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Influence of vegetation restoration on soil physical properties in the Loess Plateau, China

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Abstract

Purpose Extensive vegetation recovery has been implemented to control severe soil erosion on the Loess Plateau, China. However, no systematic study has been done on the soil improvement benefit and preferable pattern of vegetation rehabilitation. In this study, the effects of vegetation restoration on soil physical properties at ten sites with different vegetation types and varying restoration periods were investigated.

Materials and methods The experiment was carried out in the Yanhe river basin in the hilly-gully region of the Loess Plateau. Ten sites, including two replanted arboreal forests for 25 and 35 years, three replanted scrubland for 15, 30, and 45 years, four secondary natural grassland for 10, 20, 30, and 40 years, and one farmland, were selected for soil sampling. Sampling was conducted at 0–20 cm and 20–40 cm layers.

Results and discussion Vegetation restoration significantly decreased bulk density, and increased aggregate stability and saturated hydraulic conductivity (Ks), while their effects on porosity was complicated. The soil texture class did not change with vegetation succession, but minor differences in sand, silt, and clay components were observed. Bulk density, macroporosity, and > 0.25 mm aggregate stability were the principal physical parameters that affected Ks. Moreover, bulk density had the most effect on Ks (− 0.84), while > 0.25 mm aggregate stability had the lowest impact (0.38). Bulk density and Ks were correlated with most of the other soil physical properties. Replanted scrubland and secondary natural grassland had higher soil physical quality index (S_{Dexter}) than replanted arboreal forests and farmland.

Conclusions It is reasonable to take bulk density and Ks as the indicators to evaluate the effect of vegetation restoration on soil physical properties. Planting shrubs and grassland is better than forest for eco-environment rehabilitation in the study area. Results of this study provide a reference to regional eco-environmental rehabilitation and conservation.

Keywords Bulk density · Saturated hydraulic conductivity · Soil physical properties · Soil quality

1 Introduction

China's Loess Plateau is one of the most severely eroded areas in the world due to its loose loess soils, steep slopes, high intensity summer storms, and poor vegetation conditions (Li et al. 2009). The annual average sediment discharge of the Yellow River was 16×10^8 t between 1919 and 1960, indicating the seriousness of soil loss in the Loess Plateau (Mu et al. 2012). Soil erosion leads to the removal of soil nutrients and degradation of soil structure, negatively impacting vegetation development and impeding soil water transport capabilities (Berger and Hager 2000). In order to control soil erosion and restore the regional ecological functions, numerous soil and

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water conservation practices have been implemented over the Loess Plateau since the 1950s, especially after the implementation of Grain-for-Green (GFG) project (Feng et al. 2012).

With the help of large-scale vegetation rehabilitation, vegetation coverage of the Loess Plateau increased from 28.8% in the 1980s to 43.8% in 2012. Meanwhile, soil erosion has been effectively controlled, and sediment discharge into the Yellow River decreased significantly after the 1980s (7×10^8 t per year during the 1980s–2000s), particularly after the GFG project (4×10^8 t per year during 2000–2008) (Mu et al. 2012). However, the flow of Yellow River declined significantly during this period, which exacerbated water shortages in the region. Numerous researchers have studied the reasons for the decrease in runoff (Gao et al. 2011). They found that extensive forestation in this arid region is the primary cause (McVicar et al. 2007). Large-scale vegetation recovery in the eroded region increased rainfall interception, surface ground coverage, and caused changes in soil properties (Fu et al. 2003; Jiao et al. 2011). Understanding the effects of vegetation restoration on soil physical properties is important for studying the mechanisms of hydrologic processes. Moreover, a study of vegetation recovery processes and their impacts on soil properties would provide critical guide for eco-environmental restoration or rehabilitation (Li and Shao 2006).

Many efforts have been made to study the effects of vegetation recovery on soil properties because of its importance in eco-restoration and effectiveness (Cerdà 2000; Celik 2005; Erktan et al. 2016). Previous studies have indicated that revegetation can restore the integrity of disturbed ecosystems by improving soil physical quality (e.g., decreasing soil bulk density, increasing porosity and aggregate stability) (Jia et al. 2011; Li et al. 2012). Nevertheless, the impacts of vegetation restoration on soil properties may vary with the vegetation type. Li et al. (2012) assessed the effects of vegetation restoration on soil physical properties in the wind–water erosion region of the Loess Plateau. The results showed that while soil physical properties (e.g., bulk density, mean weight diameter, macro-aggregates) have been significantly ameliorated in the topsoil (0–20 cm layer) under secondary natural grasslands, they changed adversely for replanted scrubland (e.g., *Caragana korshinskii*, *Medicago sativa*). Neris et al. (2012) compared the infiltration rate of green forest and pine forest in Tenerife with farmland soils. They found that infiltration rate of the green forest was 11.9 times greater than that of the farmland soils while pine forest was 2.8 times greater. Moreover, vegetation effects on soil physical properties varied with restoration periods (Li et al. 2007; Zhang et al. 2010). The general conclusion was that the soil bulk density decreased significantly with the recovery time (linear relation), while soil organic matter increased but their relation differ according to the regions (Zhang et al. 2010).

The Loess Plateau experienced extensive vegetation restoration since the 1950s, and particularly during the recent 20 years (Gao et al. 2011). Their impacts on regional environment, such as climate, soil properties, and water resource have been widely studied (Jiao et al. 2011). Soil acts as an indispensable component of the soil–plant–atmosphere continuum (SPAC). An evaluation of the changes in soil properties as a consequence of this vegetation restoration efforts is important, especially for fragile ecological areas. Previous studies have looked at the influence of vegetation recovery on soil properties (Fu et al. 2003; Stolte et al. 2003). Wilson et al. (2005) assessed the changes of macropore flow characteristics for four conditions (i.e., 1 year following tillage, 6 years following tillage, 6 years following contour ditching, and greater than 15 years following tillage) of the Loess Plateau. They found that total number of macropores (> 1 mm), number of large (> 5 mm) macropores, and the macroporosity increased with revegetated time. Moreover, the soil matrix infiltration rate was highest in the newly established (1 year) and the oldest (> 15 years) revegetated areas. Xu et al. (2006) identified soil quality factors and indicators of the Loess Plateau by 32 soil properties. They found that organic matter, hydraulic conductivity, and anti-scourability were the most important indicators to characterize soil quality in this loess plateau. However, changes in soil properties during long-term vegetation restoration on the Loess Plateau still require further thorough studies. For instance, most studies rarely relate changes in soil physical properties with different vegetation types and restoration periods, and the choice of preferable pattern of vegetation rehabilitation (e.g., Stolte et al. 2003). Furthermore, majority of published literature focused on soil physical properties such as bulk density, total porosity, and aggregate, while less emphasis were on soil functions such as the hydraulic conductivity and hierarchical pore (e.g., Jiao et al. 2011). Even though some articles report hydraulic properties changed with vegetation restoration, their relationships with other physical parameters were limited (Li et al. 2012). Soil hydraulic properties (e.g., saturated hydraulic conductivity, Ks) are important for soil water movement and runoff yield calculations (Horton 1945), and play important roles in the understanding hydrological response to vegetation restoration. Following a general conclusion by researchers that the decrease in runoff in the yellow river is a consequence of increased vegetation recover (Gao et al. 2011), it is becoming more important to further investigate the effects of vegetation restoration on soil physical properties and some hydraulic functions.

