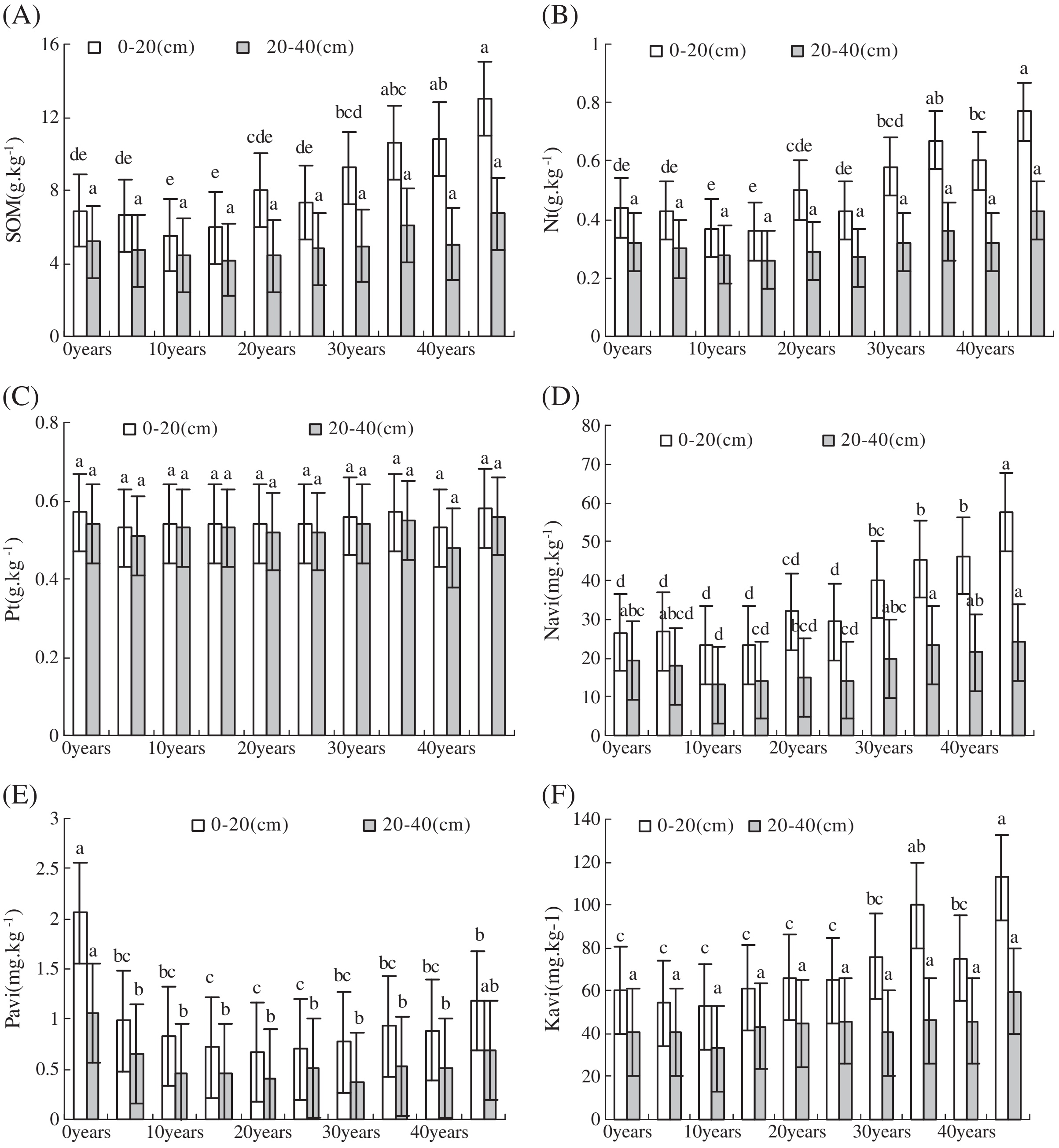


Fig. 2. Means and standard deviations of soil organic matter (SOM) (A), total nitrogen (N_t) (B), total phosphorus (P_t) (C), available nitrogen (N_{avi}) (D), available phosphorus (P_{avi}) (E) and available potassium (K_{avi}) (F) at different time points of restoration. Means with the same letter in the different row are not significantly different at the 0.05 level (LSD).

do deeper soils (Jiao et al., 2006). Human activities and natural disasters could directly affect soil nutrient decomposition and loss (Jonasson and Michelsen, 1996; Xu, 1992). However, differences in stocknutrients of the 5 vegetation types are due to the dominant species at each site, because these plants absorb nutrients at different rates.

