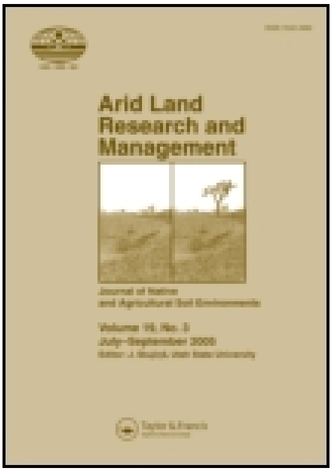

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Desert Soil Properties after Thirty Years of Vegetation Restoration in Northern Shaanxi Province of China

Yanbing Qi[1,3], Fengqun Yang[1], Manoj K. Shukla[2], Jie Pu[1], Qingrui Chang[1,3], and Wanlin Chu[1]

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The vegetation restoration sequence of "grass-shrub-tree" has been successfully employed in many degraded areas; however, its applicability in desertified area reclamation is questionable. In this study, soil properties of a desertified land in the northern Shaanxi province of China were determined to assess the performance of this restoration sequence. Soil samples were collected from a contiguous area consisting of a control area of original desertified land (bare control) and three vegetation restoration sequence communities (continuous grass, grass-shrubs, and grass-shrub-trees) for 30 years. Results indicate that revegetation on the desertified area decreased soil bulk density (BD) and increased soil organic matter (SOM), cation exchange capacity (CEC), available nutrients (N, P, and K), and readily oxidizable carbon (ROC). Nonactive organic carbon (NAOC) and carbon pool management index (CMI) also improved in the top soil layer but not in the lower layer. Soil texture as well as total potassium (TK) and phosphorus (TP) did not change significantly. Comparing the three vegetation restoration communities, soil physical properties, SOM, and available nutrient content improved in grassland and shrubland, but declined in treeland, lability of C (L) was higher in the top layer of restored area than in bare control. L was 0.35–0.54 in grassland, 0.49–0.57 in shrubland, 0.43–0.52 in treeland, and 0.24 to 0.26 in bare control. Results of this study indicate that vegetation restoration on desertified land can improve soil properties. However, the popular restoration sequence of "grass-shrub-tree" is not appropriate for the restoration of semi-arid study area with low precipitation.

Keywords desert soil, desertification, soil carbon management index, soil organic carbon, vegetation restoration

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Color versions of one or more of the figures in the article can be found online at www.tandfonline.com/uasr.

Introduction

Desertification is a type of land degradation and is one of the important environmental hazards (Luo 2003; Liu and Diamond 2005). Desertification can be reversed by applying proper restoration measures, often by revegetating the land with grass. Vegetation restoration stabilizes soil and adds organic matter (SOM) and nutrients to the soil (Zhang and Hou 2012). Altering SOM and nutrients content depends on the vegetation species, and a comprehensive understanding of this interrelationship for desertified areas can help implement successful vegetative restoration.

Severe desertification has been reported in China of which more than 60% took place in the northern agro-pastoral transition zone (Huang, Wang, and Wu 2007). In 1978, the government of China began a large afforestation program known as the Three North Forest program, which covered areas in northern, northeast, and northwest China. In 1998, a nationwide "Grain for Green," project was started in China and federal government made new regulations for controlling desertification (Oñate and Peco 2005; Haijiang et al. 2008). Many successful examples are available on the rehabilitation of degraded lands through vegetation restoration. In China's Loess Plateau area, 15 years of the Chinese government's "Grain for Green" project resulted in a 16-fold decrease of the transport of eroded soils by the Yellow River to the Bohai Sea, from 1600 million tons in 1995 to 100 million tons in 2010 (Liu et al. 2011). The successful strategy involved seeding grass as the first step of restoration, followed by shrubs, and finally trees as the last step of restoration (Feng et al. 2012). The success of this "grass-shrub-tree" sequence to restore degraded soil is widely reported for non-desertified areas. However, questions remain about the applicability of this sequence for reclaiming desertified areas (Wang et al. 2010a). Some research efforts were focused on assessing temporal changes in soil properties as a result of vegetation restoration and improvements in soil physical properties, organic matter content, and available nutrient contents were documented (Zhao et al. 2006; Zhang and Hou 2012). However, few accounts are available comparing soil properties in contiguous restored areas with grass, shrubs, and trees and adjacent unrestored areas.

In desert ecosystems, interactions between vegetation and soil have been increasingly studied in recent years (Zhang, Chang, and Qi 2009; Fu et al. 2010). Revegetation on desertified land can improve soil physical and chemical properties through the interaction of vegetation and soil ecosystems (Jiao, Wen, and An 2011). Desert vegetation and root exudates can increase soil carbon (C), nitrogen (N), and phosphorus (P) concentrations (Pei, Fu, and Wan 2008; Liu et al. 2012). Another study found that vegetative restoration resulted in SOM accumulation and attendant lowering of soil pH in the shallow soil layer (Shang et al. 2011).

Plant characteristics, growth rates, and amounts of biomass produced are highly variable among different vegetation types, and can have different effects on soil properties. Soil N, P, calcium (Ca), and SOM content were reported to increase significantly after 15 years in areas planted to shrubs than areas under fallow (Wezel, Rajot, and Herbrig 2000). Sodium (Na) and magnesium (Mg) contents were also reported to increase compared with nearby fallow sites in semi-arid Niger (Wezel, Rajot, and Herbrig 2000). Schlesinger and Pilmanis (1998) found significant differences in spatial and temporal distribution of soil nutrients between areas planted to trees and shrubs.

The vegetation community and soil property interactions vary with the vegetation type, soil type, and land use patterns (Qi, Chang, and Hui 2007; Wang et al. 2011). In the Loess Plateau area, the sequence consisting of "sloping land-grass-trees" and "terraces-meadow-forest" have better nutrient content than grassland, with tree-covered land having the highest nutrient content, followed by grasslands and sloped farmland (An et al. 2008; Ward 2008).

At present, most research focuses on the causes, processes, formation mechanisms, and measures for controlling desertification (Pei, Fu, and Wan 2008). A small number of studies also focus on desertification reversal (Li et al. 2006; Li et al. 2007). Some investigations have been done on the survival of trees replacing shrubs; to the best of our knowledge, however, none of the studies have attempted to critically examine the validity of the "grass-shrub-tree" restoration sequence. Systematic studies should be conducted to investigate the reversal of desertification and associated changes in soil properties in restored areas. This study was conducted in the northern Shaanxi Province of China where desertification reversal has occurred after about thirty years of vegetation restoration using the "grass-shrub-tree" sequence. The objectives of this research were to (1) investigate soil properties under various vegetation restorations and bare control and (2) assess the validity of the generally accepted vegetation restoration sequence of "grass-shrub-tree." Our hypothesis was that SOM and nutrient contents will be higher under the trees than shrubs and grass; therefore, grass-shrub-tree sequence would be viable for the desert restoration.

