Land preparation and vegetation type jointly determine soil conditions after long-term land stabilization measures in a typical hilly catchment, Loess Plateau of China

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Abstract

Purpose Land preparation (e.g., leveled ditches, leveled benches, adversely graded tableland, and fish-scale pits) is one of the most effective ecological engineering practices to reduce water erosion in the Loess Plateau, China. Land preparation greatly affects soil physicochemical properties. This study investigated the influence of different land preparation techniques during vegetation restoration on soil conditions, which remained poorly understood to date.

Materials and methods Soil samples were collected from depths of 0–10, 10–20, 20–40, 40–60, 60–80, and 80–100 cm, in the typical hilly watershed of Dingxi City, Loess Plateau. Soil bulk density (BD), soil organic matter (SOM), and total nitrogen (TN) were determined for different land preparations and vegetation type combinations. Fractal theory was used to analyze soil particle size distribution (PSD).

Results and discussion (1) The effect of land preparation on soil properties and PSD varied with soil depth. For each land preparation category, SOM and TN values showed a significant difference between the top soil layer and the underlying soil depths. (2) The fractal dimension of PSD showed a

significant positive correlation with clay and silt content, but a significant negative correlation with sand content. (3) The 20 cm soil layer was a boundary that distinguished the explanatory factors, with land preparation and vegetation type as the controlling factors in the 0–20- and 20–100-cm soil layers, respectively.

Conclusions Land preparation and vegetation type significantly influenced soil properties, with 20 cm soil depth being the boundary for these two factors. This study provided a foundation for developing techniques for vegetation restoration in water-limited ecosystems.

Keywords Land preparation · Loess Plateau · Soil conditions · Soil organic matter · Soil particle distribution · Vegetation restoration

1 Introduction

Soil is a key component of the Earth, influencing the chemical, erosional hydrological, and biological cycles, as well as providing services, goods, and resources (Keesstra et al. 2012; Berendse et al. 2015; Brevik et al. 2015). It consists of various particles with irregular shape and self-similar components, which vary spatially. One of the key physical properties of soil system is soil particle size distribution (PSD) that plays a critical role in biogeochemical processes and cycles, such as water retention and movement, soil nutrient sorption, solute transport, and soil erosion (Hillel 1980; Tyler and Wheatcraft 1989; Erskine et al. 2002; Liu et al. 2009; Xu et al. 2013; Gao et al. 2014a; Yu et al. 2015). Changes in PSD are therefore the key factor to monitor soil structure alterations and assess soil nutrient mobility.

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In the Loess Plateau of China, severe water erosion has resulted in widespread environmental degradation (Shi and Shao 2000). In order to improve the local environment, prevent soil and water loss, land preparation has become more common, particularly with the “Grain-for-Green” project. Here various land preparation types such as leveled benches, leveled ditches, adversely graded tableland, and fish-scale pits are widely used to improve vegetation restoration, conserve water, and prevent soil erosion. As a result of predominant water shortage in this region, these measures are considered essential in enhancing seedling establishment and reducing water loss at the slopes (Bergkamp 1998; Gentili et al. 2010). They are also considered important to enhance the survival rate of plants, promote positive succession in vegetation restoration, and restore degraded ecosystems (Wei et al. 2012).

Land preparation, which is ubiquitous on many hillslopes including on the Loess Plateau, has greatly affected the soil structure by reshaping vulnerable slopes and creating diverse micro-landforms (Liu et al. 2013; Mekuria and Aynekulu 2013; McDonagh et al. 2014). It also affects the physical, chemical, hydrological, and biological processes of the soils by changing the rate of surface runoff and removing fine particles from the soil (Kirkby and Morgan 1980). Consequently, land preparation, in combination with water erosion, often influenced soil particle distribution and related soil properties. While previous studies reported that land use changes significantly affected soil properties (Xu et al. 2013; Zhao et al. 2014; Jia and Shao 2014), fewer examined the coupling effects of land preparation technique and vegetation type on soil conditions. In addition, since the impact of land preparation on soil improvement was usually assessed through measures in only a few elected soil properties (e.g., soil organic matter, soil moisture, and total nitrogen), we still lacked information to quantify the relationship between land preparations and other key soil properties during vegetation restoration.

To address the issue, we tried to use fractal theory, a method to model soil disruption processes such as aggregate breakdown induced by either human or natural disturbances (Martinez-Mena et al. 1999; Lyu et al. 2015). It can be used to (i) describe soil physical properties (e.g., soil bulk density, pore size distribution, particle size distribution and soil micro-topography), (ii) model soil physical processes (e.g. water and solutes transport), and (iii) quantify soil spatial variability (e.g., quantify distributions of soil properties and processes) (Perfect and Kay 1995) in soil and tillage research. Fractal dimension of soil particles has also been used to characterize soil PSD and there have been numerous studies that applied fractal theory for understanding the link between PSD and soil structure, such as the influence of land use types on the fractal dimensions of PSD in the Tibetan Plateau of China (Wang et al. 2006), the use of multifractal dimensions to describe soil PSD under different land use categories of the semi-arid Loess

Plateau (Wang et al. 2008), and the monitoring of soil degradation in arid ecosystems to control desertification process (Su et al. 2004). Paz-Ferreiro et al. (2010) evaluated soil PSD using multifractal parameters under various management systems and demonstrated that multifractal analysis was useful for detecting the similarity of PSDs. Fractal theory is therefore an effective method for assessing the impacts of different land use pattern changes on soils.

