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Changes of soil hydraulic properties under early-stage natural vegetation recovering on the Loess Plateau of China

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ABSTRACT

The changes of soil hydraulic properties under early-stage (from several years to a few decades) natural vegetation recovering are not well understood in semiarid zones. We hypothesized that early-stage vegetation recovering can change measurably soil hydraulic properties and this would behave differently from long-term (from several decades to hundreds of years) vegetation recovering. This study investigated the dynamics of soil hydraulic properties under natural vegetation recovering of different ages (1, 5, 9, and 16–20 years) as compare to cropland and 30-year-old secondary grassland (two controls) on the semiarid Loess Plateau. The hydraulic properties included dry bulk density, total porosity, and near-saturated hydraulic conductivity at the potential of −0.5, −1, −3 and −5 cm of water. The results showed that the increases of vegetation species, coverage and aboveground biomass did not improve soil hydraulic properties. Specifically, dry bulk density increased while total porosity and near-saturated hydraulic conductivity at various potentials decreased with the increase of abandonment years. Moreover, we found that it would take at least 20 years to reverse the decreasing trend for soil hydraulic conductivities. These results suggest that vegetation recovering may not necessarily ameliorate soil hydraulic properties.

1. Introduction

Since the initiation of a large-scale ecological conservation program termed “Grain for Green” project in western China in 1999, land cover has been recovering on the Loess Plateau where it is well known for serious erosion (Zhang et al., 2013). Abandoning of sloping cropland is one of the primary management policies in this region to recover vegetation (Jiao et al., 2007). Over recent years, increasing croplands has been abandoned due to the economic and policy-driving factors (Fu et al., 2006). Nowadays diverse land use patterns exist in the Loess Plateau including cropland, abandoned cropland at various ages, natural grassland and forest, artificial vegetation, and so forth. Land use change can disrupt surface hydrology and water balance (Foley, 2005). This can be partly attributed to the alteration of soil hydrological properties (Scheffler et al., 2011) which determine the partitioning of precipitation into subsurface storage and surface runoff to stream networks (Price et al., 2010; Zimmermann et al., 2006).

A large literature has shown that land use and land use change have important effect on soil hydraulic properties (e.g. Agnese et al., 2011; Beerten et al., 2012; Bormann and Klaassen, 2008; Elsenbeer et al., 1999; McQueen and Shepherd, 2002; Price et al., 2010; Scheffler et al., 2011; Wang et al., 2013; Zeng et al., 2013), although a few observed insignificant effect (Hu et al., 2009; Zhou et al., 2008). On the one hand, land clearing or deforestation would increase soil compaction and then deteriorate soil infiltrability and hydraulic conductivity (Lal, 1996; Price et al., 2010; Scheffler et al., 2011; Zimmermann et al., 2006). On the other hand, vegetation regrowth tends to ameliorate soil structure and improve hydraulic properties. Several efforts have shown that the conversion of cropland/pasture to native grassland/forest decreased soil bulk density and increased hydraulic properties (Beerten et al., 2012; Li and Shao, 2006; Peng et al., 2012; Wang et al., 2012).

Although increasing interests regarding the effects of land use change on soil hydraulic properties have risen in recent years, most of these studies mainly focused on the long-term effects of vegetation succession from a few decades to several hundred years. Only a few studies have attempted to investigate the response of soil hydraulic properties to early-stage vegetation restoration. Hassler et al. (2011) reported that secondary forest of 5–8 years of age showed no significant difference of saturated hydraulic conductivity with pasture (original land use) while secondary forest of 12–15 years old held significantly higher saturated hydraulic conductivity than pasture in Panama. However, the study site of Hassler et al. (2011) was located in a tropical forest where it showed distinct climate and soil conditions with semiarid zones. Li et al. (2010) and Wang et al. (2012) investigated the changes of saturated hydraulic properties at various stages of artificial and secondary grassland on the Loess Plateau of China. However, vegetation succession

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in their studies was affected greatly by human disturbances including mowing and grazing. Therefore, the results in their studies did not represent the true changes of soil hydraulic properties under natural vegetation recovering.