The hilly-gully region of the Loess Plateau is a substantial soil loss region, which supplies nearly 60% of total sediment but only approximately 15% of total runoff into the Yellow River (Wang et al. 2007). It is critical to study the effects of vegetation restoration on soil physical properties both for the evaluation of ecological restoration and understanding of shifts in hydrological regime. For the reasons, we systematically determined effects of vegetation restoration on soil physical properties in the hilly-gully region of the Loess Plateau. Specifically, we evaluated the impacts of soil physical properties on saturated hydraulic conductivity and explored the effectiveness of vegetation restoration on soil physical properties.

2 Materials and methods

2.1 Study area

This study was carried out in the Yanhe River basin in the hilly-gully region of the Loess Plateau (middle reaches of Yellow River) of China (Fig. 1a). The study area belongs to a temperate continental semi-arid monsoon climate, with annual average precipitation and temperature of 538 mm and 9.9 °C, respectively (1952–2015). The precipitation of the area is temporally uneven, with 71.1% of the precipitation falling between June and September (Fig. 1b). Vegetation restoration of the basin started in the 1950s, and large-scale revegetation was further implemented after the GFG project (1999). The vegetation cover increased by 2.58% per year after the GFG started in 1999 and reached 58% in 2010 (Fig. 1c).

2.2 Site selection and sampling design

Ten sites (within 8 km of each other) representing the typical vegetation restoration in this region were selected within the basin. Two sites were replanted to arboreal forests (*Robinia pseudoacacia* L.) for 25 and 35 years; three replanted to scrubland (Korshinsk pea shrub) for 15, 30, and 45 years; four to secondary natural grassland for 10, 20, 30, and 40 years; and one was continuous farmland, used as a control (vegetation types or treatments are defined in Table 1). The farmland has been continuously planted to maize for more than 30 years. The conventional tillage is performed manually by hoeing and residue is removed for use as biofuel. All the vegetation was replanted on the abandoned croplands. We assumed that local soil properties are largely a consequence of plant growth and soil protection during secondary succession, and the initial conditions or management for the sites were similar (Jiao et al. 2011). The chronosequence of the vegetation was investigated to examine how soil properties change over time during restoration. This chronological approach has been applied in other ecosystem research (Fang and Peng 1997) and is considered retrospective research because existing conditions are compared with known original conditions and treatments. To reduce the effects of gradient and elevation on the soil properties, all the selected sites have the similar gradient (less than 10°) and elevation (less than 200 m) (Table 1). Three plots were established at each site (20 × 20 m in the forest sites and 10 × 10 m for other sites) for soil sampling. Three points along the diagonal of the plot were used for soil sampling and their average represents the soil parameter value of the plot. The soil sampling was taken in May, when there is no crop and tillage measure in farmland.

To determine soil physical properties, undisturbed samples were obtained from the 0–20 cm and 20–40 cm soil layer at each site. Three intact soil cores (5 cm diameter and 5 cm height) were obtained using a ring knife in each soil layer, which was used to measure the bulk density, soil water retention curve (SWRC), and Ks.

The bulk density was calculated as:

$$\mathrm{BD} = M_d / V \tag{1}$$

where BD is the bulk density (g cm^{-3}), M_d is the mass of dry soil (105–110 °C for 12 h) (g), and V is the volume of soil core (cm^3).

Soil water retention curve (SWRC) was measured in the laboratory by a high-speed centrifuge using undisturbed soil. Before the measurement, samples were first saturated in water for 24 h. Then, soil water content (g g^{-1}) at pressure heads of 10, 100, 200, 400, 600, 800, 1000, 2000, 4000, 6000, 8000, and 10,000 cm H_2O were measured. To this end, the data was used for fitting van Genuchten (1980) model (VG). The VG model was expressed as follows (Van Genuchten 1980):

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} = \left[\frac{1}{1 + (\alpha\psi)^n}\right]^m \tag{2}$$

where S_e is effective saturation, α is a scaling factor (cm^{-1} H_2O), n is pore size distribution parameter, and $m = 1 - 1/n$. Three momentous parameters of SWRC were used to calculate the soil porosity, namely, saturation moisture content (SMC), field capacity (FC), and permanent wilting point (PWC) (g g^{-1}). FC and WC was the soil water content at pressure heads of 300 and 1500 cm H_2O, respectively. Soil porosity was classified as inactive porosity (IP), microporosity (MIP), and macroporosity (MAP) in this paper according to the study of Luxmoore (1981) and Zhang et al. (2016), and they were expressed as follows:

$$IP = \frac{PWC \times BD}{WD} \times 100\% \tag{3}$$

$$MIP = \frac{(FC - PWC) \times BD}{WD} \times 100\% \tag{4}$$

$$MAP = \frac{(SMC - FC) \times BD}{WD} \times 100\% \tag{5}$$

where WD is the water density (g cm^{-3}).

A soil physical quality index S_{Dexter} (Dexter 2004) can be calculated based on the SWRC, and a higher S_{Dexter} mean a better soil physical quality. S_{Dexter} was expressed as:

$$S_{\mathrm{Dexter}} = -n(\theta_s - \theta_r)\left[\frac{1}{1 + m}\right]^{-(1+m)} \tag{6}$$