Although soil structure has been well studied using fractal theory in different ecosystems, information about the influence of land preparation techniques on the fractal dimensions of soils is limited. In the present study, land preparation and vegetation-induced changes in PSD and soil fractal dimension were investigated in relation to changes in soil organic matter (SOM), bulk density (BD), and total nitrogen (TN) in the semi-arid area of the Loess Plateau. The objectives of this study were to (1) detect changes of soil properties in different soil depths under different land preparations and (2) determine the effect of land preparations and vegetation types on soil properties during vegetation restoration.

2 Material and methods

2.1 Study site

The study was conducted in the Longtan catchment (35°43' N and 104°27' E), Dingxi City, Gansu Province, China (Fig. 1). The Longtan catchment is situated in the western part of the Loess Plateau with mean annual air temperature of 6.8 °C. The catchment has a typical hilly-gully geomorphology, with elevations ranging from about 1840 to 2260 m, and covering the area of 16.1 km². The mean annual precipitation is 386 mm (i.e., long-term average between 1961 and 2006), with more than 60 % of rain falls during the three summer months (July to September). Thunderstorms often occur around this period, causing severe soil erosion. The main soil type is loessal soil, with poor soil water field capacity (0.180–0.240 g g⁻¹ dry soil) and a low organic matter content (0.2–2.9 g g⁻¹ dry soil). The wilting point is approximately 0.054 g g⁻¹ dry soil and soil thickness varies from 40 to 60 m (Yang et al. 2014).

The catchment consists of coniferous forests, sparse shrubland, native grassland, pasture grassland, farmland, and abandoned cropland. Revegetation began in the 1980s on poor and steep cultivated lands that had low crop yields. With the implementation of the Grain-for-Green project, Chinese Pine (*Pinus tabulaeformis*), purple alfalfa (*Medicago sativa*), sea buckthorn (*Hippophae rhamnoides*), and littleleaf peashrub (*Caragana microphylla*) were widely used for vegetation restoration. The dominant natural plant species are bunge needlegrass (*Stipa bungeana*) and common leymus (*Leymus secalinus*). Furthermore, the main introduced plant species are

Fig. 1 Location of the study site, Longtan Catchment, Loess Plateau of China

Chinese red pine (*Pinus tabulaeformis*), Siberian apricot (*Armeniaca sibirica*), Chinese arborvitae (*Platycladus orientalis*), and alfalfa (*M. sativa*). Finally, the major crops here are potato (*Solanum tuberosum*), soybean (*Vigna angularis*), and maize (*Zea mays*). Overall, the typical landscape pattern of the Longtan watershed is a patchy mosaic of different vegetation types and microtopographies.

2.2 Field experimental design and soil sampling

In the early spring of 2014, several typical land preparation types in the watershed were selected, including leveled benches, leveled ditches, adverse grade tables, and fish-scale pits. All of the selected land preparation categories were widely used during the implementation of vegetation restoration projects. Overall, six sites were determined as sampling areas. The six sites represented leveled benches with littleleaf peashrub (*C. microphylla*), leveled ditches with Siberian apricot (*Armeniaca sibirica*), adverse graded tableland with Chinese arborvitae (*Platycladus orientalis*) and fish-scale pits with Chinese Pine (*Pinus tabulaeformis*), fish-scale pits with Chinese arborvitae (*Platycladus orientalis*), and adverse grade tableland with Chinese Pine (*Pinus tabulaeformis*) (Fig. 2). Leveled benches-*C. microphylla* and adversely graded tableland-*Platycladus orientalis* were built at 1984, fish-scale pits-*Pinus tabulaeformis* and adverse grade tableland-*Pinus tabulaeformis* were constructed at 1972, and leveled ditches-*A. sibirica* and fish-scale pits-*Platycladus orientalis* were established in 2003, respectively. All six sites had similar elevation and the description of each land preparations were shown in Table 1.

At each site, six sampling plots were selected randomly, with a minimum distance of 3 m between the plots to minimize sampling error. In each sampling plot, soil samples were collected separately with a soil auger

at depths of 0–10, 10–20, 20–40, 40–60, 60–80, and 80–100 cm. Soil bulk density of each soil layer was measured using the core method (stainless steel cylinders with a volume of 100 cm³). All samples were then sealed and taken to the laboratory for further analysis. The field soil sampling was completed in the growing season of 2014.

2.3 Laboratory and laser diffraction analysis

In the laboratory, all soil samples were air-dried and visible plant materials were carefully removed. One part of the samples was passed through a 2 mm sieve for particle size distribution analysis and the other part was passed through a 0.25 mm sieve for SOM and TN measurement. The SOM was determined by dry combustion at 500 °C (Storer 1984) while the TN concentration was measured using the Kjeldahl procedure (Sparks et al. 1996).