Over recent years, widespread vegetation recovering occurs in many arid and semiarid regions around the world wherein the Loess Plateau is a typical one. Therefore, there is an urgent need to understand systematically the changes of soil hydraulic properties under early-stage natural vegetation recovering on the Loess Plateau. This study defined "early stage" as from several years to a few decades as opposed to the "long term" (several decades to hundreds of years) used in previous studies (Li and Shao, 2006; Peng et al., 2012; Wang et al., 2012). Based on the field experiences, we hypothesized that early-stage natural vegetation recovering can also measurably alter soil hydraulic properties and this would behave differently with long-term vegetation recovering. This study aimed to test the hypothesis by investigating the soil hydraulic response to early-stage natural vegetation restoration of different ages (1, 5, 9, and 16–20 years) as compared to cropland and 30-year-old secondary grassland in the semiarid Loess Plateau. Soil dry bulk density, total porosity, and near-saturated hydraulic conductivity at different potentials were used for analyses. Near-saturated rather than saturated hydraulic conductivity was used for analysis here because it is more important in the Loess Plateau region where infiltration-excess runoff is the main type of overland flow.

2. Materials and methods

2.1. Study site

The study site is located in two adjacent small watersheds (37°15′ N, 118° 18′ E) of the Loess Plateau where widespread vegetation recovering has been going on. These two small watersheds are named Yuanzegou watershed (0.6 km^2) and Mazilenggou watershed (0.7 km^2), respectively. According to Gao et al. (2011), this area has a semiarid continental climate with: mean annual precipitation of 505 mm, and 70% of them falls in late summer and early autumn; a mean annual temperature of 8.6 °C, with mean monthly temperatures ranging from −6.5 °C in January to 22.8 °C in July. These two watersheds showed similar slope angles, elevation, and soils. Both of them are covered by loess soils which belong to silt loam (Inceptisols, USDA). All samples fell within the range of 10% to 30% sand, 60% to 70% silt, and 10% to 25% clay content. The field capacity and permanent wilting point of the loess in this study site is 24.3% and 8.8% (volumetric water content, hereafter), respectively.

These two small watersheds were totally agricultural watersheds twenty years ago. Thereafter, part of croplands began being abandoned gradually and now diverse land use types exist in these two watersheds including cropland, abandoned cropland of various ages, grassland and jujube orchards (Fig. 1). Cropland has been cultivated for several decades and is usually tilled twice (seeding in early May and fertilizer application in late August) per year. Except for cropland, the other land uses were subject to little human disturbance. The overall information of soil, topography and vegetation species was shown in Table 1.

2.2. Sampling design

The abandonment ages of croplands were determined according to field survey and interviewing with local farmers. In general, abandoned croplands of 1 year of age (ACL1), 5 years of age (ACL5), 9 years age (ACL9), and 16–20 years of age (ACL16) were selected to analyze the effects of early-stage vegetation recovering on soil hydraulic properties in terms of soil dry bulk density, total porosity, and near-saturated hydraulic conductivities. Soil hydraulic properties were also tested in cropland and grassland of 30–35 years of age which served as controls. Cropland was set as the original land use type before revegetation; grassland was set as the land use type of long-term revegetation. Two sites (hillslopes) were selected for each land use type and thus a total of 12 sites were selected for all land use types. Previous studies indicated that slope positions can result in strong spatial variability of soil hydraulic properties (e.g., Bodner et al., 2008). Therefore, soil hydraulic properties for different sites were measured only at upper positions (5 m away from hillslope top) of the corresponding hillslopes to diminish the spatial variability induced by slope positions. Moreover, three repeats were conducted for soil hydraulic properties at each site and the distance to each other was around 2 m. An illustration has been drawn to show the locations of measurement points at one hillslope (Fig. 2). In order to test the effects of vegetation recovering on hydraulic conductivities through statistical analysis, the 6 measurements (2 sites × 3 repeats) for each variable were pooled together for each land use type.