Materials and Methods

Study Area

The study region is located in China's northern Shaanxi Province and covers an area encompassing 37°20′-39°35′N,107°15′-111°15′E. (Figure 1). The semi-humid intensive agricultural region of the North China Plain is located to the south of the transitional region, while a region of steppes along the Mongolian Plateau is situated

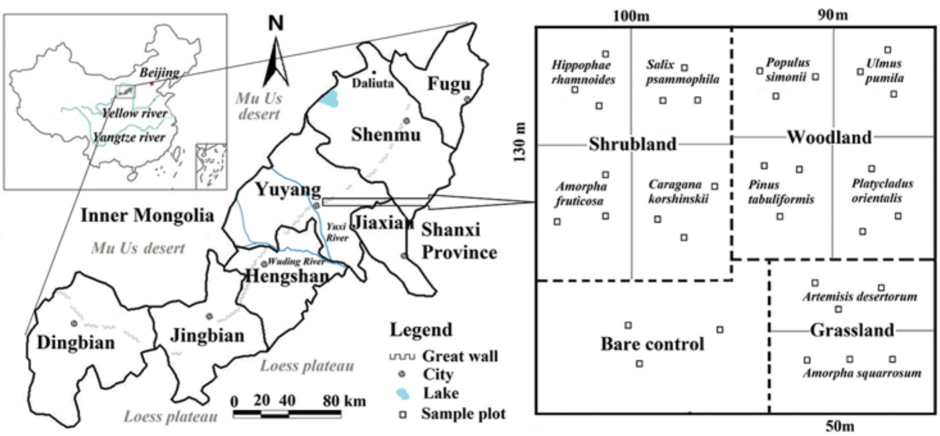

Figure 1. The location of the agro-pastoral transitional zone of northern Shaanxi Province and the layout of the research plots (not to scale).

to the north (Wang, Gao, and Quansheng 2003). The climate of the study area is classified as semi-arid. Annual precipitation varies slightly from 440 mm reported in the southeast to about 250 mm in the northwest. 60–80% of the precipitation occurs between June and August. The mean annual temperature ranges from 6.0 to 8.5°C, with a maximum temperature of 22°C in July and a minimum temperature of −11°C in January.

The elevation of the study area varies between 800 and 1400 m and there is a gentle slope from the northwest to the southeast. The study area has three distinct landforms: hard hills, soft hills, and lower wetlands. Hard hills area was formed due to the aging and erosion of bedrock, sediment accumulation resulted in the formation of soft hills area, and sediment erosion by rivers and streams created the lower wetlands. The dominant vegetation covering >80% area is grass. Among deciduous shrubs, *Artemisia ordosica* Krasch. is the most typical but steppe and meadow are also found in the area. In the sandy grassland along the river, treeland, shrubland, and farmland are present. Some of the grasslands have been brought under cultivation, management, and production of animals.

Sample Unit Selection and Sampling

Three sample units -grassland, shrubland, and trees -were established in the 1970s in a bare sand area. These three units are located south of the Yulin desertification controlling station, which was established in 1950. The first unit (established in 1978) is grassland and has an area of 40 × 50 m at present. Dominant species seeded in this unit are *Artemisia desertorum* Spreng. (AD) and *Agriophyllum squarrosum* Moq. (AS). The second unit is shrubland transformed from 10-year-old grassland and has an area of 100 × 130 m. Dominant species in this shrubland unit are *Hippophae rhamnoides* Linn. (HR), *Salix psammophila* Schneid. (SP), *Amorpha fruticosa* Linn. (AF), and *Caragana korshinskii* Kom. (CK). The third unit is in trees and was transformed from a 10-year-old shrubland previously under grassland for the same amount of time and occupies an area of 90 × 120 m. The main species in this woodland unit are *Populus simonii* Carr. (PS), *Ulmus pumila* L. (UP), *Pinus tabuliformis* Carr. (PT), and *Platycladus orientalis* L. (PO).

Prior to soil sampling in July 29, 2012, three 5 × 5 m plots for each plant species were established, and soil samples were taken from each plot. A soil pit 50 cm deep was dug in each plot, and soil layers were identified using the Munsell system of color notation prior to soil sample collection. The first or upper layer was designated as top layer and the second layer as the lower layer (Table 1). Large triplicate soil samples (about 2 kg wet weight each) were collected using a shovel from each plot and layer under each plant species, for a total of nine samples (3 samples × 3 pits) collected from each plant species. These samples were collected in zip lock plastic bags. Additional soil samples were collected from the bare sand area where no vegetation restoration measures were implemented (the "bare control"). The area of the bare sand is 30 × 30 m at present. The three sample units were part of the bare area 30 years ago. The entire sampling area is contiguous, and the four sample units (including bare control) are located next to each other. Although data on soil physical properties prior to the establishment of sampling units are unavailable, due to the close proximity of the sample units, changes

Table 1. Characteristics of sampling units in northern Shaanxi province

Vegetation types	Layer (cm)	Color	Restoration years G +S +T	Altitude (m)	Longitude (E)	Latitude (N)	Slope (°)	Cover (%)
Bare control								
Sand	0–20	10YR6/6	0	1097	109°42′46″	38°19′47″	6–8	10
Sand	0–20	10YR6/6	0	1112	109°42′39″	38°19′52″	4–6	8
Grass								
AD	TL: 0–7	7.5YR5/2	32 + 0 +0	1099	109°42′38″	38°20′00″	5–7	61
	LL:>7	10YR5/6						
AS	TL: 0–4	7.5YR5/0	27 + 0 +0	1099	109°42′39″	38°20′01″	6–8	53
	LL:>7	10YR5/6						
Shrubs*								
HR	TL: 0–20	10YR5/6	10 + 21 +0	1107	109°42′52″	38°20′04″	6–8	53
	LL:>20	10YR6/4						
SP	TL: 0–4	7.5YR4/4	10 + 18 +0	1095	109°42′38″	38°20′01″	5–8	48
	LL:>4	7.5YR5/6						
AF	TL: 0–10	7.5YR4/4	10 + 22 +0	1088	109°42′38″	38°19′59″	6–9	70
	LL:>10	7.5YR6/2						
CK	TL: 0–10	7.5YR5/2	10 + 19 +0	1088	109°42′56″	38°20′02″	7–11	58
	LL:>10	7.5YR6/6						
Trees**								
PS	TL: 0–7	10YR5/2	10 + 10 +13	1093	109°42′56″	38°20′04″	7–9	57
	LL:>7	10YR6/4						
PT	TL: 0–5	7.5YR5/4	10 + 10 +12	1094	109°42′55″	38°20′03″	5–8	62
	LL:>5	10YR6/6						
UP	TL: 0–10	10YR4/4	10 + 10 +11	1090	109°42′56″	38°20′04″	11–15	43
	LL:>10	10YR5/6						
PO	TL: 0–6	7.5YR5/3	10 + 10 +12	1104	109°42′15″	38°19′45″	8–12	65
	LL:>6	10YR6/4						

Note: *Shrubs were under grass during first 10 years, **Trees were under grass during first 10 years and then under shrubs for next ten years. TL is toper layer and LL is lower layer; AD is *Artemisia desertorum*; AS is *Agriophyllum squarrosum*; HR is *Hippophae rhamnoides*; SP is *Salix psammophila*; AF is *Amorpha fruticosa*; CK is *Caragana korshinskii*; PS is *Populus simonii*; PT is *Pinus tabuliformis*; UP is *Ulmus pumila*; PO is *Platycladus orientalis*; G +S +T indicates years under grass, shrubs, and trees.

in the soil properties are predominantly temporal developments, although minor effects due to spatial variability are plausible. A detailed description of each site is provided in Table 1.