For PSD determination, soil samples were pretreated with 6 % H₂O₂ in order to remove organic matter and HCL was added to eliminate carbonates and oxides. The samples were then soaked in distilled water for 24 h. After removal from the distilled water, samples were then chemically dispersed in 0.4 % Calgon and mechanically dispersed in an ultrasonic bath for 5 min. After pretreatment, the samples were analyzed by a laser diffraction technique by using a Mastersizer 2000 (Malvern Instruments, Malvern, England). Soil particle size was classified as clay (<2 µm), silt (2–50 µm), and sand (50–2000 µm) based on the USDA system of soil texture classification.

2.4 Soil fractal model

The mass fractal dimension (D_m) value of soil PSD was calculated in terms of the volume distribution of the soil particle

Fig. 2 Land use map and sketch on land preparation types of the catchment

Table 1 Characteristics of the experimental area and the different land preparation techniques used

	Leveled benches	Fish-scale pits	Leveled ditches	Adversely graded tableland	Adversely graded tableland	Fish-scale pits
Vegetation	<i>C. korshinskii</i>	<i>P. orientalis</i>	<i>P. armeniaca</i>	<i>P. orientalis</i>	<i>P. tabulaeformis</i>	<i>P. tabulaeformis</i>
Height/m	0.85 ± 0.35	1.49 ± 0.29	1.97 ± 0.60	3.34 ± 1.05	6.71 ± 1.28	5.98 ± 1.22
Diameter at breast height (DBH)/cm	0.93 ± 0.10	3.31 ± 0.91	4.25 ± 0.66	4.70 ± 1.55	8.35 ± 1.48	8.97 ± 1.75
Crown diameter/m						
East and west	1.16 ± 0.65	0.70 ± 0.29	1.47 ± 0.71	1.70 ± 0.59	2.51 ± 0.42	2.75 ± 0.70
South and north	0.94 ± 0.39	0.66 ± 0.25	1.50 ± 0.45	1.66 ± 0.69	2.20 ± 0.45	2.85 ± 0.49
Land preparation techniques description	Slope distance was 3.5–4.0 m, the width of the bench was 1.0–1.5 m, the counter-slope degree was 3–5°	Upside-down T-shaped fish-scale pits and the diameter, length, and width were 130, 80, and 50 cm, respectively	Slope distance was 3.5–4.0 m, the length and width of the ditch were 1.5 and 1.8 m, respectively	Slope distance was 4.0 m and the width of the tables was 0.6–1.0 m, the counter-slope degree was 5–8°	Slope distance was 1.5–2.0 m and the width of the tables was 1.0–1.5 m, the counter-slope degree was 5–8°	Upside-down T-shaped fish-scale pits and the diameter, length and width were 80, 80, and 30 cm, respectively
Understory vegetation	<i>Stipa bungeana</i> , <i>Heteropappus altaicus</i> , <i>Cymbaria dahurica</i> , <i>Peganum harmala</i>	<i>Ajanía parviflora</i> , <i>Heteropappus altaicus</i> , <i>bungeana</i>	<i>Medicago sativa</i> , <i>Artemisia capillaris</i> , <i>Stipa bungeana</i> , <i>Artemisia vestita</i>	<i>Thymus mongolicus</i> , <i>Stipa bungeana</i> , <i>Thermopsis lanceolata</i>	<i>Cleistogenes chinensis</i> , <i>Stipa bungeana</i> , <i>Heteropappus altaicus</i>	<i>Cleistogenes chinensis</i> , <i>Artemisia frigida</i> , <i>Heteropappus altaicus</i> , <i>Leymus secalinus</i>
Understory layers cover	55	35	40	40	30	45
Soil						
Bulk density, g cm ⁻³ (0–100 cm)	1.22 ± 0.04	1.27 ± 0.04	1.21 ± 0.03	1.19 ± 0.05	1.13 ± 0.04	1.15 ± 0.04
Sand%	20.75 ± 4.03	21.68 ± 3.98	17.38 ± 3.89	21.96 ± 3.70	18.38 ± 6.87	14.87 ± 4.38
Silt%	69.53 ± 3.26	70.12 ± 3.71	71.84 ± 2.96	67.79 ± 2.95	71.94 ± 5.18	73.41 ± 3.63
Clay%	9.72 ± 1.37	8.20 ± 0.73	10.77 ± 1.19	10.25 ± 0.88	9.68 ± 1.92	11.72 ± 0.82

Data in the table are given as means and standard deviations (S.D.)

size. This model has been widely used in soil science using the following equation (Gao et al. 2014b):

$$\frac{V(r < R_i)}{V_T} = \left(\frac{R_i}{R_{\max}} \right)^{3-D} \quad (1)$$

where r is the soil particle size, R_i is the soil particle size of grade i in the particle size grading, $V(r < R_i)$ is the volume of soil particle size less than R_i , $R_{\max}$ is the maximum diameter of the soil particles, V_T is the total volume of soil particles, and D is the volume-based fractal dimension.