Wetness conditions could affect significantly soil hydraulic conductivity (Hu et al., 2012). Therefore, two periods with different soil wetness conditions were selected for measurements. The dry condition was selected in early August with mean surface soil moisture (0–10 cm) of

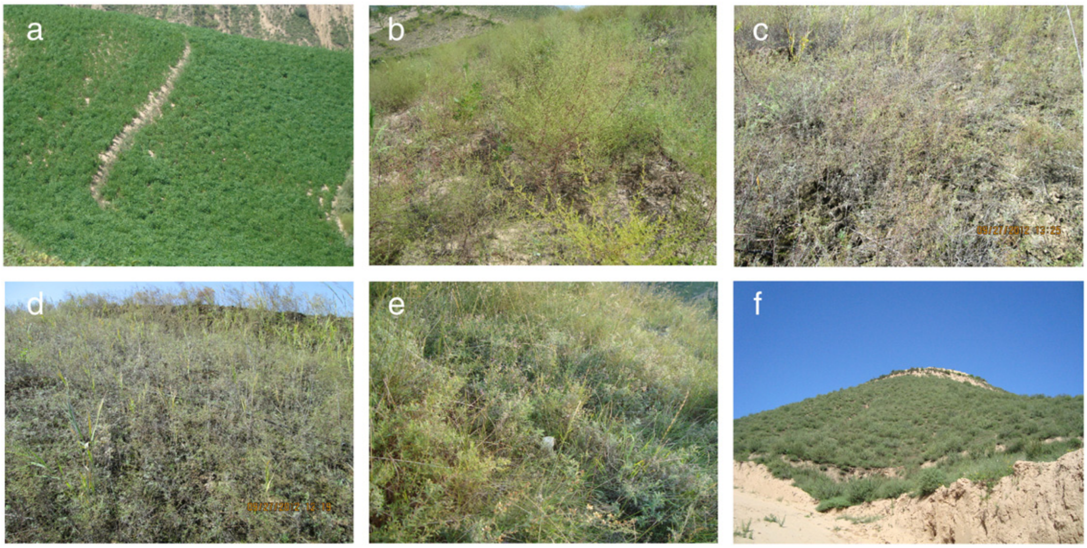

Fig. 1. Photos of different land use types in the study site, (a) cropland, (b) abandoned cropland of 1 year age (ACL1), (c) abandoned cropland of 5 year age (ACL5), (d) abandoned cropland of 9 year age (ACL9), (e) abandoned cropland of 16–20 year age (ACL16), (f) grassland.

Table 1
Summary of features of soil, topography and vegetation for different land uses in the study site.

Land use	Soil type	Clay content (%)	θ_s (%, vol/vol)	θ_r (%, vol/vol)	Soil organic carbon ($g \cdot kg^{-1}$)	Average slope (°)	Elevation (m)	Main species
Cropland	Silt loam	16.2	54.0	8.7	3.3	15.7	980–1028	*Phaseolus valgaris*
ACL1	Silt loam	16.4	53.3	7.8	2.8	17.2	972–1033	*Artemisia scoparia*
ACL5	Silt loam	17.1	53.3	8.0	3.2	16.9	976–1049	*Artemisia scoparia, Salsola collina* Pall
ACL9	Silt loam	21.9	52.9	8.9	3.5	24.3	982–1047	*Artemisia scoparia, Heteropappus altaicus*
ACL16	Silt loam	22.1	51.2	10.2	5.1	18.1	994–1061	*Bothriochloa ischemum, Artemisia gmelinii, Lespedeza davurica*
Grassland	Silt loam	22.7	52.8	8.1	6.1	21.8	1005–1055	*Artemisia gmelinii, Artemisia giraldii, Lespedeza davurica*

θ_s: saturated soil water content.
θ_r: residual soil water content.
ACL1: abandoned cropland of 1 year age.
ACL5: abandoned cropland of 5 years age.
ACL9: abandoned cropland of 9 years age.
ACL16: abandoned cropland of 16–20 years age.

12.5% (volumetric moisture content, hereinafter). The wet condition was in late September before harvesting crops just following a rainstorm with mean surface soil moisture of 18.4%.