5. Conclusion

Land use has an important influence on soil bulk density, total porosity and capillary porosity of only the surface soil layer. Shrubland has greater soil bulk density, capillary porosity and lower total porosity than do other types of land uses. In most cases, terrace land has low levels of soil fertility, but after long periods of cultivation, the land degrades year after year. Our results indicate that land use changes and revegetation of eroded soils result in significant changes in soil properties. The results also showed that soil fertility recovers more as plantation age increases.

Acknowledgments

This study was sponsored by the Western Light Project of Chinese Academy of Sciences (2010y236), key NSFC program (41030532), the Knowledge Innovation Program of the Chinese Academy of Sciences (Grant No.KZCX2-EW-406) and the Foundation for Youth Teachers by Northwest A&F University.

Author's personal copy

Appendix A. General properties of selected plots with different land uses

Land use	Topography	Slope (°)	Altitude (m)	Plantation duration (years)	Soil type
Farmland 1	Middle slope	25	1223	0	Gray loessi orthic primosols
Farmland 2	Terrace	2	1282	0	Gray loessi orthic primosols
Farmland 3	Down slope	20	1367	0	Gray loessi orthic primosols
Farmland 4	Upper slope	10	1508	0	Gray loessi orthic primosols
Farmland 5	Middle slope	22	1076	0	Gray loessi orthic primosols
Artificial grassland 1	Middle slope	11	1280	1	Typic loessi orthic primosols
Artificial grassland 2	Upper slope	18	1598	4	Typic loessi orthic primosols
Artificial grassland 3	Middle slope	30	1569	6	Typic loessi orthic primosols
Natural grassland 1	Middle slope	30	1344	30	Typic loessi orthic primosols
Natural grassland 2	Upper slope	20	1267	40	Typic loessi orthic primosols
Natural grassland 3	Middle slope	35	1204	30	Typic loessi orthic primosols
Natural grassland 4	Upper slope	27	1271	22	Typic loessi orthic primosols
Natural grassland 5	Middle slope	30	1358	38	Typic loessi orthic primosols
Woodland 1	Down slope	25	1369	42	Typic loessi orthic primosols
Woodland 2	Upper slope	23	1369	40	Typic loessi orthic primosols
Woodland 3	Upper slope	26	1159	40	Typic loessi orthic primosols
Woodland 4	Middle slope	8	1132	40	Typic loessi orthic primosols
Woodland 5	Down slope	29	1460	21	Typic loessi orthic primosols
Woodland 6	Middle slope	25	1212	4	Typic loessi orthic primosols
Woodland 7	Down slope	27	1212	28	Typic loessi orthic primosols
Shrubland 1	Middle slope	20	1387	42	Typic loessi orthic primosols
Shrubland 2	Down slope	29	1182	30	Typic loessi orthic primosols
Shrubland 3	Upper slope	23	1142	30	Typic loessi orthic primosols
Shrubland 4	Middle slope	25	1392	15	Typic loessi orthic primosols
Shrubland 5	Down slope	33	1585	20	Typic loessi orthic primosols
Shrubland 6	Down slope	18	1212	28	Typic loessi orthic primosols
Shrubland 7	Down slope	20	1212	28	Typic loessi orthic primosols

Appendix B. General information about selected plots for different vegetation communities