After taking the logarithm of both sides of Eq. (1), we derived Eq. (2) to get the D value using the following equation:

$$D = 3 - \frac{\log V(r < R_i) / V_T}{\log(R_i / R_{\max})} \quad (2)$$

2.5 Data analysis

Means and standard deviations of the selected soil properties of the different land preparations and soil depths were determined. Analyses of variance (ANOVA) on selected properties and PSD were conducted using the MIXED procedure in SAS. This procedure used restricted maximum likelihood estimates of the variance components and computed Wald-type F -statistics using generalized least squares (GLSE). Multi-ANOVA was used to identify the effects of depth, land preparations, vegetation, and their interaction on soil properties; the differences in soil properties and PSD between different land preparations and depths were compared using one-way ANOVA. If there were significant differences in the Wald F -statistics at $P \leq 0.05$, treatment means were then compared using a least significant different (LSD) test. Meanwhile, the PROG REG procedure with the RSQUARE selection method was used for regression analyses (SAS 2002). In addition, redundancy analyses (RDA) were performed with R software version 3.2.0 (R Core Team 2013), with the main focus on the relationships between the soil conditions and the factors influencing them (land preparation and vegetation). The soil properties were quantitative response variables in these

analyses; the explanatory variables included the categorical variables, land preparations with soil depth and vegetation types. In order to distinguish the influence of land preparation and vegetation on soil properties, we used dummy variables (absence or presence) to represent land preparation and vegetation variables. The raw data were factorized before the RDA analyses, and the significance of the variables was tested with Monte Carlo simulations.

3 Results

3.1 BD, SOM, and TN variations under different land preparations

Soil BD, SOM, and TN differed significantly among different land preparations and soil depths ($P < 0.05$; Table 2). Adversely graded tableland-*Pinus tabulaeformis* soils had the lowest overall BD values (1.13 g cm^{-3}), whereas the fish-scale pits-*Platycladus orientalis* soils had the highest (1.27 g cm^{-3}). The median BD was found in the leveled ditched soils. While fish-scale pits-*Platycladus orientalis* soils consistently showed the highest BD values across different soil depths in comparison with the other land preparations, different vegetation types of the same land preparation led to different BD values, depending on soil depths (Table 3). For example, in the top soil layer (0–40 cm) of the adversely graded tableland, BD values of *Platycladus orientalis* soils were significantly higher than for *Pinus tabulaeformis* soils. In addition, the SOM values below the depth of 40 cm were similar among the different land preparations, and all were significantly lower than the surface layer (0–20 cm) in each plot ($P < 0.05$). Finally, the TN values significantly differed between the top soil layer and the underlying soil depths. The leveled benches-*C. microphylla* land preparation type showed the highest TN value (0.64 g kg^{-1}), whereas it was lowest for the adversely graded tableland-*Platycladus orientalis* combination (0.36 g kg^{-1}).

3.2 PSD and fractal features

The percentage of clay, silt, and sand significantly differed among different land preparation types and soil depths

Table 2 Results of Multi-ANOVA for the effect of soil depth, land preparations, and vegetation type on BD, SOM, and TN

	BD/g cm ⁻³	SOM/g kg ⁻¹	TN/g kg ⁻¹
Depth	<0.001	<0.001	<0.001
Land preparation	0.004	0.017	0.011
Vegetation	0.002	0.008	0.004
Land preparation × vegetation	0.035	0.040	0.014
Depth × land preparation × vegetation	0.011	0.009	0.037

Table 3 Variations in bulk density (BD), soil organic matter (SOM), and total nitrogen (TN) among the different land preparation-vegetation type combinations

Land preparations	Depth/ cm	BD/g cm ⁻³	SOM/g kg ⁻¹	TN/g kg ⁻¹
Leveled benches- <i>C. microphylla</i>	0–10	1.22 ± 0.07abB	20.19 ± 0.50aB	1.12 ± 0.09aA
	10–20	1.16 ± 0.02bC	15.85 ± 2.85bAB	0.88 ± 0.16bA
	20–40	1.18 ± 0.03bAB	13.90 ± 3.46bcAB	0.62 ± 0.39cAB
	40–60	1.26 ± 0.02aB	12.26 ± 3.35cA	0.46 ± 0.26cA
	60–80	1.27 ± 0.05aB	11.01 ± 0.22cA	0.36 ± 0.15cA
	80–100	1.22 ± 0.03abA	11.64 ± 1.21cA	0.41 ± 0.24cA
Fish-scale pits- <i>P. orientalis</i>	0–10	1.29 ± 0.02aC	12.45 ± 1.18aD	0.60 ± 0.06aB
	10–20	1.31 ± 0.05aD	10.62 ± 0.12bB	0.40 ± 0.02abBC
	20–40	1.26 ± 0.04aB	11.18 ± 1.59bAB	0.32 ± 0.02bB
	40–60	1.22 ± 0.06aAB	9.78 ± 0.22bA	0.29 ± 0.01bA
	60–80	1.26 ± 0.02aB	10.04 ± 0.22bA	0.28 ± 0.02bA
	80–100	1.26 ± 0.01aA	10.88 ± 2.31bA	0.28 ± 0.02bA
Leveled ditches- <i>M. sativa</i>	0–10	1.15 ± 0.02bBC	16.01 ± 1.84aC	0.79 ± 0.10aB
	10–20	1.21 ± 0.08abC	10.48 ± 0.19bB	0.56 ± 0.12bB
	20–40	1.22 ± 0.02abB	11.44 ± 1.14bAB	0.48 ± 0.22bcAB
	40–60	1.24 ± 0.04aB	11.20 ± 0.46bA	0.38 ± 0.08bcA
	60–80	1.22 ± 0.03abAB	11.24 ± 0.59bA	0.31 ± 0.02bcA
	80–100	1.22 ± 0.02abA	11.21 ± 0.22bA	0.45 ± 0.21cA
Adversely graded tableland- <i>P. orientalis</i>	0–10	1.15 ± 0.10aB	15.51 ± 1.85aD	0.67 ± 0.09aB
	10–20	1.17 ± 0.05aC	12.45 ± 0.77bB	0.34 ± 0.04bC
	20–40	1.20 ± 0.08aAB	11.11 ± 0.38bB	0.32 ± 0.06bB
	40–60	1.17 ± 0.01aAB	11.62 ± 0.59bA	0.30 ± 0.05bA
	60–80	1.17 ± 0.04aA	11.36 ± 0.44bA	0.26 ± 0.02bA
	80–100	1.26 ± 0.01bA	11.11 ± 0.38bA	0.27 ± 0.02bA
Fish-scale pits- <i>P. tabulaeformis</i>	0–10	1.01 ± 0.03aA	24.08 ± 2.48aA	1.07 ± 0.11aA
	10–20	0.97 ± 0.03aA	18.93 ± 2.91bA	0.84 ± 0.13bA
	20–40	1.15 ± 0.08bA	14.61 ± 2.89cA	0.67 ± 0.23bcA
	40–60	1.25 ± 0.08cB	11.69 ± 0.79cdA	0.47 ± 0.22cA
	60–80	1.24 ± 0.01cAB	12.45 ± 2.76cdA	0.41 ± 0.23cA
	80–100	1.25 ± 0.05cA	10.93 ± 0.44dA	0.34 ± 0.05cA
Adversely graded tableland- <i>P. tabulaeformis</i>	0–10	0.96 ± 0.02aA	18.34 ± 1.43aBCD	0.91 ± 0.15aAB
	10–20	1.08 ± 0.11bB	13.83 ± 0.60bB	0.52 ± 0.07bB
	20–40	1.17 ± 0.03cAB	11.64 ± 0.38bAB	0.44 ± 0.10bB
	40–60	1.16 ± 0.06cA	11.14 ± 0.43bA	0.42 ± 0.06bA
	60–80	1.19 ± 0.02cAB	11.39 ± 0.22bA	0.32 ± 0.04bA
	80–100	1.20 ± 0.01cA	11.01 ± 0.57bA	0.30 ± 0.01cA