Physical and Chemical Analyses

Gravimetric soil moisture content was determined by drying a small subsample of soil collected in 2012 at each location, separately, at 105°C (Lu 2000). Air-dried soil samples were passed through a 2-mm sieve. Pipette method was used to determine the particle size distribution (Lu 2000). Soil cores (volume = 100 cm^3) were oven-dried at 105°C for 24 h and dry weight of soil was obtained. Soil bulk density (B_d) was calculated as the ratio of dry soil weight and the volume of the soil (CAS 1978). Total soil porosity (P_t) was obtained from known B_d and soil particle density ($d_s = 2.65$ g cm^{-3}) as follows:

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

SOM content was determined by the dichromate-wet combustion method (Nelson and Sommers 1982), total nitrogen (TN) by the Kjeldahl method (Bremner and Mulvaney 1982), and available nitrogen (N_{avi}) by the alkali diffusion method. Total phosphorus (TP) content was measured colorimetrically with ammonium molybdate after acid digestion. Soil available phosphorus (P_{avi}) content was extracted with 0.5 mol L^{-1} $NaHCO_3$ at a pH of 8.5, and P was obtained colorimetrically by the molybdate method (Olsen et al. 1954). For total potassium (TK) content, samples were digested in hydrofluoric acid and perchloric acid. Soil available potassium (K_{avi}) content was determined by extraction with 1 N ammonium acetate and using an atomic absorption spectrometer (AAS) (Lu 2000). A glass electrode was used to measure the soil pH in 1:2.5 soil:water suspension and cation exchange capacity (CEC) was obtained by the sodium saturation method (Lu 2000).

The components of total organic C (TOC) are readily oxidizable carbon (ROC) and non-active organic carbon (NAOC). ROC is important for indicating early changes in SOM in soil and was determined by titration with ferrous sulfate after oxidation with potassium dichromate (0.2 mol L^{-1}) and sulfuric acid (1:3) by heating at 130–140°C. NAOC was derived by subtracting ROC from TOC. Changes in the lability of C can be related to sustainability (Lefroy, Blair, and Strong 1993). The lability of C (L), lability index (LI) and C pool index (CPI) were calculated as follows: (Shen, Cao, and Xu 2000).

$$\mathrm{L} = \mathrm{ROC}\left(\mathrm{g\ kg^{-1}}\right)/\mathrm{NAOC}\left(\mathrm{g\ kg^{-1}}\right) \tag{2}$$

$$\mathrm{LI} = \mathrm{L\ of\ a\ sample}/\mathrm{L\ of\ the\ control\ sample} \tag{3}$$

$$\mathrm{CPI} = \mathrm{TOC\ of\ sample}\left(\mathrm{g\ kg^{-1}}\right)/\mathrm{TOC\ of\ control\ sample}\left(\mathrm{g\ kg^{-1}}\right) \tag{4}$$

The continuity of C is a function of C pool size and lability (LI) and both are taken into account to develop C pool management index (CMI) as follows:

$$\mathrm{Carbon\ pool\ management\ index(CMI)} = \mathrm{CPI} \times \mathrm{LI} \times 100\% \tag{5}$$

Data Analysis

Statistical analyses were carried out using the SPSS software version 13.0 for Windows (Levesque 2007) and include analysis of variance (ANOVA) with least-significant-difference (LSD) test. Although experimental design is not a typical randomized design, random samples were collected from each plot and one-way ANOVA was used to examine the effects of restoration with three vegetation communities.

Results

Soil Physical Properties

Small variations in the soil color were observed. In general in the experimental units, the predominant soil color indicated by Hue varied from 7.5 to 10 YR, Value from 5 to 6, and Chroma from 2 to 6. Soil texture under the vegetation communities varied slightly, and according to USDA textural classification ranged from sand to loamy sand and was consistent with low variations in soil color and low organic matter content of soil. Overall sand content was more than 80% and silt and clay contents were less than 20% (Table 2). The dominant soil texture is classified as sand, and no significant differences were detected in sand, silt, and clay contents among the vegetation communities. The soil bulk density in the top layer followed the order: shrubland (1.07–1.26, average 1.19 g cm^{-3}) < grassland (1.33–1.44, average 1.39 g cm^{-3}) < woodland/trees (1.37–1.56, average 1.45 g cm^{-3}) < bare control (average 1.61 g cm^{-3}). No consistent trends in soil bulk density were detected in the lower soil layer.

Soil Chemical Properties

No significant differences were found for the soil pH among vegetation species and among depths even after 30 years of vegetation restoration (Figure 2). Soil CEC was significantly higher in the top layer than the lower layer for all vegetation species. CEC showed an increase under vegetation species in the top layer compared to the control. However, no differences in CEC were observed between restored areas and the control at the lower depth. Increases in soil CEC were significantly higher for shrubs under SP and AF than grass or trees. Subsequent conversion of shrubs to trees was associated with a decline in soil CEC (Figure 2).

The available N, P, K, and total N of the top layer increased significantly after 30 years of vegetation restoration compared with the bare control, but no significant differences were found between restored areas and the bare control in the lower layer (Figures 3–5). Both TN and available N were generally higher under shrubs than other vegetation species (Figure 3). AF is a legume still TN and N_{avi} were higher under SP than under other shrub species. TN and N_{avi} were lowest under all the tree species than under grass or shrubs. No significant differences were observed in TP and TK contents among restored areas under different vegetation species or the control (Figures 4, 5). Visual trends show that TP in top layer decreased from grass to tree while P_{avi} was consistently higher under shrub species of SP, AF, and CK than under grass (except AD) and tree species in the restored area (Figure 4). The K_{avi} was higher in all grass and shrub species than under trees (Figure 5).