Restoration years	Topography	Slope (°)	Altitude (m)	Vegetation types	Soil type
5 years 1	Upper slope	21	1321	*Artemisia scoparia*	Typic loessi orthic primosols
5 years 2	Upper slope	26	1344	*Leymus secalinus*	Typic loessi orthic primosols
5 years 3	Down slope	13	1148	*Lespedeza daurica, Stipa bungeana*	Typic loessi orthic primosols
5 years 4	Upper slope	29	1624	*Artemisia scoparia, Bothriochloa ischaemun*	Typic loessi orthic primosols
5 years 5	Down slope	8	1315	*Leymus secalinus, Artemisia scoparia*	Typic loessi orthic primosols
10 years 1	Down slope	24	1469	*Leymus secalinus*	Typic loessi orthic primosols
10 years 2	Down slope	27	1470	*Leymus secalinus, Lespedeza daurica*	Typic loessi orthic primosols
10 years 3	Middle slope	29	1459	*Bothriochloa ischaemun, Stipa bungeana*	Typic loessi orthic primosols
10 years 4	Upper slope	28	1567	*Artemisia scoparia*	Typic loessi orthic primosols
10 years 5	Upper slope	6	1392	*Lespedeza daurica*	Typic loessi orthic primosols
15 years 1	Middle slope	18	1363	*Stipa bungeana, Lespedeza daurica*	Typic loessi orthic primosols
15 years 2	Down slope	20	1329	*Lespedeza daurica, Artemisia sacroru*	Typic loessi orthic primosols
15 years 3	Middle slope	26	1180	*Bothriochloa ischaemun, Lespedeza daurica*	Typic loessi orthic primosols
15 years 4	Middle slope	24	1379	*Lespedeza daurica, Potentilla Chinensis*	Typic loessi orthic primosols
15 years 5	Middle slope	25	1482	*Stipa bungeana, Lespedeza daurica*	Typic loessi orthic primosols
20 years 1	Upper slope	5	1337	*Stipa bungeana*	Typic loessi orthic primosols
20 years 2	Upper slope	35	1180	*Artemisia sacrorum,*	Typic loessi orthic primosols
20 years 3	Upper slope	28	1371	*Stipa bungeana*	Typic loessi orthic primosols
20 years 4	Middle slope	26	1344	*Artemisia sacrorum, Cleistogenes*	Typic loessi orthic primosols
20 years 5	Upper slope	5	1587	*Stipa bungeana,Potentilla acaulis L.*	Typic loessi orthic primosols
25 years 1	Upper slope	27	1205	*Lespedeza daurica, Stipa bungeana*	Typic loessi orthic primosols
25 years 2	Down slope	24	1369	*Bothriochloa ischaemun, Artemisia scoparia*	Typic loessi orthic primosols
25 years 3	Middle slope	27	1355	*Lespedeza daurica, Artemisia sacrorum*	Typic loessi orthic primosols
25 years 4	Upper slope	35	1282	*Bothriochloa ischaemun, Artemisia scoparia*	Typic loessi orthic primosols
25 years 5	Middle slope	30	1358	*Artemisia sacrorum, Bothriochloa*	Typic loessi orthic primosols

Author's personal copy

References

Aaron, B.S., Robert, L., Sanford, J., 2001. Soil nutrient differences between two Krummholz-form tree species and adjacent alpine tundra. Geoderma 102, 205–217.

Aerts, R., Chapin, F.S., 2000. The mineral nutrition of wild plants revisited: a re-evaluation of processes and patterns. Advances in Ecological Research 30, 2–67.

An, S.S., Huang, Y.M., Zheng, F.L., 2009. Evaluation of soil microbial indices along a revegetation chronosequence in grassland soils on the Loess Plateau, Northwest China. Applied Soil Ecology 41, 286–292.

Anderson, J.M., Ingram, J.I., 1989. Tropical Soil Biology and Fertility: A handbook of Methods. CAB International, Wallingford, UK.

Berger, T.W., Hager, H., 2000. Physical top soil properties in pure stands of Norway spruce (Picea abies) and mixed species stands in Austria. Forest Ecology and Management 136, 159–172.

Bhojvaid, P.P., Timmer, V.R., 1998. Soil dynamics in an age sequence of *Prosopis juliflora* planted for sodic soil restoration in India. Forest Ecology and Management 106 (2–3), 181–193.

Chang, Q.R., An, S.S., Liu, J., Wang, B., Wei, Y., 1999. Study on benefits of recovering vegetation to prevent land deterioration on Loess Plateau. Journal of Soil Erosion and Soil and Water Conservation 5 (4), 6–9 44.

Chen, H.S., Wang, K.L., Shao, M.A., 2005. A Review on the Effect of Vegetation Rehabilitation on the Desiccation of Deep Soil Layer on the Loess Plateau. Scientia Silvae Sinicae 41 (4), 155–161.

Dias, A.C.C.P., Northcliff, S., 1985. Effects of two land clearing methods on the physical properties of an Oxisol in the Brazilian Amazon. Tropical Agriculture 62, 207–212.

Fang, W., Peng, S.L., 1997. Development of species diversity in the restoration process of establishing a tropical manmade forest ecosystem in China. Forest Ecology and Management 99 (1–2), 185–196.

Fu, B.J., Chen, L.D., Ma, K.M., Zhou, H.F., Wang, J., 2000. The relationships between land use and soil conditions in the hilly area of the Loess Plateau in northern Shaanxi, China. Catena 39 (1), 69–78.

Fu, B.J., Wang, J., Chen, L.D., Qiu, Y., 2003. The effects of land use on soil moisture variation in the Danangou catchment of the Loess Plateau, China. Catena 54 (1–2), 197–213.