Data represent means and standard deviations (S.D.). Different uppercase letters indicate a significant difference among land preparation types by soil depth; different lowercase letters indicate significant differences among soil depths by land preparation type ($P < 0.05$)

($P < 0.05$; Table 4), although most of the soil particles was dominated by silt (i.e., 2–50 μm) for all land preparation types, as typically found in loess soils (Table 5). In the surface soil, the clay content of the leveled ditches-*A. sibirica* combination and the fish-scale pits-*Pinus tabulaeformis* was significantly higher than other land preparation types. For the overall 0–100 cm depth,

the fish-scale pits-*Pinus tabulaeformis* combination had the highest average clay content (Table 5).

The leveled ditches-*A. sibirica* soils had the highest surface soil layer fractal dimension values, followed by the fish-scale pits-*Pinus tabulaeformis* combination, and the adversely graded tableland-*Platyclusus orientalis*. The fish-scale pits-*Platyclusus orientalis* surface soil layer had the lowest fractal

Table 4 Results of Multi-ANOVA for the effect of soil depth, land preparations, and vegetation type on clay, silt, sand, and D_m

	Clay (<2 μm) %	Silt (2–50 μm) %	Sand (50–2000 μm) %	D_m
Depth	0.171	0.009	0.010	0.226
Land preparation	0.657	0.038	0.092	0.548
Vegetation	<0.001	0.474	0.184	<0.001
Land preparation $\times$ vegetation	<0.001	0.219	0.160	<0.001
Depth $\times$ land preparation $\times$ vegetation	0.606	0.821	0.220	0.897

dimension values. For the 10–20-cm layer, the fish-scale pits-*Platyclusus orientalis* fractal dimension values were also significantly lower than those in the leveled ditches-*M. sativa* and fish-scale pits-*Pinus tabulaeformis* soils. The fish-scale pits-*Pinus tabulaeformis* had the highest average overall fractal dimension in the 0–100-cm soil depth, whereas it was lowest for fish-scale pits-*Platyclusus orientalis*. The fractal dimension values of the six land preparations were in the following order: fish-scale pits-*Platyclusus orientalis* < leveled benches-*C. microphylla* < adversely graded tableland-*Platyclusus orientalis* < adversely graded tableland-*Pinus tabulaeformis* < leveled ditches-*A. sibirica* < fish-scale pits-*Pinus tabulaeformis*.

3.3 Relationship between fractal dimension and PSD

The fractal dimensions had significant and positive linear relationship with clay ($R^2 = 0.938$, $P < 0.001$; Fig. 3) and silt content ($R^2 = 0.513$, $P < 0.001$; Fig. 3) but had significant negative relationship with sand content ($R^2 = 0.764$, $P < 0.001$; Fig. 3).