Table 2. Physical properties of soil under different vegetation communities in the sampling units

Vegetation species	Layerr	Sand/%	Silt/%	Clay %	Bulk density	Soil moisture %	Total Porosity %
Bare Control							
Bare	TL	92.91 ± 18.37a	3.61 ± 0.85ab	3.48 ± 0.78ab	1.61 ± 0.52a	0.12 ± 0.04d	39.30 ± 7.26b
Bare	TL	93.91 ± 22.46a	2.61 ± 1.02ab	3.48 ± 1.17ab	1.62 ± 0.57a	0.13 ± 0.06d	39.13 ± 6.13b
Grass							
AD	TL	83.41 ± 12.28a	9.87 ± 3.22a	6.72 ± 2.26ab	1.33 ± 0.37b	0.67 ± 0.27ab	49.74 ± 6.49a
	LL	89.68 ± 14.31a	4.62 ± 1.25ab	5.70 ± 2.41ab	1.60 ± 0.45a	0.43 ± 0.13c	39.63 ± 7.53b
AS	TL	83.79 ± 16.29a	8.47 ± 2.26a	7.74 ± 2.75a	1.44 ± 0.42b	0.83 ± 0.34a	54.54 ± 6.87a
	LL	87.67 ± 14.36a	5.22 ± 1.67ab	7.11 ± 2.69a	1.59 ± 0.39a	0.43 ± 0.15c	39.90 ± 5.32b
Shrubs							
HR	TL	82.14 ± 12.24a	7.88 ± 2.63a	9.98 ± 2.69a	1.07 ± 0.31c	1.00 ± 0.36a	59.44 ± 8.75a
	LL	89.98 ± 17.62a	3.71 ± 1.47ab	6.31 ± 1.75ab	1.56 ± 0.34a	0.43 ± 0.12c	56.06 ± 9.67a
SP	TL	85.40 ± 15.21a	6.15 ± 2.45a	8.45 ± 2.38a	1.21 ± 0.26c	0.85 ± 0.26a	54.25 ± 9.25a
	LL	87.26 ± 13.27a	5.72 ± 2.08a	7.02 ± 2.42 a	1.55 ± 0.32a	0.51 ± 0.21c	49.15 ± 7.54a
AF	TL	87.06 ± 14.34a	3.62 ± 1.39ab	9.32 ± 3.13a	1.20 ± 0.28c	0.73 ± 0.18a	46.56 ± 8.14a
	LL	88.47 ± 14.28a	6.63 ± 2.87a	4.90 ± 1.05ab	1.47 ± 0.35a	0.47 ± 0.21c	44.43 ± 7.91ab
CK	TL	79.83 ± 9.27a	11.06 ± 3.26a	9.11 ± 2.89a	1.26 ± 0.38c	1.46 ± 0.42a	52.51 ± 8.53a
	LL	89.49 ± 15.35a	4.81 ± 1.27ab	5.70 ± 1.88ab	1.64 ± 0.43a	0.30 ± 0.14c	38.00 ± 5.35b
Trees							
PS	TL	85.74 ± 10.23a	6.33 ± 1.26a	7.93 ± 2.12a	1.37 ± 0.24b	0.60 ± 0.24ab	48.32 ± 6.44a
	LL	89.48 ± 14.36a	4.02 ± 1.08ab	6.5 ± 2.24ab	1.53 ± 0.32a	0.35 ± 0.15c	42.34 ± 7.29ab
PT	TL	71.81 ± 9.72ab	16.88 ± 4.36a	11.31 ± 3.25a	1.42 ± 0.41b	1.12 ± 0.37a	46.30 ± 5.58a
	LL	84.62 ± 11.06a	6.44 ± 2.24a	8.94 ± 2.14a	1.51 ± 0.46a	0.68 ± 0.26ab	42.87 ± 7.38b
UP	TL	84.02 ± 12.68a	8.45 ± 2.23a	7.53 ± 2.58a	1.46 ± 0.26b	0.61 ± 0.27ab	49.96 ± 7.24a
	LL	92.40 ± 13.23a	3.51 ± 0.78ab	4.09 ± 1.43ab	1.56 ± 0.37a	0.27 ± 0.14c	41.17 ± 6.29b
PO	TL	86.47 ± 8.52a	4.92 ± 1.43ab	8.61 ± 2.54a	1.56 ± 0.52a	0.40 ± 0.17c	48.96 ± 6.47a
	LL	91.30 ± 19.36a	4.21 ± 2.02ab	4.49 ± 1.23ab	1.59 ± 0.43a	0.29 ± 0.12c	40.18 ± 5.64b

Note: All parameters were determined from soil samples collected in 2012. The mean and standard errors are calculated from nine measurements. TL is toper layer and LL is lower layer, AD is *Artemisia desertorum*, AS is *Agriophyllum squarrosum*, HR is *Hippophae rhamnoides*, SP is *Salix psammophila*, AF is *Amorpha fruticosa*, CK is *Caragana korshinskii*, PS is *Populus simonii*, PT is *Pinus tabuliformis*, UP is *Ulmus pumila*, PO is *Platycladus orientalis*. Significant differences were at $\alpha = 5\%$. Different letters in each column indicate significant differences.

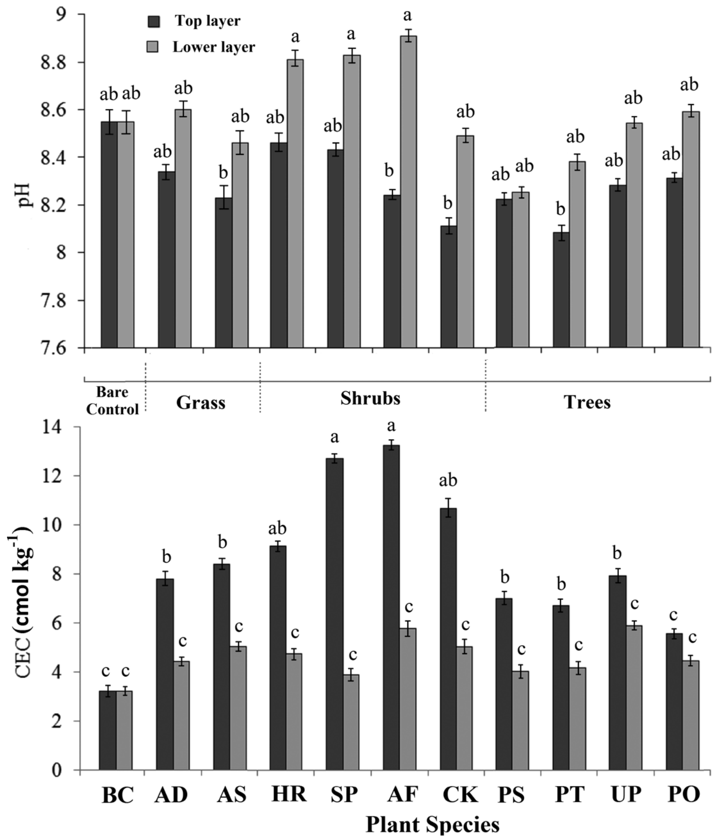

Figure 2. Soil pH and soil CEC under different plant species in northern Shaanxi province (PS: *Populus simonii* Carr., PT: *Pinus tabuliformis* Carr., UP: *Ulmus pumila* L., PO: *Platycladus orientalis* L, HR: *Hippophae rhamnoides* Linn., SP: *Salix psammophila* Schneid., AF: *Amorpha fruticosa* Linn., CK: *Caragana korshinskii* Kom., AD: *Artemisia desertorum* Speng., AS: *Agriophyllum squarrosum* Moq., BC: bare control). Significant differences were at $\alpha = 5$ percent. Different letters on the bar indicate significant differences.

