

Dynamic monitoring of soil bulk density and infiltration rate during coal mining in sandy land with different vegetation

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Abstract To investigate the effects of coal mining on soil physical properties, sandy lands with three major vegetation types (*Salix psammophila*, *Populus simonii*, and *Artemisia ordosica*) were investigated by the ring knife method and double-ring infiltrometer. Specifically, variations in soil bulk density and water infiltration rate and the influences of coal mining and vegetation type on the properties during different subsidence stages were studied at the Shendong Bulianta mine. The results showed that, in the period before mining, soil bulk density occurred in the order $A. ordosica > P. simonii > S. psammophila$, with a negative correlation between the initial infiltration rate and steady infiltration rate being observed. In the period during mining and 3 months after mining, there were no significant differences in soil bulk density and water infiltration rate among vegetation types. At 1 year after mining, the soil bulk density occurred in the order $A. ordosica > S. psammophila > P. simonii$, having a negative correlation with the steady infiltration rate. The water infiltration depths of the *S. psammophila*, *P. simonii* and *A. ordosica* were 50, 60, and 30 cm, respectively. The infiltration characters were simulated by the Kostiakov equations, and the simulated and experimental results were consistent. Linear regression revealed that vegetation types and soil bulk density had significant effects on soil initial infiltration rate during the four study periods, and the infiltration rate of the period 1 year after mining was mainly influenced by the soil bulk density of the period before mining. The results indicated that vegetation types had significant effects on soil bulk density, and that the tree–shrub–grass mode was better than one single plantation for water conservation and vegetation recovery in sandy land subjected to mining.

Keywords Soil bulk density · Soil infiltration rate · Sandy land · Vegetation type

1 Introduction

Shendong mining area is located in the transition zone of the Loess Plateau and the Mu Us Sand land, where the ecological environment is fragile. It is covered by hilly sand and loose soil, and the developments of the vertical joints are rich. In the area, water flowing fractures generated by mining come through the overlying bedrock, and even reach the surface in some areas, resulting in damage

to overlying aquifers. The most obvious impact is that there are many ground fissures and a large amount of surface subsidences (Cai and Sui 2008; Kang 2008; Miao et al. 2009).

Many studies and reports have shown that ground fissures and surface subsidence in arid areas result in a decline of water tables, withering of plants, increased soil erosion and desertification (Bian et al. 2009; Aysen et al. 2010; Xu et al. 2012; Zhang et al. 2012). As important ecological factors for vegetation restoration and reconstruction, soil water and the movement rules of it have always been the focus of many studies (Zang et al. 2010; Zou et al. 2012, 2013). Based on analysis of parameter changes of moisture characteristic curves and penetration coefficient curves caused by changes in soil structure as a

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result of mining, as well as the adverse effects on the local environment caused by changes in the vadose zone, it can be concluded that ground fissures and surface subsidence have a large impact on soil water migration. Wang et al. (2006) found that soil porosity increased and bulk density decreased because of coal mining subsidence, which led to high soil water losses in the dry season. Zang et al. (2012) studied the effects of coal mining subsidence on lateral seepage and vertical infiltration rate for the sandy slope.

Soil bulk density and infiltration capacity are important soil hydrological parameters that are indicators of soil degradation and drought. Infiltration is the movement of water into the soil from the surface by downward or gravitational flow. The rate at which this occurs is known as the infiltration rate, which mainly depends on the characteristics of the soil (Bharati et al. 2002; Osuji et al. 2010; Thompson et al. 2010; Zhang et al. 2010). The major soil and water characteristics affecting infiltration rates are the initial moisture content, hydraulic conductivity of the soil profile, texture, porosity, degree of swelling of soil colloids, organic matter, vegetative cover, and duration of irrigation or rainfall. Some studies have shown that plant biomass and productivity increased significantly with increasing soil infiltration rates, which have close relationships with covered vegetation types (Luo et al. 2005; Wang and Liu 2009; Li et al. 1998, 2010; Lin et al. 2010).

Based on the above studies, it is known that coal mining reduces water resources via destruction of hydrogeological conditions and soil physical properties, and that soil bulk density and infiltration capacity are two important soil hydrological parameters that also are closely related to types of covering vegetation. To identify the effects of mining subsidence on infiltration and soil bulk density in sandy land with consideration of vegetation, changes in soil bulk density and water infiltration rate generated by mining subsidence under different vegetation coverage conditions and the relationship between infiltration rates and these factors were studied at the Shendong Bulianta mine.

2 Materials and methods

2.1 Site description

The study area is located at Bulianta mine in the Shenfu Dongsheng coalfield, which is in the northeastern portion of the Ordos coal basin and southeastern Mu Us Sandland. The altitude of the study area is 1,100–1,300 m, its geographic coordinates are 109°45′–110°40′E and 38°50′–39°50′N, the major landform type is wavy sand covered by Quaternary aeolian sand, and the major soil types are wind sand and cotton sand. The area is characterized by a semi-arid and semi-desert plateau continental climate, which is