2.3. Measurement methods

A portable infiltrometer, mini-disk tension infiltrometer (MDI) (Decagon Devices, Pullman, USA), was used in this study for determining near-saturated soil hydraulic conductivity. The main tube (water reservoir) of the MDI has a radius of 1.55 cm. A 2.25-cm radius stainless steel disk makes contact with the surfacial material at the base of the tube. A bubble chamber at the top of the apparatus allows for tension control. Because of its portability and relatively small radius, it is very suitable and has been widely used recently to measure soil hydraulic conductivity on hillslopes (Gonzalez-Sosa et al., 2010; Moody et al., 2009; Ronayne et al., 2012). To evaluate conditions near saturation, four potentials ($\psi = -0.5, -1, -3$, and -5 cm of water) were selected for infiltration tests and the four corresponding hydraulic conductivities were expressed as $K(-0.5)$, $K(-1)$, $K(-3)$ and $K(-5)$, respectively. The random variability of bulk density in our study site is high because of uneven spatial distribution of plants and broken terrains caused by soil erosion in some places. As selecting measurement locations, we tried to select places with uniform plants distribution and avoid broken terrains. Before the infiltration test, the litter and leaves were removed and vegetation was also cut while roots were left in place if necessary. For simplicity, the details of measurements and calculations of hydraulic conductivity through MDI would not be indicated here, which have been given by Decagon (2006) and Ronayne et al. (2012).

After the measurements of $K(\psi)$, at each site, surface intact soil cores (5 cm long and 5 cm diameter) were sampled and then taken to lab for dry bulk density determination. These soil cores were oven-dried at 105 °C for 48 h and then weighed to calculate bulk density. The calculations of soil total porosity followed Li and Shao (2006). For each site, the number of vegetation species was counted in a quadrate of 5 m × 5 m. Vegetation coverage (canopy cover) was measured in early August at three quadrates of 1 m × 1 m for each site; aboveground biomass was also sampled in these corresponding quadrates in late September by destructive sampling at each site. The harvested vegetation samples were oven-dried at 60 °C for 48 h and then weighed to calculate aboveground dry biomass (Jiang et al., 2010).

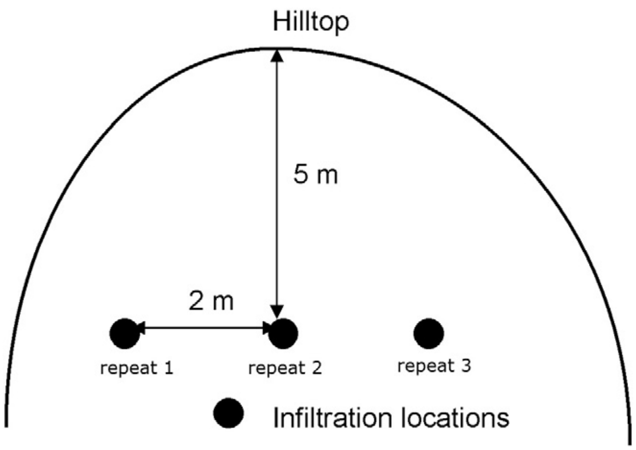

Fig. 2. The illustration of infiltration locations for one hillslope.

2.4. Statistical methods

One-way ANOVA was used to analyze the effect of land use types on soil hydraulic properties and the least significant difference (LSD) method was employed to characterize the difference of values of soil hydraulic properties between land uses. All the analyses were performed within SPSS 16.0 (SPSS Inc., Chicago, USA).

3. Results

Q–Q plots showed that the normal distribution can describe the datasets of bulk density, total porosity and hydraulic conductivities. Thus statistical analysis could be done without data transformation. As croplands were abandoned, species number increased sharply with the years of abandonment (Fig. 3a). Although the vegetation coverage decreased in the first year of abandonment (ACL1), it increased significantly thereafter and peaked after 16–20 years of abandonment (ACL16) (Fig. 3b). The aboveground dry biomass behaved similarly with vegetation coverage (Fig. 3c) as it is one of the main factors controlling aboveground biomass (Spehn et al., 2000). However, the rapid vegetation regrowth after abandonment of cropland did not lead to the improvement of soil hydraulic properties. As shown in Fig. 4a and b, one-way ANOVA indicated that significant differences existed for soil dry bulk density ($p < 0.001$) and total porosity ($p = 0.001$) between different land use types. Soil dry bulk density increased significantly for ACL1 (a 5.7% increase of mean value) compared to cropland, then experienced a gentle increase over the following eight years, peaked at ACL16 (14.7% higher than cropland) and dropped thereafter. The alternation of total porosity with vegetation recovering almost mirrored that of bulk density; total porosity decreased largely as croplands were abandoned and the lowest value was observed in ACL16 (Fig. 4b). These results indicated that early-stage vegetation recovering increased dry bulk density and decrease total porosity.