Soil SOM, ROC, and NAOC

As shown in Table 3, after 30 years of vegetation restoration, the SOC, ROC, and NAOC contents increased significantly in all the restored areas under vegetation species for both layers compared to the bare control. As a result soil moisture content and total porosity values were significantly higher and soil bulk density was lower under vegetation than under the bare control in the upper layer. The increases were much higher in the top layer than in the lower layer. The SOC, ROC, and NAOC contents were generally similar under grass and shrub but were lower under trees. Among the shrubs, SOM, SOC and ROC contents in the top layer followed the order HR > AF = SP = CK. Among the trees, SOM, SOC and ROC contents in the top layer followed the order PS>PT = PO = UP. In the bare control, the NAOC to TOC ratio was about 81% and the ROC to TOC ratio was 20% for both layers. The proportion of ROC increased due to vegetation restoration in the top layer compared to the bare control, but no definite trend is visible among restored areas

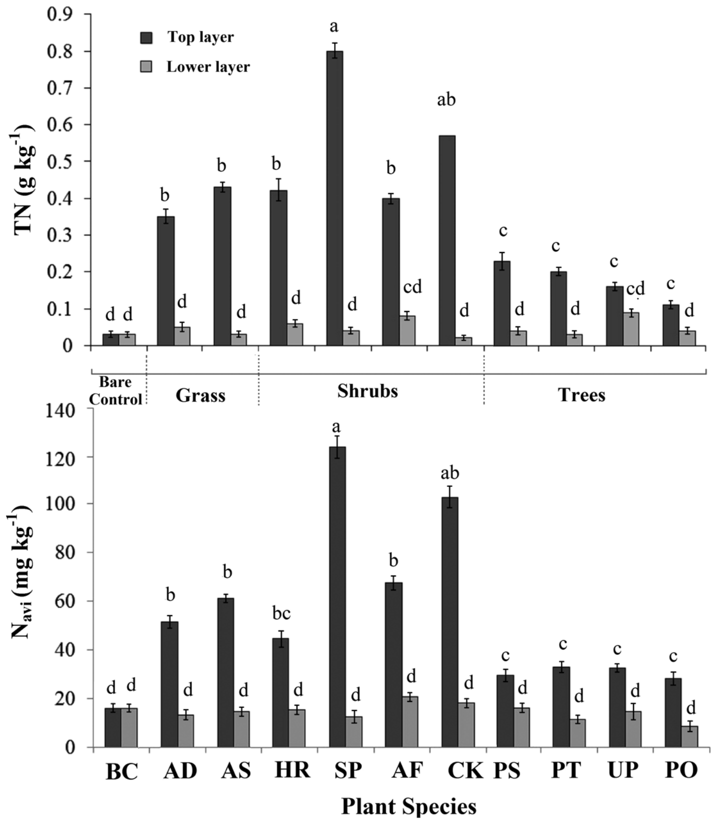

Figure 3. Soil total nitrogen (TN) and available nitrogen (N_{avi}) under different plant species in northern Shaanxi province (PS: *Populus simonii* Carr., PT: *Pinus tabuliformis* Carr., UP: *Ulmus pumila* L., PO: *Platycladus orientalis* L, HR: *Hippophae rhamnoides* Linn., SP: *Salix psammophila* Schneid., AF: *Amorpha fruticosa* Linn., CK: *Caragana korshinskii* Kom., AD: *Artemisia desertorum* Speng., AS: *Agriophyllum squarrosum* Moq., BC: bare control). Significant differences were at $\alpha = 5$ percent. Different letters on the bar indicate significant differences.

under grass, shrub, and trees. ROC and TOC ratios also differed significantly among some grass, shrub, and tree species (Table 3). The results did indicate that vegetation restoration not only increased SOM quantity but also improved SOM quality.

Soil Carbon Management Index

As shown in Table 4, L is less than 0.5 for most vegetation species, indicating that the lability of the organic carbon content is much lower than the NAOC content. All the values of L are positive and LI is greater than one, indicating that both L and LI have increased during 30 years of vegetation restoration compared to the bare control. In the top layer, L and CMI for most vegetation species increased significantly when grassland was transformed into shrubland. However, most L and CPI values generally decreased when shrubs were replaced by trees. No consistent patterns were observed for LI and CPI among three vegetation species.

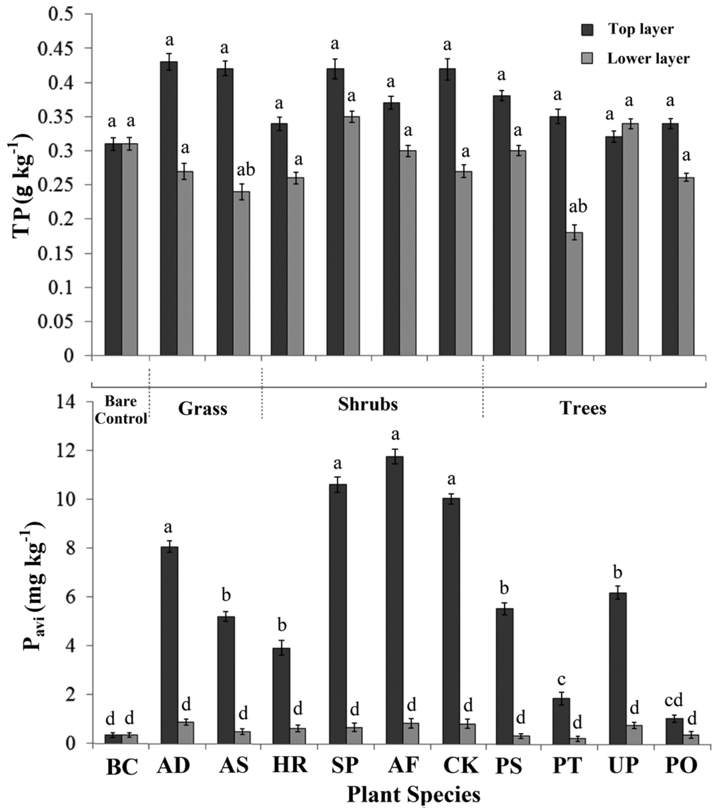

Figure 4. Soil total phosphorus (TP) and available phosphorus (P_{avi}) under different plant species in northern Shaanxi province (PS: *Populus simonii* Carr., PT: *Pinus tabuliformis* Carr., UP: *Ulmus pumila* L., PO: *Platycladus orientalis* L, HR: *Hippophae rhamnoides* Linn., SP: *Salix psammophila* Schneid., AF: *Amorpha fruticosa* Linn., CK: *Caragana korshinskii* Kom., AD: *Artemisia desertorum* Speng., AS: *Agriophyllum squarrosum* Moq., BC: bare control). Significant differences were at $\alpha = 5$ percent. Different letters on the bar indicate significant differences.