Giertz, S., Junge, B., Diekkruger, B., 2006. Assessing the effects of land use change on soil physical properties and hydrological processes in the sub-humid tropical environment of West Africa[J]. Physics and Chemistry of the Earth 30, 485–496.

Harrington, G.N., 1991. Effects of soil moisture on shrub seedling survival in a semi-arid grassland. Ecology 72 (3), 1138–1149.

Huang, C.Y., 2003. Soil Science[M]. China Agriculture Press, pp. 89–92.

Institute of Soil Science,Chinese Academy of Sciences (CAS), 1978. Soil Physical and Chemical Analysis. Shanghai Science Technology Press, Shanghai of China, pp. 524–525.

Jiao, J.Y., Ma, X.H., Bai, W.J., 2005. Correspondence analysis of vegetation communities and soil environmental factors on abandoned cropland on hilly-gullied loess plateau. Acta Pedologica Sinica 42 (5), 744–752.

Jiao, F., Wen, Z.M., Jiao, W.J., 2006. Reciprocal effects among vegetation, soil moisture and nutrients of croplandto forest on the Loess Plateau. Journal Community. under stress: abiotic factors. New York: Wiley;1998 of *Bouteloua gracilis* in the shortgraand grassland in the Loess Hilly Region. Acta prataculturae Sinica 15 (2), 79–84.

Jonasson, S., Michelsen, A., 1996. Nutrient cycling in subarctic and arctic ecosystems, with special reference to the Abisko and Tometrask region. Ecol. Bull. 45, 45–52.

Li, Y.Y., Shao, M.A., 2003a. Impact of tillage on water transformation and unoff-sediment-yielding characteristics on slope land. Transactions of The Chinese Society of Agricultural Engineering 19 (1), 46–50.

Li, Y.Y., Shao, M.A., 2003b. Natural succession and evolution of structural characteristics of forest community in Ziwuling area on the Loess Plateau. Acta Botanica Boreali-Occidentalia Sinica 23 (5), 693–699.

Lovich, J.E., Bainbridge, D., 1999. Anthropogenic degradation of the Southern California Desert ecosystem and prospects for natural recovery and restoration. Environmental Management 24, 309–326.

Paniagua, A., Kammerbayuer, J., Avedillo, M., Andrews, A.M., 1999. Relationship of soil characteristics to vegetation successions on a sequence of degraded and rehabilitated soils in Honduras. Agriculture, Ecosystems and Environment 72, 215–255.

Shao, G.F., Zhao, G., Zhao, S., Shugart, H.H., Wang, S., Schaller, J., 1996. Forest cover types from landsat ™ imagery for Changbai Mountain area of China. Canadian Journal of Forest Research 26, 206–216.

Stolte, J., van Venrooij, Zhang, B.G., Trouwborst, K.O., Liu, G., Ritsema, C.J., Hessel, R., 2003. Landuse induced spatial heterogeneity of soil hydraulic properties on the Loess Plateau in China. Catena 54 (1–2), 59–75.

Wang, G.L., Liu, G.B., Xu, M.X., 2002. Effect of vegetation restoration on soil nutrient change in Zhifanggou watersheds of loess hilly region. Bulletin of Soil and Water Conservation 22 (1), 1–5.

Wang, J., Fu, B.J., Qiu, Y., Chen, L.D., 2003. Analysis on soil nutrient characteristics for sustainable land use in Danangou catchment of the Loess Plateau, China. Catena 54 (1–2), 17–29.

Xu, Z.A., 1992. A periodic summary of the research on forest ecosystems on Changbai Mountain. Research for Ecosystem 6, 1–13.

Zha, X., Tang, K., 2003. Change about soil erosion and soil properties in reclaimed forestland of loesshilly region. Acta Geographica Sinica 58 (3), 464–469.

Zhang, B., Yang, Y., Zepp, H., 2004. Effect of vegetation restoration on soil and water erosion and nutrient losses of a severely eroded clayey Plinthudult in southeastern China. Catena 57, 77–90.

Zhao, Z., Li, P., Wang, N.J., 2000. Distribution patterns of root systems of main planting tree species in Weibei Loess Plateau. Chinese Journal of Applied Ecology 11 (1), 37–39.

Zheng, F.L., Zhang, C.E., 2002. Study on sloping soil erosion processes and soil nutrient loss after forest removal. Journal of Soil and Water Conservation 16 (1), 44–46.