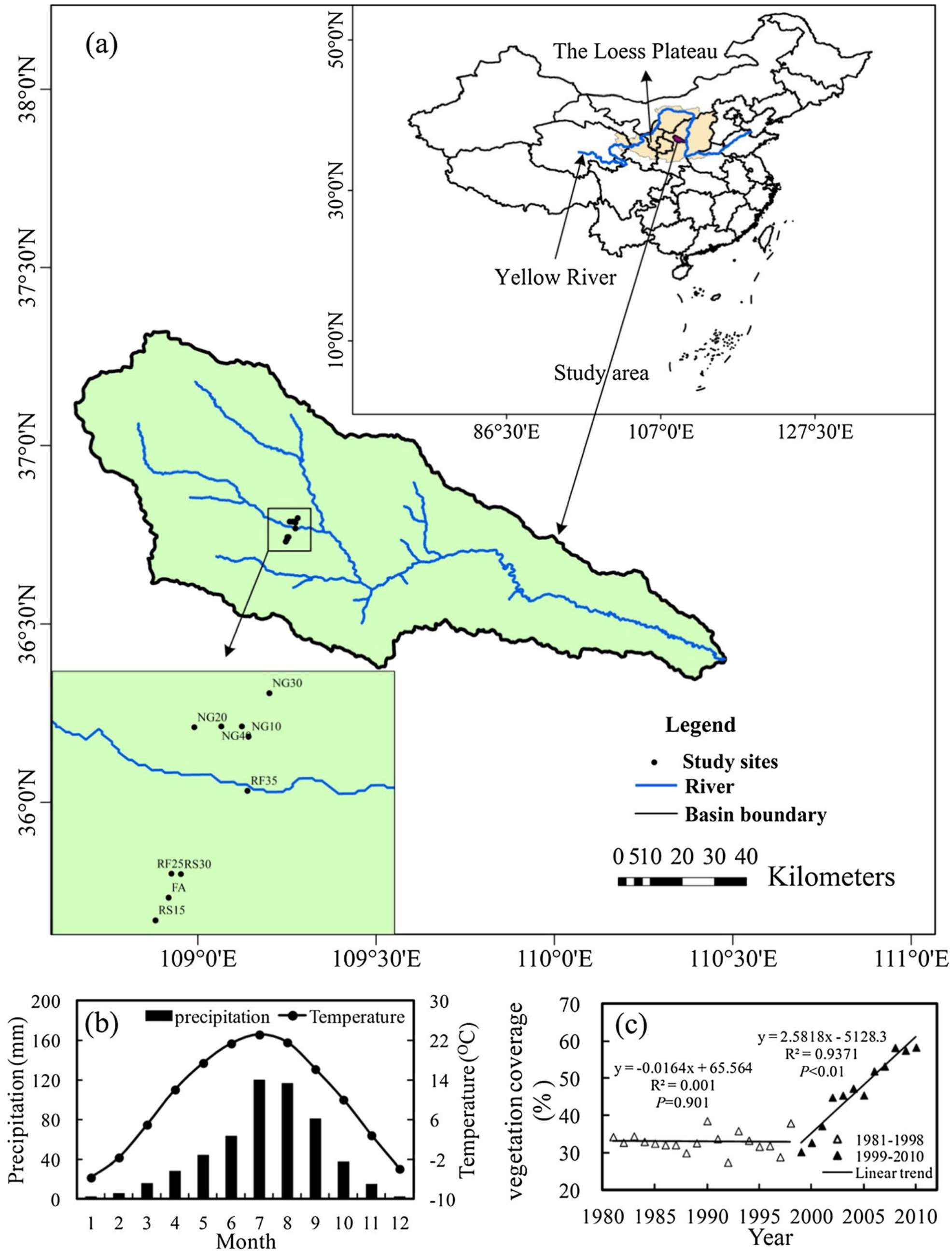

Fig. 1 The location of selected sites (**a**), mean monthly precipitation and temperature during 1952–2015 (**b**), and vegetation coverage (1980–2010) (**c**) for the study area

Approximately 1 kg of composite sample was collected at each plot from each sampling depth for soil texture and aggregate stability measurement. Air-dried soil sieved through 2 mm sieve was used for soil particle size measurement by the laser diffraction technique using a MasterSizer 2000 (Malvern Instruments, Malvern, England). The soil particle size was classified into sand (2–0.05 mm), silt (0.05–0.002 mm), and clay (< 0.002 mm) according to USDA classification system. Aggregate stability was measured based on air-dried aggregates and was evaluated according to wet-sieving effects (Li and Shao 2006).

Ks was measured by the constant water head method using distilled water at a 5 cm water head (Reynolds et al. 2002). When a constant flow rate had been established, percolated water volume per unit time was measured and used to calculate Ks according to Darcy's Law (Eq. (7)).

$$v = -Ks\left(\frac{dh}{ds}\right) \quad (7)$$

where v is the percolation velocity (m s^{-1}), Ks is the saturated hydraulic conductivity (m s^{-1}), and dh/ds is the hydraulic gradient (m m^{-1}). The percolation velocity can be expressed

Table 1 Description of the sample sites in the Yanhe watershed

ID	Vegetation type	Age (years)	Latitude	Longitude	Elevation (m)	Slope (°)	SOM (g kg^{-1})
RF35	Replanted arboreal forest	35	36°46′08″	109°16′23″	1140	21	8.32
RF25	Replanted arboreal forest	25	36°44′41″	109°15′03″	1152	26	6.98
RS40	Replanted scrubland	40	36°47′16″	109°16′17″	1200	28	8.26
RS30	Replanted scrubland	30	36°44′37″	109°15′13″	1260	20	8.55
RS15	Replanted scrubland	15	36°43′52″	109°14′46″	1340	20	8.41
NG40	Secondary natural grassland	40	36°47′16″	109°15′30″	1200	25	8.61
NG30	Secondary natural grassland	30	36°47′51″	109°16′46″	1250	26	7.39
NG20	Secondary natural grassland	20	36°47′15″	109°15′27″	1230	25	6.57
NG10	Secondary natural grassland	10	36°47′16″	109°16′24″	1180	20	5.58
FA	Farmland	0	36°44′23″	109°15′0″	1173	26	8.49

ID is the sample site identification and SOM is the soil organic matter in 0–20 cm layer. Age refers to the number of years since the cessation of farming activities

as $v = Q/A$ with Q being the water flux (m^3 s^{-1}) and A the cross-section area that the water flowed through (m^2). The Ks was transformed to 10 °C in this study to eliminate the effects of experiment temperature on Ks (Chi and Wang 2009).

$$Ks_{10} = \frac{Ks_t}{0.7 + 0.03t} \quad (8)$$

where Ks_{10} was the Ks at 10 °C, Ks_t is the Ks at t °C, and t is the temperature of measurement water. Hereafter, Ks denotes the saturated hydraulic conductivity at 10 °C.

2.3 Data analysis

Analysis of variance (ANOVA) was used to assess the differences of the soil properties among the ten sites. When ANOVA indicated the differences were significant according to the F values, a Duncan's test at $P < 0.05$ was performed to compare means of soil variables. All the soil variables were tested whether the data followed a normal distribution and variance homogeneity by Shapiro test (Shapiro and Wilk 1965) and Bartlett test (Bartlett 1954), respectively. If the data failed to meet the two conditions, the non-parametric method (Kruskal–Wallis test) was used for above analysis. Stepwise regression and path analysis were employed to evaluate the effects of other soil physical properties on the Ks. Principal components analysis (PCA) was used to explore the relation between vegetation restoration and soil properties. All the statistical tests were performed with R version 3.3.3.

3 Results

3.1 Bulk density and porosity

Soils in vegetated areas had lower BD at the two different depths ($P < 0.01$) (Fig. 2a). In the 0–20 cm layer, BD of the 40-year replanted scrubland (RS40) and natural grass (NG40) were significantly lower than other treatments. For the RS and NG treatments, the BD significantly decreased with time while no significant difference was found between replanted forestland of 35 years (RF35) and 25 years (RF25). In the 20–40 cm layer, the difference between NG40 and other years (NG30, NG20, and NG10) was significant, but no significant differences for the other vegetation types were found for the different replanted years.