Discussion

Effects of Vegetation Restoration on Soil Properties

This study compared various soil properties among three restored sites and a control. All four sites were located in a contiguous area. The grass site was restored 30 years ago, the shrub site was 10 years under grass and 20 years under shrubs, and the tree site was 10 years under grass, 10 years under shrubs, and the last 10 years under trees. Limitations of this study include sampling design not randomized, pseudo-replicates, and only nine random samples used for the analysis. Overall, this study demonstrates that bringing desertified area under vegetation is effective for restoration of arid desert areas. Critical factors for soil property improvement in the desert area during the vegetation restoration include increases in aboveground and belowground biomass (Shukla, Lal, and VanLeeuwen 2007; Fu et al. 2010; Afrifa et al. 2011) with attendant improvements in soil chemical and physical properties and soil organic matter contents.

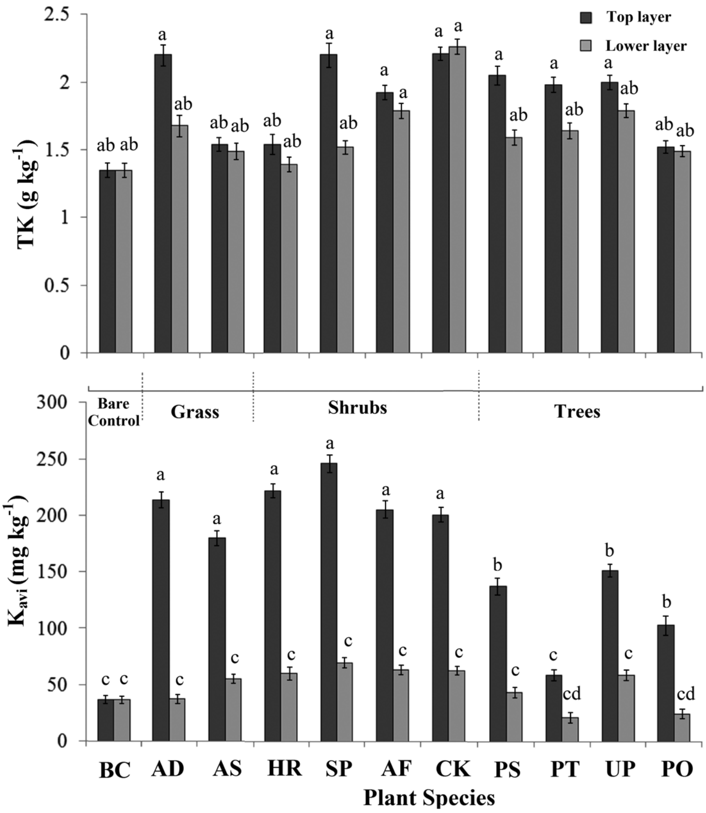

Figure 5. Soil total potassium (TK) and available potassium (K_{avi}) under different plant species in northern Shaanxi province (PS: *Populus simonii* Carr., PT: *Pinus tabuliformis* Carr., UP: *Ulmus pumila* L., PO: *Platycladus orientalis* L, HR: *Hippophae rhamnoides* Linn., SP: *Salix psammophila* Schneid., AF: *Amorpha fruticosa* Linn., CK: *Caragana korshinskii* Kom., AD: *Artemisia desertorum* Speng., AS: *Agriophyllum squarrosum* Moq., BC: bare control). Significant differences were at $\alpha = 5$ percent. Different letters on the bar indicate significant differences.

In this research, compared with the bare control, soil BD decreased and total porosity increased under restored areas. Li and Shao (2006) also reported that soil BD decreased significantly during the succession of natural vegetation from grassland to forest on degraded farmland. Changes in soil texture are reported in some studies (Zhang and Hou 2012); however, in this study no changes in soil texture were seen after 30 years of vegetation restoration. The growth of roots and plant litter did not change the texture of the desert soil significantly because soil texture changes are predominantly due to a very slow process known as pedogenesis.

The dead roots, decomposed litter, and root secretions in the soil change soil property during the vegetation restoration process in the degraded area. Available literature documents that vegetation restoration decreased soil pH because of the increase of CO_2 produced by root respiration, organic acids secreted by roots, and the increase of acidic substances from the decomposition of litter (Wu and Brookes 2005; Peng et al. 2011). Accretions in soil CEC are associated with increasing SOM during the vegetation restoration process (Wang et al. 2010b). This study also indicated that both the quantity and quality of SOM increased significantly with the

Table 3. Soil chemical properties related to quantity and quality of soil organic matter under different vegetation species in the sampling units