Near-saturated soil hydraulic conductivity at relatively dry and wet conditions was shown in Fig. 5a and b, respectively. One-way ANOVA also indicated that significant differences ($p < 0.05$) of hydraulic conductivities at different potentials existed for different land use types, and decreased with vegetation restoration independent of wetness conditions. It is noteworthy that standard deviation of hydraulic

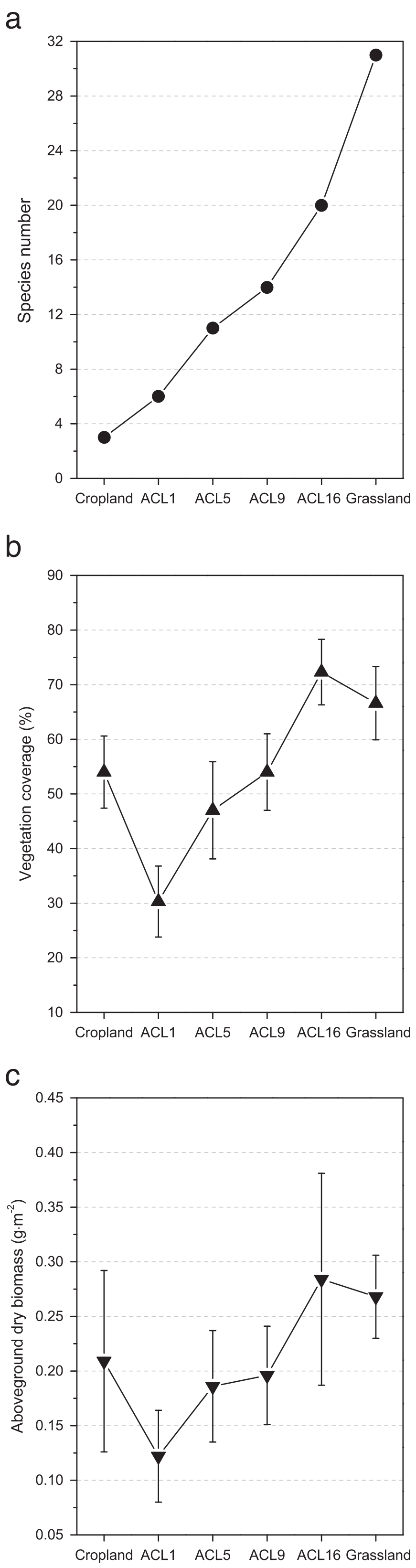

Fig. 3. Changes of vegetation species number (a), coverage (b), and aboveground dry biomass (c) with vegetation restoration.

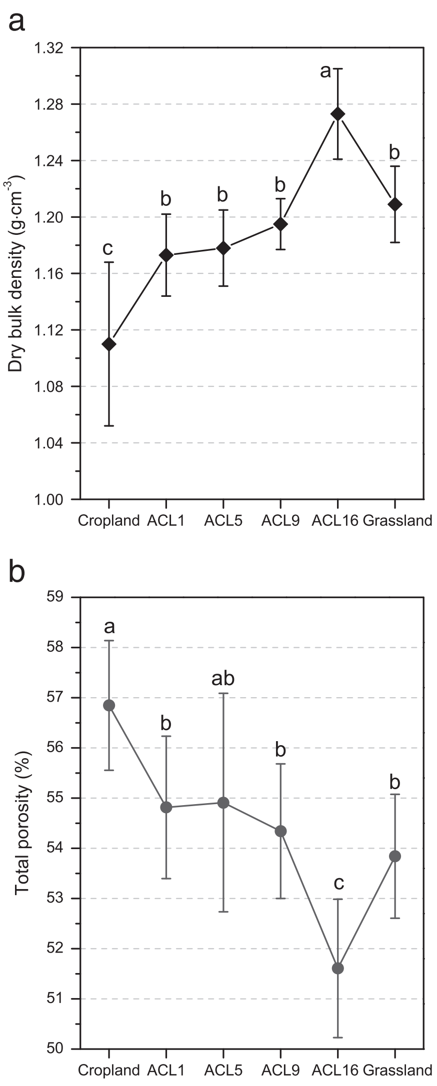

Fig. 4. Changes of soil dry bulk density (a), soil total porosity and capillary porosity (b) with vegetation restoration. Error bars represent ± one standard deviation.