Figure 3a shows the soil water content at each pressure heads could be well fitted by VG model. The average coefficient of determination (R^2) was 0.984, and the mean root-mean-square error (RMSE) was 0.616 (Fig. 3a). A relative big difference was found in the soil water characteristic curves (SWRCs) at the low-pressure heads (< 100 cm) among the sites compared with high-pressure heads (> 100 cm). The soil water holding capacity of RS35 was the greatest among the ten sites at low-pressure heads for 0–20 cm soil layer, while it dropped sharply at the high-pressure heads (> 100 cm) (Fig. 3b).

Three categories of soil porosity were calculated based on SWRC. Inactive porosity (IP) and microporosity (MIP) at 0–20 cm soil layer were generally lower than that of 20–40 cm (Fig. 2b, c). IP of RF35 was significantly higher than other sample plots at 0–20 cm layer, while it was the highest in RS40 for 20–40 cm layer (Fig. 2b). In both 0–20 and 20–40 cm soil layers, natural secondary grassland soil had lower MIP while replanted forest soil had higher MIP (Fig. 2c). However, the difference of MIP between most vegetated areas and farmland was not significant. Macroporosity (MAP) at 0–20 cm layer for most sample plots was higher than that of 20–40 cm soil layer (Fig. 2d). Replanted scrubland and natural secondary grassland had higher MAP than replanted forestland and farmland, especially for RS40, RS30, NG30, and NG10.

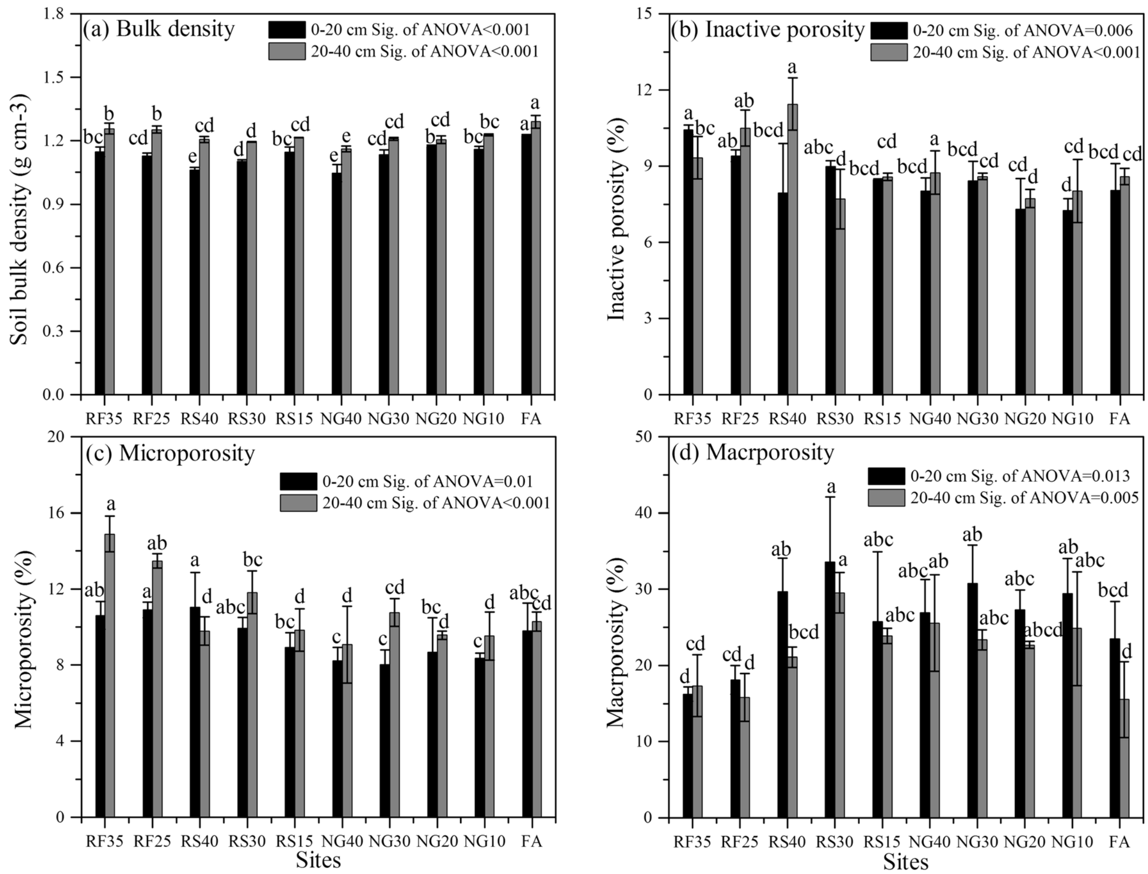

Fig. 2 Soil bulk density (**a**), inactive porosity (**b**), microporosity (**c**), and macroporosity (**d**) for different sample plots. The same letter above the point denotes they are not significantly different at the 0.05 probability level (Duncan's test)

3.2 Soil particle size composition

Mechanical analysis (Table 2) showed that there was significantly lower sand contents in soil from revegetated than farmland. Additionally, for sand contents in 0–20 cm layer, secondary natural grassland of 40 and 30 years (i.e., NG40, NG30) were lower than NG20 and NG10. Silt contents of soils in most restored sites were significantly higher than the farmland soil (FA). For each soil from revegetated, only NG30 was significantly higher than NG20. There was no significant difference among the ten sites for clay content. However, there was a trend where clay content increased the longer the plots were vegetated. Changes of soil particle size composition in the 20–40 cm layer were similar to the topsoil. Soil texture

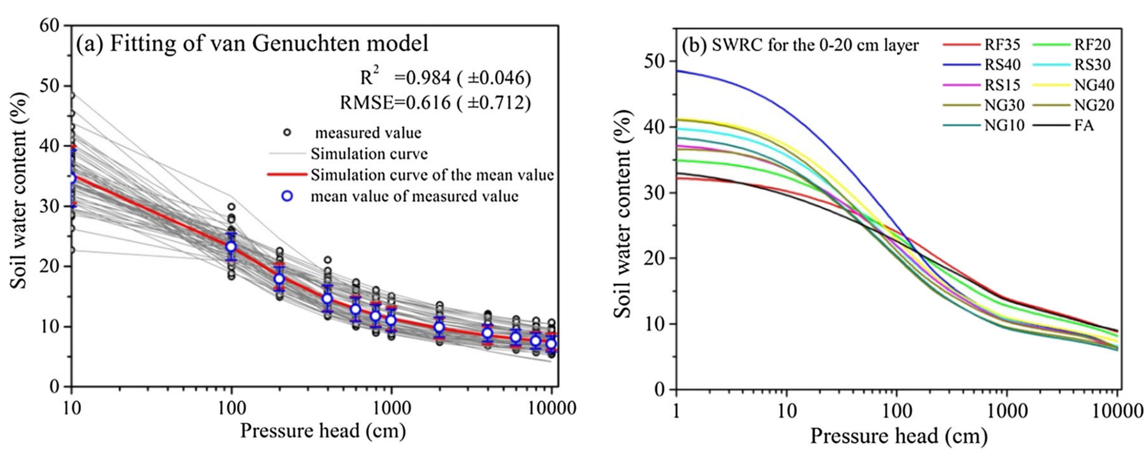

Fig. 3 The fitting of VG model (**a**) and the soil water retention curves of the 0–20 cm layer (**b**) for the ten study sites