3.4 RDA analysis

There was a strong association between soil properties and the explanatory factors (land preparation and vegetation types), although their importance differed among soil depths (Fig. 4). While land preparation and vegetation significantly affected soil properties in the surface soil (0–20 cm), land preparation (41.6 %) was the more important driver for this soil layer compared with vegetation (37.2 %). In contrast, vegetation was the dominant factor influencing soil properties at depths below 20 cm. Although land preparation significantly influenced soil conditions in the 20–40- and 60–80-cm soil layers, this influence was not significant in the 40–60- and 80–100-cm layers. Overall, 20 cm soil depth was the boundary for distinguishing the influence of the two factors, with land preparation having a major effect on soil conditions above this depth.

4 Discussion

4.1 Joint effects of land preparation and vegetation on soil properties

The knowledge of variability in soil properties is the foundation for understanding the influence of land preparation or land use on soil quality and the site-specific management practices or designs (Shukla et al. 2006). Our result showed that effect of land preparation on soil BD, SOM, and TN distribution varied with soil depth, consistent with previous studies (Wang et al. 2009; Daryanto et al. 2012). SOM is an index of soil quality that reflects soil nutrient conditions, and it is a critical parameter for evaluating land use patterns (Pulleman et al. 2000; Franzluebbers 2002). Here, the fish-scale pits-*Pinus tabulaeformis* combination and the leveled benches-*C. microphylla* exhibited the highest SOM and highest TN levels, respectively. In contrast, the lowest SOM and TN levels were observed for fish-scale pits-*Platyclusus orientalis* soils. SOM and TN were significantly higher in the surface soil layer than the deep soil layer, indicating that both land preparation and vegetation could improve SOM and TN content of the topsoil. Lower SOM and TN levels in the fish-scale pits-*Platyclusus orientalis* combination could be attributed to the reduced residue input as well as severe soil erosion due to limited canopy cover of the species. Meanwhile, we attributed higher TN in the leveled benches-*C. microphylla* soils to the N_2 -fixing capacity of the *C. microphylla*.

These effects of vegetation were also consistent with our results on fractal dimension. For example, the soils of the fish-scale pits-*Pinus tabulaeformis* combination had a significantly higher fractal dimension than the fish-scale pits-*Platyclusus orientalis* soils, most likely due to differences not only in the canopy but also the root system of the species. In our study, the projected area of the *Pinus tabulaeformis* crown was significantly larger than that of *Platyclusus orientalis*. Therefore, this species was probably better at mitigating erosion through rainfall than *Platyclusus orientalis* as canopy cover was critical in reducing runoff and soil loss. These results were consistent with other studies (Daryanto et al. 2013a, b) which indicated that vegetation canopy changed the distribution of

Table 5 Characteristic of soil particle size distribution (PSD) and mass fractal dimension (D_m) variation of different land preparation techniques