conductivity for cropland was noticeably larger than that of other land use types. This may be probably because of the much stronger human disturbance there (e.g., tillage). For $K(-0.5)$, a sharp drop (~20%) of mean value was observed in the one-year-old abandoned cropland (ACL1) compared to cropland although no significant difference was observed between them, whereas the decreasing rate became slow with vegetation restoration. The lowest value emerged in ACL16 (39.2% lower than cropland) where the highest bulk density was observed; thereafter soil hydraulic conductivity began to recover as higher value was observed in grassland. This implies that it takes at least 20 years to reverse the decreasing trend of soil hydraulic properties. The $K(-1)$ showed a very similar behavior with $K(-0.5)$. Nevertheless, for $K(-3)$ and $K(-5)$, there were minor increases at ACL1 as compare to cropland and then similar behaviors with $K(-0.5)$ and $K(-1)$ were observed. In addition, soil hydraulic conductivity was slightly higher in wet soil condition than in dry soil condition probably because the wetting process would facilitate soil expansion and effectively decrease soil bulk density (Hu et al., 2012).

4. Discussion

The changes of soil hydraulic properties can be induced by vegetation growth and/or the intrinsic spatial variability of soils (Russo and Bresler, 1981). In order to evaluate the single contribution of vegetation recovering to the changes of soil hydraulic properties under different land use types, the effects of the intrinsic spatial variability of soils

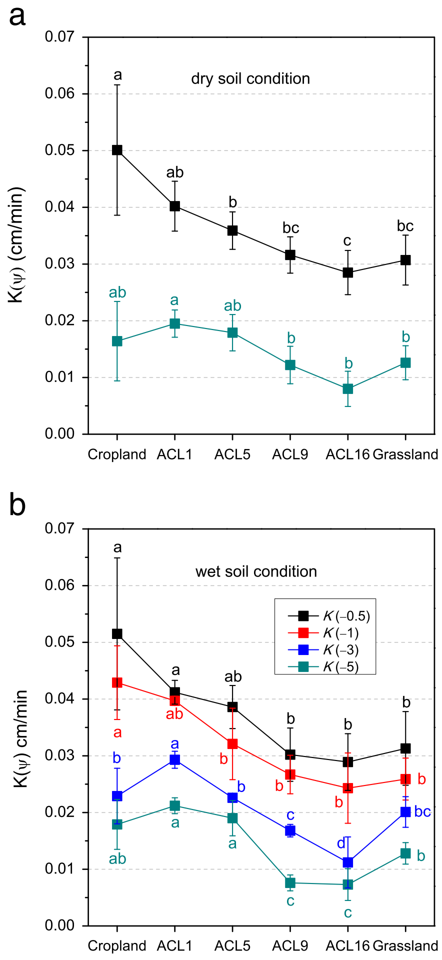

Fig. 5. Changes of near-saturated soil hydraulic conductivities of various potentials under dry soil condition (a) and wet soil condition (b); Dry soil condition with mean surface moisture content (0–10 cm) of 12.5% (vol./vol.) while wet soil condition with the value of 18.4% (vol./vol.). Error bars represent ± one standard deviation.

should be diminished as much as possible. On the one hand, the loess soils covering the whole study site have uniform soil texture, i.e. silt loam; thus the spatial variability of soil hydraulic properties resulted from soil texture should be negligible. On the other hand, slope positions could lead to strong spatial variability of soil hydraulic conductivity due to the redistribution of soil fine particles (Bodner et al., 2008). Here we only measured soil hydraulic properties at the upper positions (5 m away from hillslope top) at each site and thus the effect of slope positions on spatial variability of soil hydraulic properties was also diminished to a low level. In addition, the two watersheds have similar land use history. They were almost fully cultivated twenty years ago except for some steep hillslopes. Thereafter, parts of agricultural lands have been abandoned gradually due to economic and policy-driving factors. At present, cropland, abandoned cropland and grassland exist in both watersheds. Therefore, the significant differences of dry bulk density, total porosity and hydraulic conductivities (Figs. 4 and 5) should be mainly linked to vegetation recovering in this study.