Table 2 Mechanical composition (%) for different vegetation recovery types

ID	0–20 cm Sand (%) (0.05–2 mm)	0–20 cm Silt (%) (0.002–0.05 mm)	0–20 cm Clay (%) (< 0.002 mm)	20–40 cm Sand (%) (0.05–2 mm)	20–40 cm Silt (%) (0.002–0.05 mm)	20–40 cm Clay (%) (< 0.002 mm)
RF35	10.76 (0.90)cd	63.07 (1.05)abcd	26.17 (0.24)	12.61 (0.15)b	61.57 (0.01)cd	25.82 (0.14)
RF25	10.05 (0.16)d	64.05 (0.13)a	25.90 (0.28)	12.40 (0.02)bc	61.83 (0.03)bc	25.78 (0.05)
RS40	10.08 (0.53)d	63.24 (0.30)abc	26.68 (0.46)	11.88 (0.17)d	62.29 (0.09)ab	25.84 (0.14)
RS30	10.43 (0.25)cd	62.9 (0.11)abcd	26.67 (0.25)	12.54 (0.24)b	61.73 (0.15)cd	25.73 (0.28)
RS15	10.17 (0.19)d	63.39 (0.57)abc	26.44 (0.42)	12.06 (0.42)cd	62.07 (0.52)abc	25.88 (0.13)
NG40	10.04 (0.06)d	63.30 (0.45)abc	26.67 (0.50)	11.81 (0.39)d	62.03 (0.39)abc	26.16 (0.32)
NG30	10.16 (0.20)d	63.63 (0.24)ab	26.21 (0.10)	12.02 (0.23)cd	62.47 (0.42)a	25.52 (0.23)
NG20	11.59 (0.15)ab	62.34 (0.23)cd	26.07 (0.22)	11.91 (0.29)d	62.37 (0.02)a	25.72 (0.29)
NG10	11.19 (0.73)bc	62.59 (1.04)bcd	26.22 (0.70)	12.81 (0.11)ab	61.63 (0.20)cd	25.57 (0.32)
FA	12.3 (0.55)a	62.01 (0.99)d	25.69 (0.48)	13.25 (0.19)a	61.30 (0.36)d	25.45 (0.46)
Significance of ANOVA	< 0.001	0.024	0.073	< 0.001	< 0.001	0.126

Mean values in the same column followed by the same letter are not significantly different at the 0.05 probability level (Duncan's test)

triangle showing texture class for both topsoil and subsoil were silt loam texture class (Fig. 4a USDA classification system). Moreover, sand content of soil for 20–40 cm layer was generally higher than soil in the 0–20 cm (Fig. 4b).

3.3 Aggregate stability

Table 3 shows RF35 had the highest proportions of > 5 mm aggregates, while FA had the lowest proportions in the 0–20 cm layer. A significant difference between the soils of farmland and replanted vegetation sites was also found for 2–5 mm, 2–1 mm, 0.5–1 mm, and 0.25–0.5 mm aggregates. For the total percent aggregates (> 0.25 mm), replanted forestland had the highest values, followed by NG40. FA had the lowest percent aggregates and was not significantly different from NG20 and NG10. Aggregate stability in the 20–40 cm soil layer was significantly lower than that of 0–20 layer, and the difference of the sites was slight compared with the topsoil (data not shown).

3.4 Saturated hydraulic conductivity

Figure 5 shows vegetation restoration soils had significantly higher Ks than farmland in the topsoil, while the differences were less for the subsoil. Ks ranged from 13.8 (FA) to 27 mm h^{-1} for (RS40) in the 0–20 cm layer and 7.2 (FA) to 12 mm h^{-1}(RS30) in the 20–40 cm layer for the ten sites. Of all vegetation types, RS40 was significantly higher than RS30 and RS15. No distinguishable differences were found for other vegetation types in the topsoil. In the subsoil, there was no significant difference among the restoration periods for the each vegetation type. Moreover, RF35, RF25, and NG10 were not significantly different from farmland.

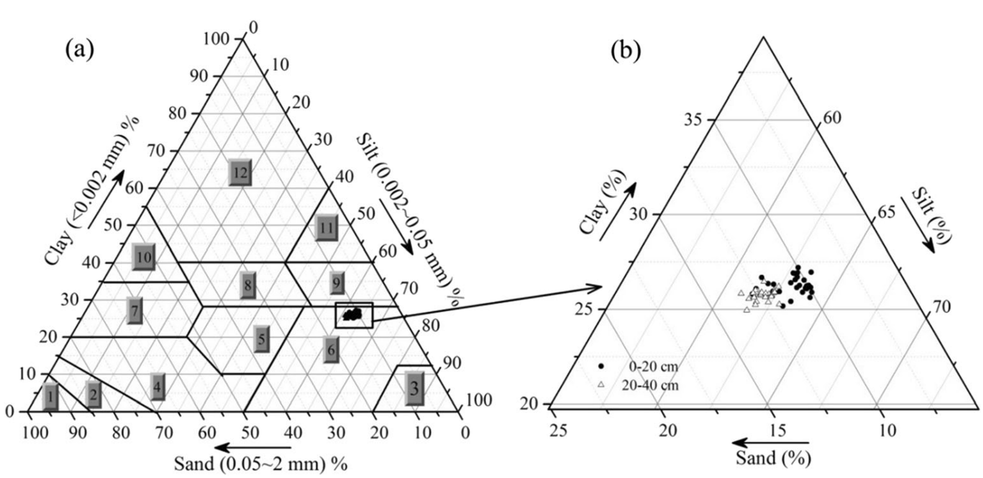

Fig. 4 Soil texture triangle showing the range of textures for different vegetation recovery types (1, sand; 2, loamy sand; 3, silt; 4, sandy loam; 5, loam; 6, silt loam; 7, sandy clay loam; 8, clay loam; 9, silty clay loam; 10, sandy clay; 11, silty clay; 12, clay)

Table 3 Percent (%) of aggregates by size in the surface layer (0–20 cm) for different vegetation recovery types