Land preparations/depth (cm)	Clay (<2 μm) %	Silt (2–50 μm) %	Sand (50–2000 μm) %	D_m
Leveled benches- <i>C. microphylla</i>				
0–10	9.71 $\pm$ 1.61aB	66.32 $\pm$ 2.11aB	23.97 $\pm$ 3.73aB	2.52 $\pm$ 0.04aBC
10–20	9.75 $\pm$ 1.19aAB	70.58 $\pm$ 1.62abA	19.68 $\pm$ 2.81abA	2.54 $\pm$ 0.03aAB
20–40	9.96 $\pm$ 1.37aAB	72.63 $\pm$ 1.81bA	17.41 $\pm$ 1.47bAB	2.55 $\pm$ 0.03aAB
40–60	9.94 $\pm$ 1.99aB	72.40 $\pm$ 2.34bB	17.66 $\pm$ 3.13bAB	2.55 $\pm$ 0.04aB
60–80	9.27 $\pm$ 0.86aBC	68.39 $\pm$ 3.53abB	22.34 $\pm$ 4.22abA	2.52 $\pm$ 0.03aC
80–100	9.69 $\pm$ 0.52aAB	69.02 $\pm$ 2.65abB	21.29 $\pm$ 2.45abAB	2.54 $\pm$ 0.01aB
Fish-scale pits- <i>P. orientalis</i>				
0–10	7.75 $\pm$ 0.25aB	62.38 $\pm$ 3.49aC	29.86 $\pm$ 3.66aA	2.47 $\pm$ 0.02aC
10–20	9.10 $\pm$ 0.93aB	70.81 $\pm$ 0.79bA	20.09 $\pm$ 0.89bA	2.53 $\pm$ 0.02bB
20–40	8.61 $\pm$ 0.34aB	72.41 $\pm$ 3.72bA	18.98 $\pm$ 3.55bAB	2.52 $\pm$ 0.01bB
40–60	7.46 $\pm$ 1.29aC	69.31 $\pm$ 4.34bBC	23.23 $\pm$ 3.41bA	2.48 $\pm$ 0.04abC
60–80	7.69 $\pm$ 1.23aC	72.08 $\pm$ 0.75bB	20.23 $\pm$ 1.64bA	2.50 $\pm$ 0.03abC
80–100	7.68 $\pm$ 0.90aB	73.05 $\pm$ 2.22bAB	19.27 $\pm$ 2.46bB	2.50 $\pm$ 0.02abB
Leveled ditches- <i>M. sativa</i>				
0–10	11.94 $\pm$ 0.44aA	74.38 $\pm$ 2.37aA	13.67 $\pm$ 2.81bC	2.59 $\pm$ 0.01aA
10–20	11.22 $\pm$ 0.54abA	72.59 $\pm$ 2.21aA	16.18 $\pm$ 2.68abA	2.57 $\pm$ 0.01abA
20–40	10.47 $\pm$ 1.52abB	70.86 $\pm$ 1.03aAB	18.67 $\pm$ 1.79abAB	2.56 $\pm$ 0.03abAB
40–60	10.05 $\pm$ 0.06abB	70.21 $\pm$ 0.71aBC	19.74 $\pm$ 0.76aAB	2.55 $\pm$ 0.01abB
60–80	9.64 $\pm$ 0.50bB	69.67 $\pm$ 0.57aB	20.69 $\pm$ 0.82aA	2.54 $\pm$ 0.01bBC
80–100	9.70 $\pm$ 0.57bAB	70.06 $\pm$ 0.30aAB	20.24 $\pm$ 0.85aAB	2.54 $\pm$ 0.01bB
Adversely graded tableland- <i>P. orientalis</i>				
0–10	9.85 $\pm$ 0.92aB	66.47 $\pm$ 1.56aBC	23.67 $\pm$ 2.46aB	2.53 $\pm$ 0.02aBC
10–20	10.68 $\pm$ 0.73aAB	69.52 $\pm$ 2.65aA	19.80 $\pm$ 3.09aA	2.56 $\pm$ 0.02aAB
20–40	10.05 $\pm$ 0.69aAB	67.69 $\pm$ 1.97aB	22.26 $\pm$ 2.64aA	2.54 $\pm$ 0.02aB
40–60	9.97 $\pm$ 0.34aB	66.89 $\pm$ 1.72aC	23.14 $\pm$ 2.05aA	2.53 $\pm$ 0.01aB
60–80	10.43 $\pm$ 0.72aB	68.17 $\pm$ 2.64aB	21.39 $\pm$ 4.35aA	2.55 $\pm$ 0.02aBC
80–100	10.45 $\pm$ 0.68aA	67.57 $\pm$ 0.81aB	21.98 $\pm$ 1.37aAB	2.55 $\pm$ 0.02aAB
Fish-scale pits- <i>P. tabulaeformis</i>				
0–10	10.61 $\pm$ 0.55bA	68.45 $\pm$ 0.95aB	20.95 $\pm$ 1.01aB	2.55 $\pm$ 0.01bB
10–20	11.31 $\pm$ 0.70abA	71.70 $\pm$ 2.00aA	16.99 $\pm$ 2.62abA	2.57 $\pm$ 0.02abA
20–40	11.78 $\pm$ 0.23abA	72.48 $\pm$ 5.00aA	15.74 $\pm$ 4.91abB	2.59 $\pm$ 0.01abA
40–60	12.41 $\pm$ 2.30abA	78.45 $\pm$ 1.86bA	9.13 $\pm$ 3.56cB	2.61 $\pm$ 0.04aA
60–80	13.11 $\pm$ 2.24a	77.30 $\pm$ 0.45bA	9.59 $\pm$ 2.59cB	2.62 $\pm$ 0.04aA
80–100	11.53 $\pm$ 0.58abA	73.80 $\pm$ 1.33abA	14.67 $\pm$ 0.59bcB	2.58 $\pm$ 0.01aA
Adversely graded tableland- <i>P. tabulaeformis</i>				
0–10	8.31 $\pm$ 1.55aB	68.53 $\pm$ 2.68bB	23.16 $\pm$ 4.01aB	2.50 $\pm$ 0.04aC
10–20	10.33 $\pm$ 1.33bAB	73.06 $\pm$ 4.48abA	16.61 $\pm$ 5.77bA	2.56 $\pm$ 0.04bAB
20–40	10.63 $\pm$ 2.61bA	73.88 $\pm$ 5.77aA	15.49 $\pm$ 1.57bB	2.56 $\pm$ 0.08bAB
40–60	10.88 $\pm$ 0.88bA	74.62 $\pm$ 2.70aA	14.50 $\pm$ 3.58bB	2.57 $\pm$ 0.02bA
60–80	10.62 $\pm$ 2.00bA	77.00 $\pm$ 4.97aA	12.38 $\pm$ 1.11bB	2.57 $\pm$ 0.05bB
80–100	8.07 $\pm$ 0.34aB	66.82 $\pm$ 1.09bB	25.11 $\pm$ 1.40bA	2.49 $\pm$ 0.01aB

Data in the table represent means and standard deviations (S.D.). Different uppercase letters indicate significant differences among land preparation types by soil depth; different lowercase letters indicate significant differences among soil depths by land preparation type ($P < 0.05$)

Fig. 3 Relationships between fractal dimensions of particle size distribution (PSD) and clay, silt, and sand content

soil organic matter and soil infiltrability. As plant roots penetrated the soils, they actively changed infiltration rate which consequently led to changes in PSD (Angers and Caron 1998; Zuazo and Pleguezuelo 2008). Similarly, plant roots played essential role in influencing the responses of SOM, TN, and soil texture to different land preparation types. In the deep soil layer, the amount of TN was generally low as mineralized

“*” stand for significant level less than 0.05

Fig. 4 The proportion of vegetation types and land preparations contributing to the variance of the soil properties at different soil depths, based on the redundancy analysis (RDA)

organic residues were smaller compared to the amount of N absorbed by plant roots. Overall, land preparation can modify soil properties through abiotic influences by reducing soil water erosion, sediment transport, and runoff, whereas vegetation influences soil properties through biotic mechanisms, such as the development of canopy and root activity (Hillel 2008).