We found that soil hydraulic conductivity and total porosity decreased and dry bulk density increased under early-stage vegetation recovering. This result was contrary with previous findings under long-term vegetation restoration (Li and Shao, 2006; Peng et al., 2012). For instance, Li and Shao (2006) found that the soil hydraulic conductivity of the 150-year-old abandoned cropland increased by a factor of 4.6 compared to cropland in the Loess Plateau. Then why do the changes of soil hydraulic properties behaved distinctively at different stages of vegetation recovering? It is well known that vegetation may enhance soil hydraulic conductivity though the reduction in rain splash compaction, root action, and biological and chemical factors (Bhark and Small, 2003). The increase of soil hydraulic conductivity under long-term vegetation restoration from a few decades to several hundred years could be ascribed to the functioning of vegetation. Nevertheless, vegetation factor may be not mainly responsible to the alteration of soil hydraulic conductivity of early-stage vegetation restoration since the increase of soil organic carbon (Table 1), vegetation cover and aboveground biomass (Fig. 3) with vegetation regrowth did not increase soil hydraulic conductivities. Therefore, another different mechanism may exist for the effect of early-stage vegetation restoration on soil hydraulic properties.

The increase of bulk density suggests a natural compaction process under early-stage vegetation recovering (Liu et al., 2012). During rainfall events, raindrop and surface runoff may carry away fine soil particles (clay and silt) to clog macro- and meso-pores and thus seal surface soil (Hu et al., 2012). These fine particles in macro- and meso-pores would gradually deposit by gravity and accumulate in these pores. The consequence of this process would be an increase of soil bulk density and a decrease soil porosity and hydraulic conductivity (Figs. 4 and 5). The sharp increase of soil bulk density in ACL1 compared to cropland (Fig. 3a) suggests that this process is rapid as soon as cropland is abandoned. Actually, this process could also happen in cropland soils. However, human activities such as tillage can often destroy this process and the accumulation of fine particles would not persist in croplands. Nevertheless, the alternation of soil hydraulic properties under natural vegetation restoration may not be fully explained by natural soil compaction featuring an increase of bulk density (Hu et al., 2012). Jiao et al. (2011) showed that soil nutrients (e.g., total nitrogen, available nitrogen, and available phosphorus) decreased, although not significant, at the early-stage of vegetation restoration on the Loess Plateau, which may be also responsible for the decrease of soil hydraulic properties. However, as revegetation proceeds further, the increase of soil organic carbon and soil nutrients (Jiao et al., 2011) and the development of roots and its architecture ameliorate soil quality and thus would increase soil hydraulic properties.

In fact, our findings here are indirectly supported by the experimental results of Gao et al. (2011) and Liu et al. (2012) on the Loess Plateau. Gao et al. (2011) found that subsurface soil moisture in cropland was higher than abandoned cropland and grassland, suggesting greater amount of water in cropland was transported into subsoil through infiltration. Liu et al. (2012) found that larger magnitude of runoff was observed with increasing year of abandonment of cropland at the early-stage natural recovering at plot scale. In general, the studies above showed the effect of early-stage vegetation recovering on soil hydrological and hydraulic properties was different from the long-term process. This also implies that revegetation of abandoned cropland may not necessarily improve soil hydraulic properties.

5. Conclusions

This study investigated the changes of soil hydraulic properties induced by early-stage natural vegetation recovering of different ages (1, 5, 9, and 16–20 years) as compared to cropland and 30-year-old secondary grassland (two controls) on the semiarid Loess Plateau. Early-stage vegetation recovering exhibited a very different effect on soil hydraulic properties as compared to the findings based on long-term vegetation recovering. In general, natural vegetation recovering at early stages did not improve soil hydraulic properties; dry bulk density increased while soil porosity and hydraulic conductivity decreased with vegetation restoration. Moreover, it would take at least 20 years to reverse the decreasing trend of soil hydraulic conductivities in this study.

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