ID	> 5 mm	5–2 mm	2–1 mm	0.5–1 mm	0.25–0.5 mm	> 0.25 mm
RF35	15.08 (1.08)a	13.58 (0.18)ab	12.06 (0.80)b	10.59 (0.56)b	9.38 (1.01)b	60.68 (0.56)a
RF25	3.98 (2.51)b	9.38 (2.48)cd	16.61 (0.21)a	18.64 (3.97)a	15.56 (2.52)a	64.16 (1.72)a
RS40	13.42 (7.05)a	9.38 (1.81)cd	6.07 (1.09)c	4.98 (0.55)cde	5.53 (1.98)b	39.39 (11.13)c
RS30	12.70 (2.25)a	12.09 (3.11)abcd	6.93 (1.33)c	5.64 (1.56)cde	5.52 (2.08)b	42.88 (6.33)bc
RS15	13.19 (7.32)a	9.90 (1.09)bcd	6.75 (0.99)c	5.95 (0.92)cde	6.65 (2.80)b	42.45 (5.26)bc
NG40	11.18 (3.11)a	12.86 (1.88)abc	10.31 (2.67)b	8.19 (2.82)bc	6.71 (2.31)b	49.24 (6.54)b
NG30	11.68 (0.96)a	14.90 (3.83)a	5.62 (0.48)c	3.09 (0.64)e	8.13 (3.78)b	39.42 (5.11)c
NG20	9.35 (2.96)ab	11.39 (0.59)abcd	5.37 (0.77)c	3.11 (0.72)e	6.18 (0.12)b	35.40 (4.22)cd
NG10	4.45 (0.63)b	8.97 (0.52)d	6.91 (1.43)c	6.97 (1.73)cd	8.18 (1.48)b	35.49 (1.40)cd
FA	2.95 (0.81)b	9.10 (0.80)cd	6.09 (0.77)c	3.78 (1.52)de	5.98 (0.76)b	27.91 (0.83)d
Significance of ANOVA	0.003	0.011	< 0.001	< 0.001	< 0.001	< 0.001

Mean values in the same column followed by the same letter are not significantly different at the 0.05 probability level (Duncan's test)

3.5 Correlation analysis of soil physical properties

BD showed a significant negative relationship to most measured soil physical properties ($P < 0.01$) (Table 4). Sand contents were negatively related to most soil properties (except for BD and MIP); however, silt were positively correlated with most soil properties. Total aggregates were significantly related to most soil physical properties except for soil porosity. IP was significantly positively correlated with silt content. MIP was significantly positive correlated with BD and sand contents, while it was negatively correlated with most other soil properties. MAP was just significantly positive correlated with clay content and Ks. The Ks was negatively correlated with BD and sand contents, while it was significantly positively related to other soil physical properties except for IP.

3.6 Effects of soil physical properties on saturated hydraulic conductivity

A stepwise regression (forward) was performed to select the optimal factors that influenced Ks. Results showed that when BD (X_1), MAP (X_2), and > 0.25 mm aggregate stability (X_3) were included, the model had the highest efficiency. The regression equation was expressed as:

$$Y = -52.893X_1 + 0.164X_2 + 0.081X_3 + 69.845 \left(R^2 = 0.763, N = 60, P < 0.001\right) \quad (9)$$

where Y is the saturated hydraulic conductivity.

Because of changes in MAP, > 0.25 mm aggregate stability could also cause the changes in BD. Path coefficients were conducted to determine the direct and indirect effects of the soil physical properties on Ks. Figure 6 shows that BD had the highest direct effects (− 0.84) on Ks, followed by MAP (0.43), while the lowest was found in aggregate stability (0.38). Moreover, the direct effect of BD on Ks was negative, while it was positive for other factors. In terms of the indirect effects, the highest indirect effect was exerted by MAP (− 0.47), followed by aggregate stability (− 0.38). They exerted influences on Ks via BD. Moreover, the indirect effect of MAP was higher than its direct effects, which revealed the importance of BD in Ks.

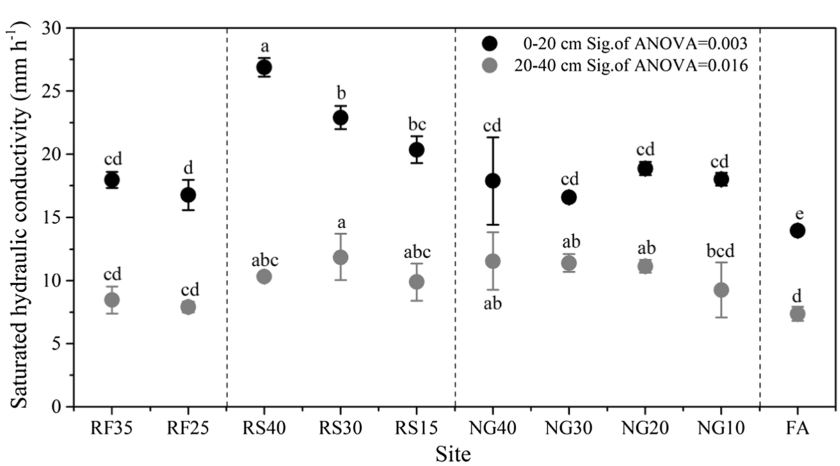

Fig. 5 Saturated hydraulic conductivity of 0–20 cm and 20–40 cm soil layer for all sample plots. The same letter above the point denotes they are not significantly different at the 0.05 probability level (Duncan's test)

Table 4 Correlation coefficient matrix ($N=60$) of main soil physical properties in the vegetation recovery plots

	BD	Sand	Silt	Clay	Aggregates	IP	MIP	MAP	Ks
BD	1								
Sand	0.853**	1							
Silt	− 0.539**	− 0.845**	1						
Clay	− 0.787**	− 0.609**	0.089	1					
Aggregates	− 0.345**	− 0.433**	0.368**	0.260*	1				
IP	0.186	0.014	0.254*	− 0.402**	0.084	1			
MIP	0.365**	0.348**	− 0.180	− 0.380**	0.091	− 0.441**	1		
MAP	− 0.443**	− 0.356**	0.118	0.488**	− 0.093	0.156	− 0.432**	1	
Ks	− 0.834**	− 0.760**	0.445**	0.755**	0.830**	− 0.251	− 0.323*	0.471**	1

BD bulk density, *sand* sand contents, *silt* silt content, *clay* clay content, *Aggregates* > 0.25 mm aggregate stability, *IP* inactive porosity, *MIP* microporosity, *MAP* macroporosity, *Ks* saturated hydraulic conductivity

*Significant at $P \leq 0.05$

**significant at $P \leq 0.01$

3.7 Linkages between vegetation restoration and soil properties

Principal component analysis (PCA) revealed that the first two principal components explained 65.8% (PC1 = 42.7%, PC2 = 23.1%) of the variance, indicating they could express most information of the data structure. Figure 7a shows the scatter plot for the study sites and the relationship between the soil properties based on the first two principal components. The sample plots could be divided into three categories. The first category includes RS40, RS30, and NG40, which have high clay contents, MAP, and Ks. However, BD, sand contents, IP, and MIP of the first category were fairly low. RF35, RF25, RS15, and NG30 belong to the second category. These sample plots had higher aggregates stability, IP, MIP, and silt contents, while they had relatively lower MAP. The third category covers FA, NG20, and NG10. This category had higher BD and sand contents compared with others. In terms of the soil physical quality index (S_{Dexter}), all the sites were higher than 0.035, indicating the studied soil had relatively good quality (Fig. 7b). For the sites, S_{Dexter} of RS40 is the highest (0.112), followed by RS30 (0.099) and NG40 (0.094). S_{Dexter} of RS35 and FA were 0.052 and 0.043, respectively, and were significantly lower than others.