The fractal dimension was also responsive to land preparation and soil depth, indicating that both natural and managerial factors influence this indicator. Land preparation significantly affected the extent of water erosion by changing the path of water flow during rainfall events, resulting in different soil particle distributions, soil water regimes, and nutrient transportation, particularly the surface SOM and TN concentrations (Appels et al. 2011; Thompson et al. 2010; Wang et al. 2015). Water erosion occurred mainly in the surface soil layer, while land preparation techniques could decrease erosion and increase soil clay content, indicated by the higher SOM and TN in the surface soil. Furthermore, soil PSD was sensitive to land preparations, as significant differences in the fractal dimensions of the PSD were detected among the different land preparation types.

Our study indicated that soil texture (i.e., clay content) greatly affected the fractal dimensions of PSD by changing the amount of SOM. In loess soils, clay-rich soils can store more organic matter by forming soil humus than clay poor soils (Liu et al. 2007). SOM therefore increased when soil fractal parameter values increased and particles became less coarse and vice versa (Wang et al. 2007; Gao et al. 2014b). In the present study, the fractal dimension of PSD showed a significant positive relationship with clay and silt content, but a significantly negative relationship with sand content. In other words, higher clay and silt contents but lower sand content led to higher fractal dimension, consistent with the previous studies (Liu et al. 2009; Su et al. 2004).

4.2 Respective role of land preparation and vegetation

Our RDA results indicated that land preparation techniques and the plant species growing on the sites had a great influence on the soil properties, with land preparation as the dominant factor influencing soil properties in the top 20 cm of the soil while vegetation types in the deeper soil layers. During vegetation restoration, land preparations have significant local impacts on the geomorphologic and hydrological dynamics. Since land preparation can affect geomorphic processes via soil water erosion (and later the vegetation type), the influence of land preparation techniques was more apparent on surface soil (Fig. 2). On the other hand, vegetation was the main factors influencing soil properties below 20 cm, suggesting that roots play an essential role in changing soil properties as a response to different land preparations in the Loess Plateau. Roots are closely related to soil structure and pedohydrology, and play a vital role in regulating soil resistance. With increasing plant growth and successional stage, the development and decay of the roots impacted soil pore structure, soil moisture status, and soil aggregate stability (Wang et al. 2013). Our study was conducted more than 13 years after restoration. As these impacts of vegetation on soil properties (e.g., vertical distribution, SOM, TN, and biomass of the roots) usually increase with increasing restoration years (Daryanto et al. 2012; Yu and Jia 2014), it is unsurprising if greater effects of vegetation can be explained by larger influence of roots in the deeper soil after long-term land stabilization measures.

4.3 Implications of this study and suggestions for further research

In the hilly watershed of the Loess Plateau, the interacting pressures of anthropogenic and environmental change drive the environmental systems towards almost irreversible modifications. Both natural changes and management modify soil properties during long-term vegetation restoration projects. Our findings have important implications on soil and water conservation, environmental engineering, and ecological restoration in water-limited ecosystems. From the theoretical point of view, the aims of land preparation are to prevent runoff and water erosion, and to supply limited water for vegetation. Our study demonstrated that land preparation techniques and vegetation type jointly determine soil conditions, and that land preparation is a recommended method to improve and rehabilitate degraded ecosystems. From the practical point of view, our result indicated that 20 cm was the boundary layer to distinguish land preparation and plant species as the dominant factor influencing soil conditions. It is necessary to pay attention to this boundary layer during the process of land preparation engineering at the current study site.

Our results indicated that different vegetation-land preparation combinations resulted in different soil conditions, thus selecting certain vegetation-land preparation combinations rather than using random plant species could be critical for ecosystems restoration. To date, partly due to the different kinds of land preparation types and their related eco-hydrological or biological responses, detailed relationships between land preparation and plant species choice had not been explored thoroughly. Although land preparation is ubiquitous among different kinds of ecosystems, the detailed mechanism underlying the influence of land preparation techniques on vegetation patterns and even ecosystem services remains unclear, including the responses of erosion processes or nutrient cycling under the coupling effects of land preparation and vegetation pattern. Hence, long-term monitoring and consecutive measurements of different land preparation types are required for future studies, to better evaluate their effects on soil properties, as well as on eco-hydrological and biological responses.

5 Conclusions

Our results showed that land preparation type and plant species jointly affected soil conditions in a hilly watershed in the Loess Plateau. Significant differences for major soil properties such as SOM, TN, D_m , and clay, silt, and sand content were detected among different land preparation-dominant plant species combinations. The fish-scale pits-*Pinus tabulaeformis* and leveled benches-*C. microphylla* soils had the highest SOM and TN content, respectively. The SOM and TN in each soil depth exhibited surface aggregation under the coupling effects of land preparation techniques and vegetation type. RDA analyses showed that land preparation techniques and vegetation type significantly affected soil properties at different depth (i.e., land preparation had a major impact on the surface soil properties, whereas plant species on the deeper soil layer), considering site-specific land preparation-plant species combinations could be critical to ensure long-term land stabilization.

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