Vegetation type	Layer	SOM ($g \cdot kg^{-1}$)	SOC ($g \cdot kg^{-1}$)	ROC ($g \cdot kg^{-1}$)	NAOC ($g \cdot kg^{-1}$)	ROC/TOC (%)	NAOC/TOC (%)
Bare control							
Bare	TL	0.71 ± 0.12e	0.41 ± 0.10e	0.08 ± 0.02e	0.33 ± 0.07e	19 ± 5c	81 ± 36a
Bare	TL	0.68 ± 0.14e	0.39 ± 0.08e	0.08 ± 0.03e	0.31 ± 0.08e	20 ± 7c	80 ± 29a
Grass							
AD	TL	17.38 ± 5.34b	10.08 ± 2.23b	2.29 ± 0.56b	7.79 ± 2.18b	23 ± 11c	77 ± 24b
	LL	3.20 ± 0.86d	1.86 ± 0.38d	0.48 ± 0.13d	1.38 ± 0.29d	26 ± 10b	75 ± 18b
AS	TL	19.92 ± 6.52b	11.55 ± 0.25b	4.03 ± 0.91b	7.49 ± 1.76b	35 ± 13a	65 ± 23c
	LL	1.52 ± 0.31e	0.88 ± 0.18e	0.25 ± 0.06e	0.63 ± 0.12e	28 ± 7b	72 ± 15b
Shrubs							
HR	TL	34.95 ± 9.77a	20.27 ± 5.69a	7.16 ± 1.87a	13.13 ± 3.59a	35 ± 10a	65 ± 21c
	LL	2.34 ± 0.43de	1.36 ± 0.31de	0.25 ± 0.07de	1.11 ± 0.28de	18 ± 5c	82 ± 25a
SP	TL	19.26 ± 0.12b	11.17 ± 2.68b	3.67 ± 0.76b	7.51 ± 2.27b	33 ± 9a	67 ± 18c
	LL	4.23 ± 1.17d	2.45 ± 0.58d	0.68 ± 0.22d	1.77 ± 0.43d	28 ± 11b	72 ± 26b
AF	TL	25.91 ± 0.12b	15.03 ± 3.31b	4.93 ± 1.16b	10.11 ± 3.07b	33 ± 14a	67 ± 21bc
	LL	1.49 ± 0.26e	0.86 ± 0.28e	0.17 ± 0.04e	0.69 ± 0.26e	20 ± 6c	80 ± 28a
CK	TL	12.44 ± 3.43bc	7.22 ± 1.68bc	2.63 ± 0.64bc	4.58 ± 1.14bc	36 ± 11a	64 ± 17c
	LL	3.71 ± 1.02d	2.15 ± 0.24d	0.61 ± 0.21d	1.55 ± 0.43d	28 ± 7b	72 ± 24b
Trees							
PS	TL	16.71 ± 3.53b	9.69 ± 2.06b	3.04 ± 0.75b	6.66 ± 2.37b	31 ± 9ab	69 ± 18b
	LL	1.94 ± 0.49d	1.13 ± 0.24d	0.32 ± 0.08d	0.80 ± 0.21d	29 ± 11b	71 ± 19b
PT	TL	9.86 ± 1.87c	5.72 ± 1.57c	1.84 ± 0.48c	3.88 ± 0.84c	32 ± 12a	68 ± 23bc
	LL	1.91 ± 0.51d	1.11 ± 0.36d	0.28 ± 0.05d	0.81 ± 0.23d	25 ± 9b	73 ± 19b
UP	TL	6.77 ± 1.44c	3.93 ± 0.95c	1.35 ± 0.28c	2.57 ± 0.67c	34 ± 15a	66 ± 21c
	LL	4.33 ± 0.95d	2.51 ± 0.67d	0.49 ± 0.10d	2.03 ± 0.51d	19 ± 7c	81 ± 25a
PO	TL	7.81 ± 1.87c	4.53 ± 1.12c	1.37 ± 0.32c	3.16 ± 0.73c	30 ± 4a	70 ± 14b
	LL	1.09 ± 0.26e	0.63 ± 0.22e	0.13 ± 0.03e	0.50 ± 0.13e	21 ± 6c	79 ± 16a

Note: SOM is soil organic matter, SOC is soil organic carbon, ROC is readily oxidization carbon, NAOC is non-active organic carbon, TL is toper layer and LL is lower layer, AD is *Artemisia desertorum*, AS is *Agriophyllum squarrosum*, HR is *Hippophae rhamnoides*, SP is *Salix psammophila*, AF is *Amorpha fruticosa*, CK is *Caragana korshinskii*, PS is *Populus simonii*, PT is *Pinus tabuliformis*, UP is *Ulmus pumila*, PO is *Platycladus orientalis*. Significant differences were at an $\alpha = 5$ percent. Different letters each row indicate significant differences.

Table 4. Soil carbon management index under different vegetation species in the sampling units located in northern Shaanxi province

Vegetation types	Layer	L	LI	CPI	CMI %
Bare control					
Bare	TL	0.24 ± 0.05c	–	–	–
Bare	TL	0.26 ± 0.07c	–	–	–
Grass					
AD	TL	0.37 ± 0.10b	1.56 ± 0.41b	24.59 ± 7.43b	3133.19 ± 473.96b
	LL	0.35 ± 0.08b	1.47 ± 0.32b	4.52 ± 1.14d	651.39 ± 153.64c
AS	TL	0.54 ± 0.13a	2.24 ± 0.52a	20.92 ± 5.87b	4695.25 ± 968.46b
	LL	0.39 ± 0.12b	1.64 ± 0.36b	2.34 ± 0.95d	384.40 ± 87.34c
Shrubs					
CK	TL	0.57 ± 0.15a	2.39 ± 0.79a	36.66 ± 12.38ab	8763.03 ± 1734.58ab
	LL	0.39 ± 0.07b	1.63 ± 0.43b	2.10 ± 0.62d	342.93 ± 75.47c
HR	TL	0.55 ± 0.11a	2.27 ± 0.58a	17.60 ± 4.06b	3996.54 ± 861.32b
	LL	0.22 ± 0.06c	0.92 ± 0.23c	5.25 ± 1.33d	482.49 ± 100.59c
SP	TL	0.49 ± 0.08ab	2.04 ± 0.57ab	63.59 ± 15.46a	12943.30 ± 3469.37a
	LL	0.38 ± 0.06b	1.60 ± 0.46b	3.31 ± 0.73d	528.81 ± 147.51c
AF	TL	0.49 ± 0.13ab	2.03 ± 0.54ab	42.43 ± 11.24ab	8618.03 ± 2373.69ab
	LL	0.25 ± 0.04c	1.03 ± 0.27c	7.82 ± 2.27d	806.56 ± 219.06c
Trees					
PS	TL	0.46 ± 0.16ab	1.90 ± 0.45ab	23.64 ± 6.79b	4495.79 ± 1267.29b
	LL	0.41 ± 0.11ab	1.69 ± 0.37b	2.75 ± 0.57d	463.98 ± 118.25c
PT	TL	0.48 ± 0.13ab	1.98 ± 0.41ab	25.53 ± 6.43b	5050.59 ± 1353.58b
	LL	0.34 ± 0.08b	1.43 ± 0.35b	3.09 ± 0.81d	443.10 ± 103.79c
UP	TL	0.52 ± 0.16a	2.16 ± 0.51a	11.27 ± 2.46c	2456.18 ± 579.38b
	LL	0.24 ± 0.07c	1.00 ± 0.24c	6.12 ± 1.58d	613.09 ± 148.94c
PO	TL	0.43 ± 0.09ab	1.81 ± 0.37ab	11.04 ± 3.19c	1997.23 ± 324.47b
	LL	0.27 ± 0.05c	1.11 ± 0.26c	1.54 ± 0.43d	170.27 ± 48.61c

Note: TL is toper layer and LL is lower layer, AD is *Artemisia desertorum*, AS is *Agriophyllum squarrosum*, HR is *Hippophae rhamnoides*, SP is *Salix psammophila*, AF is *Amorpha fruticosa*, CK is *Caragana korshinskii*, PS is *Populus simonii*, PT is *Pinus tabuliformis*, UP is *Ulmus pumila*, PO is *Platycladus orientalis*. L is Lability of carbon, LI is Lability index, CPI is carbon pool index, CMI is Carbon pool management index. Significant differences were at an $\alpha = 5$ percent. Different letters indicate significant differences.

decomposition of plant litter and roots. SOM and other C indices could be important in soil property assessment during vegetation restoration in degraded areas. Vegetation restoration also increased soil nutrient content because of the decomposition of plant litters and roots, as well as likely fixation of N by some plant species such as CK and AF.