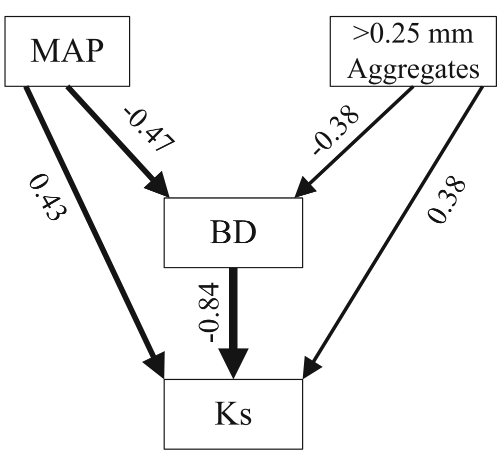

Fig. 6 Path diagram for the relationship between soil properties and saturated hydraulic conductivity. The magnitudes of the numerical values in the figure indicate the level of effects on saturated hydraulic conductivity. MAP, macroporosity; BD, bulk density; Ks, saturated hydraulic conductivity

4 Discussion

4.1 Changes in soil physical properties along with vegetation restoration

A common perception is that vegetation restoration can decrease BD and increase the porosity, especially the CP (Celik 2005; Li et al. 2007; Neris et al. 2012). In our study, the highest BD and lowest porosity were found in farmland, which was mainly credited to compaction from tillage and harvest operations (Zhang et al. 2010). In contrasts, soils from the re-vegetated areas had a lower BD and higher porosity. This is partly due to the accumulation of organic matter in the soils from the re-vegetated (Table 1, $r = -0.685$, $P < 0.001$). A relatively higher organic matter in the farmland was mainly the result of fertilization which produced a high rate of vegetation turnover (Wang et al. 2011).

Our results showed that the soil texture of all study sites did not significantly change (Fig. 4), which implies the soil texture was slow to transform in the Loess Plateau (Li and Shao 2006). Although significant differences in sand, silt, and clay were lacking, sands were generally lower with silt and clay higher in the plots with longer years in vegetation. This would indicate that vegetation protects the soil from erosion loss of highly erodible finer particles. Aggregate stability plays an

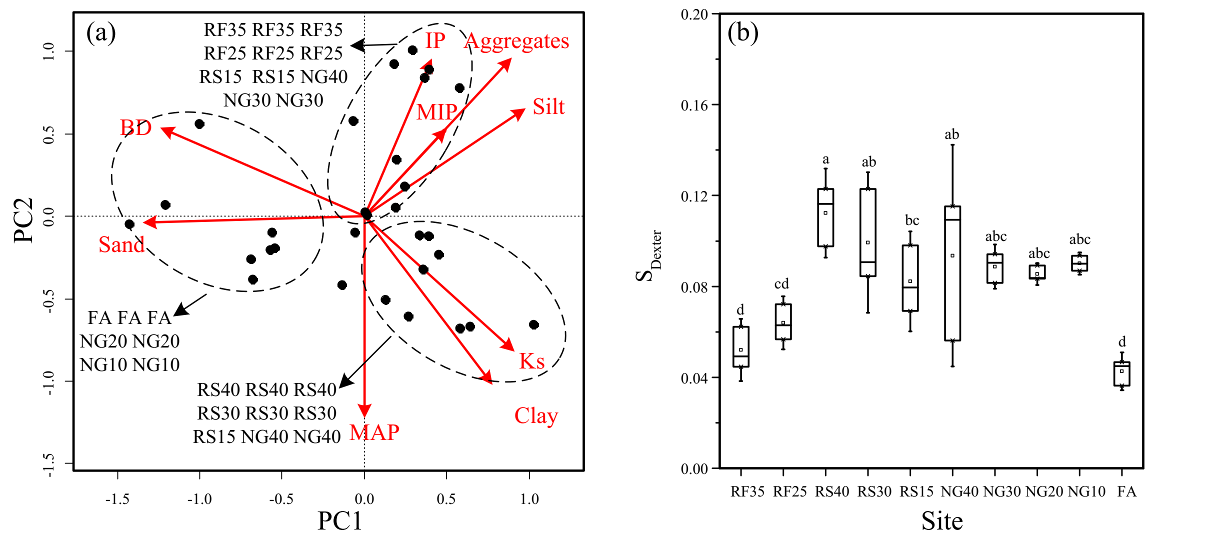

Fig. 7 Results of principle component analysis (PCA) (**a**) and the soil physical quality index (S_{Dexter}) (**b**) for different sample plots based on the soil properties in 0–20 cm soil layer. BD, bulk density; Sand, sand content; Clay, clay content; Silt, silt content; Ks, saturated hydraulic conductivity; MAP, macroporosity; MIP, microporosity; IP, inactive porosity; Aggregates, > 0.25 mm aggregates stability. The same letter above the point denotes they are not significantly different at the 0.05 probability level (Duncan's test)

important role in anti-erodibility and stabilizing soil structure (Bissonnais 1996; Erktan et al. 2016; Van Hall et al. 2017). Areas with vegetation restoration had higher aggregate stability than farmland (Table 3), which indicates that farmland is more vulnerable to erosion than soils from the revegetated. The low aggregate stability of farmland was mainly because of anthropogenic disturbance resulting from agriculture (Cerdà 2000). MAP of replanted RS40, RS30, and NG40 were higher while IP and MIP were lower than others, indicating they have better porosity (Fig. 2b–d). BD was significantly related to most other soil parameters (Table 4); hence, it could be used as an indicator of soil structure evolution. The reductions in the BD of soils from the re-vegetated illustrated the amelioration effects on soil structure.

Vegetation restoration increased Ks compared with farmland (Fig. 5). The higher Ks indicated that soils from the revegetated had better soil permeability than farmland, which is a cause for runoff reduction in the region (Gao et al. 2011). Ks correlated with most of the studied soil physical parameters, which demonstrated that Ks also could be used as an indicator of soil structure change. The stepwise regression showed that BD, MAP, and > 0.25 mm aggregates stability were the principal soil physical parameters that affect the Ks. Furthermore, the indirect effects of MAP via soil BD were higher than its direct effects, implying the great effect of BD on Ks (Fig. 6). Many studies in the literature show that there is a significant exponential relationship between Ks and BD (Jabro 1992), which is in accordance with our results ($y = 64.435e^{-4.806x}$, $R^2 = 0.7007$, $P < 0.001$) (Fig. 8a). With the succession of vegetation, soil BD decreased while porosity and aggregate stability increased. These changes in the soil properties enhanced the soil water conductive capability. MAP was more closely related to Ks than IP and MIP, and acting as an input of Eq. 9. MAP could form macropore flow in the soil, which was shown to be a main determinant for Ks (Ahuja et al. 1984). Biological macropore (e.g., root channels) has good connectivity and large pore diameter that is better for the flow processes in the soil (Lado et al. 2004; Ajayi and Horn 2016). Additionally, the length of vegetation time affects Ks. Wilson et al. (2005) found that soil matrix infiltration rate was highest in the newly established (1 year) and the oldest (> 15 years) revegetated areas, and biogenic surface crust was the main reason. In our study, Ks increased along with vegetation time for each vegetation type because there is no biogenic surface crust for our soil samples.

On the other hand, organic matter accumulation in vegetated areas plays an important role in Ks increases. Bissonnais and Arrouays (1997) used a rainfall simulator and found that reduction of the organic carbon content of a loamy soil below 1.5 to 2.0% decreased the soil infiltration rate. A quadratic function was identified by others between soil organic matter and Ks (Celik 2005; Li and Shao 2006) as well as this study (i.e., $y = -0.0014x^2 + 0.0481x + 0.0183$, $R^2 = 0.6545$, $P < 0.001$) (Fig. 8b). Increases in organic matter were positively correlated to aggregate formation, reduced BD, and decreased the susceptibility of the soil to seal formation (Lado et al. 2004). Those functions were conducive to the increases of Ks. However, the quadratic relation indicated that the role of organic matter on Ks was not monotonic. There was a threshold value for soil organic matter. When soil organic matter to affect Ks lower than the threshold, it played a positive role in Ks. Otherwise, the role was adverse. The main reason is that soil organic matter has retention effect on soil moisture (Van Hall et al.

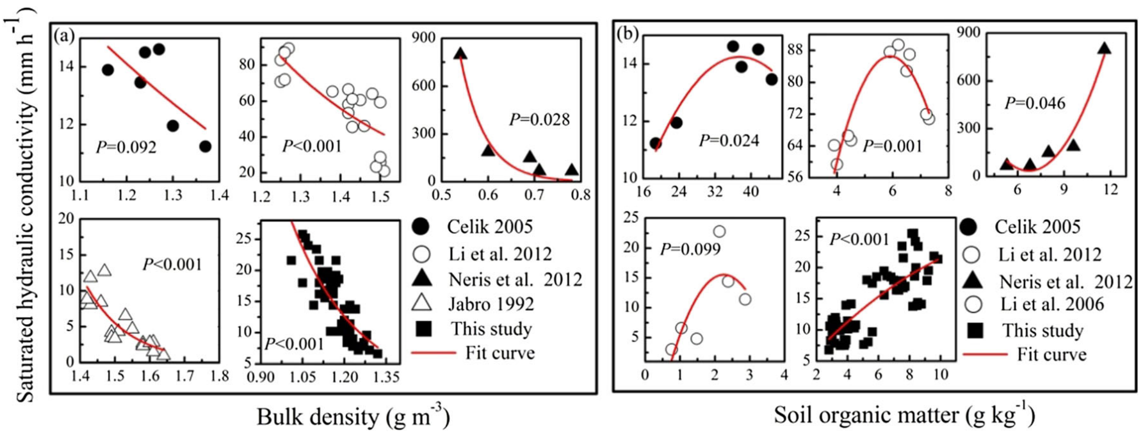

Fig. 8 Relationships between saturated hydraulic conductivity and bulk density (**a**) and soil organic matter (**b**)

2017). If the retention effect is higher than the threshold, the increases of soil organic matter would impede the increases of Ks.

4.2 Effectiveness of vegetation restoration in the Loess Plateau

Due to water shortage in the Loess Plateau, there are many issues during vegetation restoration (Feng et al. 2012). Some studies have found that a number of woody (e.g., *Pinus tabulaeformis*, *Platycladus orientalis*) and shrub species (e.g., *Hippophae rhamnoide*) grow well at the beginning, but they often degrade once the initial water supply has been exploited (Li 2000). Large-scale afforestation in the water-limited arid and semiarid regions may increase the severity of groundwater shortages. PCA analysis showed that RS40, RS30, and NG40 were grouped together (Fig. 7a). They have the best soil properties among the sites including low BD, high MAP, and high Ks. However, RF35 and RF25 belong to the second category (Fig. 7a), of which the soil properties were of less quality, relative to RS40, RS30, and NG40. The S_{Dexter} showed similar result as PCA, i.e., RS40, RS30, and NG40 had highest value while RF35 and FA had the lowest (Fig. 7b). The findings indicated that the effectiveness of replanted forest to ameliorate soil health was less than replanted scrubland. Forest uses more soil water and form drier soil layers (Li 2000), which leads to soil degradation. We found that soil moisture of replanted forest was the highest at 0–30 cm layer, while it sharply decreased thereafter (Fig. 9). At depths lower than 100 cm, replanted forest had the lowest soil moisture among the four land-use types (Fig. 9). The results further indicated that forest consumed more soil water than others, which was adverse to sustainability of vegetation restoration. NG20, NG10, and FA were combined into the same category, which implied that soil natural rehabilitation of abandoned cropland needs a long time period. If the rehabilitation period is long enough (more than 40 years), the secondary natural grassland could effectively improve soil properties like the shrub (Fig. 7).

5 Conclusions

Vegetation restoration in the hilly-gully region of the Loess Plateau, China had significant effects on soil physical properties and saturated hydraulic conductivity. The bulk density decreased significantly, while aggregate stability increased significantly during vegetation restoration. Change of soil porosity was complex, which showed that inactive porosity and microporosity was higher in replanted forest while macroporosity was higher in replanted scrubland. Vegetation restoration resulted in significant increases in soil saturated hydraulic conductivity, but did not alter soil texture. Bulk density, macroporosity, and > 0.25 mm aggregate stability were the main soil physical parameters that influenced saturated hydraulic conductivity. Bulk density and saturated hydraulic conductivity were strongly correlated with most measured soil physical properties. Hence, bulk density and

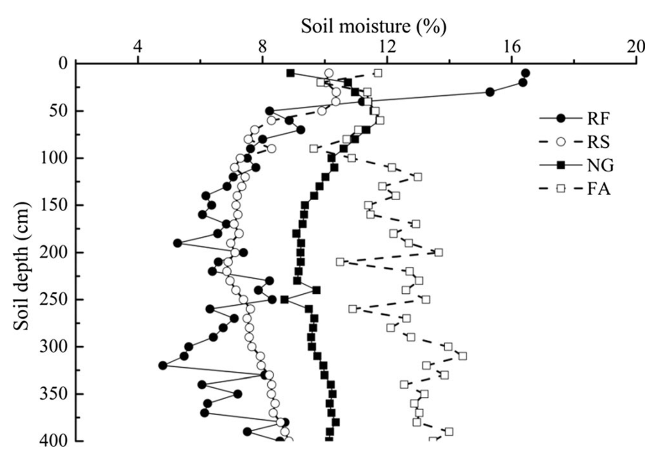

Fig. 9 Average vertical soil moisture (%) distributions among different land-use pattern (RF, replanted forest; RS, replanted scrubland; NG, secondary nature grassland; FA, farmland)

saturated hydraulic conductivity could be used as indicators to evaluate the impact of vegetation restoration on soil properties. It is better to plant scrub or grassland than forest in the study area for eco-environment rehabilitation. When selecting the tree species for vegetation restoration on the Loess Plateau, water conditions should be considered as a major limiting factor.

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