The trends of SOM and nutrients in this paper are in accord with other published results in degraded areas such as Loess Plateau (An et al. 2008; Jiao, Wen, and An 2011) and red soil areas (Zhang and Xu 2002) of China, but the increase of SOM and nutrient contents in the top layer is higher in the desert area than in the Loess Plateau. In this study, SOM and nutrient contents in the vegetation species after 30 years of restoration increased by about 10 to 40 times compared to the bare control. In contrast, SOM and nutrient contents only increased by about 5 to 10 times compared to the eroded farmland in the Loess Plateau (Jiao, Wen, and An 2011). Another difference was that the increase of SOM and nutrient contents extended up to 20 cm in the red soil area (Zhang and Xu 2002), but was restricted to about 10 cm depth in the desert area of this study.

Reclamation Sequence and Soil Properties

The grass-shrub-tree sequence of vegetation restoration has been successful for non-desert areas. Rehabilitation of drastically disturbed land starts with bringing the topography close to it's predisturbance state. Placement of the stored topsoil on the surface is followed by seeding grass. The grass establishment is usually accompanied by fertilizer application and irrigation. This is an important step because it stops soil erosion that could further degrade the land. After several years under grass, the restored area is planted with shrubs, and tree planting is usually the last step of restoration. The survival of trees indicates successful restoration of degraded land area.

Desertification is severe land degradation, and soil properties and nutrient availability are consequently low. In the mobile dunes characterized by low nutrient contents, only grasses can survive and grow by developing a deep root system within three to five years after seeding. The growth of grasses gradually makes the mobile dunes stationary, adds soil organic matter and nutrients in the top layer with increasing amounts of roots and leaves, and helps the formation of soil structure. One of the important results of this study was the demonstrated significant increase in SOM and nutrient contents after 30 years of vegetation restoration by grass. Zhang and Hou (2012) reported that after 12 years of restoration with grass, SOM, TN, Av-N, Av-P, and Av-K contents increased from 0.38 g kg^{-1}, 0.11 g kg^{-1}, 7.58 mg kg^{-1}, 27.23 mg kg^{-1} and 3.55 mg kg^{-1} (respectively) in mobile sand to 18.02 g kg^{-1}, 1.09 g kg^{-1}, 39.40 mg kg^{-1}, 139.78 mg kg^{-1} and 10.60 mg kg^{-1} (respectively) in stationary, restored sand. Similar results were reported by Qi, Chang, and Hui (2007) in the Shazhuyu desert area after 15 years of vegetation restoration.

Shrubs—the intermediate steps for vegetation restoration in the degraded areas—seemed to produce more biomass than grass because of their branches and deeper roots; consequently, the SOM and nutrient additions to soil also increased. In this research, SOM, TN, Av-N, Av-P, and Av-K contents increased more in the grass-shrub chronosequence than in continuous grass. Similarly, after 20 years of vegetation restoration in the Loess Plateau, SOM and TN contents in grass-shrubs were reported to be 1.36 and 1.48 times greater, respectively, than in continuous grass

(Jiao, Wen, and An 2011). In contrast, Peng et al. (2011) reported that SOM and nutrient contents were higher in continuous grassland than in the grass-shrub chronosequence after ten years of vegetation restoration in the Karst area in Guangxi, China. It is likely that higher precipitation of 1000 mm could have resulted in higher biomass produced by grass in the Karst area than in the present study area where annual precipitation is only 400 mm.

Trees produce much more aboveground and belowground biomass than grasses or shrubs. For example, for a 10-year-old Simon poplar in northern China, root depth is about 170 cm, but is only 55 cm for a 10-year-old CK (Lv 2011). Many researchers have reported improvement in soil properties when shrublands are converted to woodlands/trees. The soil SOM and TN contents of soils in woodlands are reported to be 1.64 and 1.68 times higher, respectively, than those in shrubs in the karst area of China (Chen et al. 2012). Similar trends for SOM and nutrient contents are reported for the Loess Plateau during vegetation restoration of eroded farmland (An, Huang, and Zheng 2009; Jiao, Wen, and An 2011). In contrast, this study showed that the SOM and nutrient contents decreased after trees replaced shrubs.

This study showed that the soil carbon management index increased when grassland was transformed into shrubland. However, when shrubland was converted to woodland, soil carbon management index decreased. Some of the trees also died after 30 to 50 years of recovery and, as a consequence, some of the stationary dunes went back to being mobile dunes (Chang et al. 2003). Possible reasons for the failure of trees could be high soil salt content and high water requirements of trees. In the hinterland of the Taklimakan desert, poor tree survival was due to the high soil salt content, ranging from 0.55 to 0.85 g kg^{-1} with soil electrical conductivity (EC; water: soil = 5:1) ranging from 0.5 to 0.38 decisiemens (Zhou et al. 2002). However, in the present study area, salt content is not high, and EC values ranged from 2 to 5 decisiemens (Chang et al. 2003). Additionally, most of the vegetation communities in this experiment are moderately to highly salt-tolerant (Agri-facts 2001). Therefore, salt content is not a likely reason for the tree failure.

In northern China, the annual water requirement for *Robinia pseudoacacia* is 440 mm for a 17-year-old tree and 477 mm for a 23-year-old tree. For old pine, the water requirement is 417 mm for a 23-year-old tree and 534 mm for a 36-year-old tree (Yu and Wang 2011). The water requirement for a nine-year-old PO ranges from 430 to 484 mm (Zhang et al. 2006). In the study area, total annual precipitation ranges from 380 to 420 mm, and about 70% of the precipitation occurs during July and September. The evaporation in the desert study area ranges from 1800 to 2000 mm. Thus, amount of precipitation is not enough to meet the trees water requirements. Thus, one of the reasons for tree failure is low water availability (Hou et al. 1991). Tree failure changed some of the stationary dunes back into mobile dunes. This reversal can expand and increase the severity of desertification further. The popular vegetation restoration sequence of "grass-shrub-tree" should therefore be critically examined for desert restoration.

Conclusions

In the northern Shaanxi province China, soil properties on the desertified land improved with restoration using a succession of grasses, shrubs, and trees. Comparing the three vegetation restoration communities, improvements in soil properties including reduced bulk density, increased SOM and nutrient contents under grass and grass-shrub sequence were reversed when restoration was switched to trees. Results of this study indicate that overall vegetation restoration on desertified land improves soil properties, but the present restoration sequence of "grass-shrub-tree" is not appropriate for the restoration of present study area. The study area is semi-arid characterized by low precipitation, and survival of trees will be a challenge. More research is needed on determining the appropriate time-span of shrubs prior to conversion to trees.

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