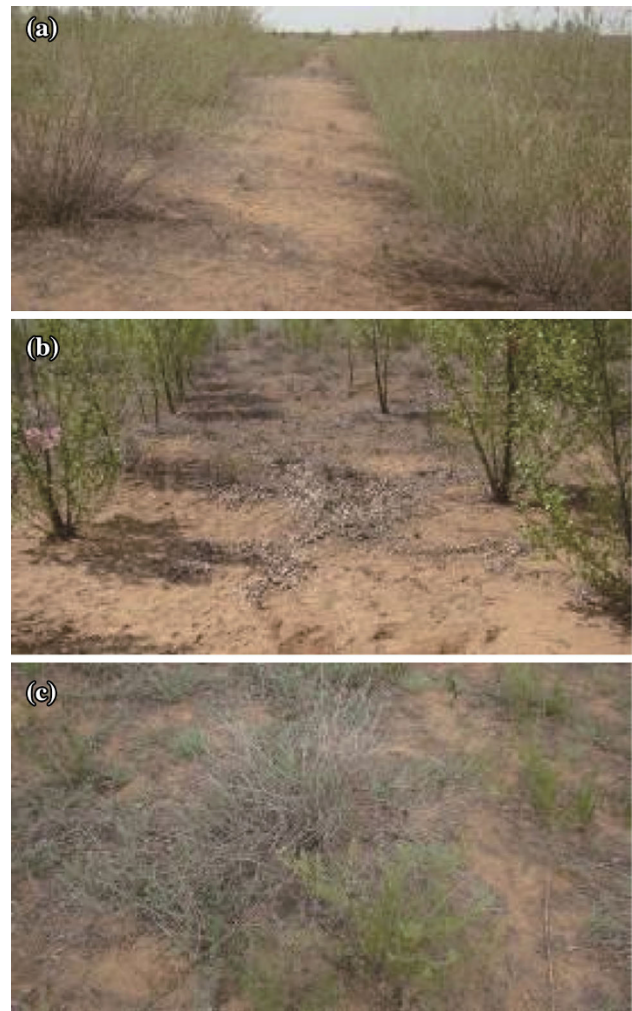


Fig. 1 Land coverage conditions for different vegetation types: **a** *Salix psammophila*, **b** *Populus simonii* and **c** *Artemisia ordosica*

cold in winter and hot in summer, with a large temperature variation between day and night. The area is also subjected to frequent sandstorms, drought and strong evaporation. The annual average rainfall is 194.7–531.6 mm and the annual evaporation is 2,297.4–2,838.7 mm. The area is at the warm-temperate steppe and shrub land steppe area in the eastern area of the Loess Plateau, where the vegetation primarily consists of psammophytes.

2.2 Experimental design

Three sites of typical and representative plant communities with substantially similar topographic properties were selected. The vegetation types of the three sites were *Salix psammophila*, *Populus simonii*, and *Artemisia ordosica*, which had average heights of 1.6, 4.5 and 0.7 m, respectively. The land coverage conditions for different vegetation types are shown in Fig. 1, and a detailed description of each plot is given in Table 1.

Table 1 Description of plots with different vegetation types

Plot	Site description
<i>Salix psammophila</i>	The plantations of <i>Salix psammophila</i> were planted in 1988. Some plants were located in the plains area of the sandy land, while others were located on the gentle windward slope of the sandy land, with fewer herbaceous plant under the bush. The line spacing was about 2 m, the bushes were about 1.78 m high, and the crowns were about 1.30 m long
<i>Populus simonii</i>	The plantations of <i>Populus simonii</i> were planted in 1988. Trees were located on the gently fixed aeolian sandy soil, growing well, with little herbaceous understory and few dry branches and fallen leaves under the trees. The average height of the trees was about 4.23 m, and the crown was about 1.58 m long
<i>Artemisia ordosica</i>	The population pattern was of clustered distribution. The plants were about 72.5 cm high, with crowns about 87 cm long. Additionally, the coverage was about 50 %, with 1–3 cm biological crusts on the land surface

Mining passed through these three sites in June 2011, immediately after which subsidence, cracks and dislocation appeared. As the mining continued moving forward, the experimental areas gradually stabilized and the cracks began to close. The main soil physical properties of each plot are shown in Table 2. Soil bulk density sampling and field experiments to investigate the soil infiltration rate were conducted in four different stages: before mining, during mining, 3 months after mining, and 1 year after mining.

Table 2 Soil physical properties of experiment plots

Plot	Depth (cm)	Soil particle composition			Soil bulk density (g/cm ³)	Saturated soil water content (cm ³ /cm ³)
		Sand (%)	Silt (%)	Clay (%)		
<i>Salix psammophila</i>	10	89.02	8.26	2.73	1.58	38.82
	30	85.56	7.62	6.82	1.58	33.28
	50	87.48	8.68	3.84	1.56	37.78
	70	85.94	9.06	4.99	1.63	29.65
	90	88.44	8.68	2.88	1.65	32.63
<i>Populus simonii</i>	10	86.12	13.84	0.04	1.64	33.36
	30	85.76	13.74	0.50	1.65	33.02
	50	88.06	8.26	3.68	1.61	28.75
	70	84.8	10.56	4.64	1.54	32.81
	90	75.39	17.09	7.52	1.48	33.35
<i>Artemisia ordosica</i>	10	90.56	6.82	2.62	1.58	33.96
	30	88.64	7.68	3.68	1.68	33.62
	50	84.80	9.60	5.60	1.65	35.11
	70	88.64	7.45	3.87	1.63	34.07
	90	95.56	4.24	0.20	1.66	34.33

Each type of vegetation was selected according to size (large, medium, small), and four replicates of each size were collected; thus, 12 representative strains of each vegetation type and 36 total representative strains were selected. The distance between each selected plant was about 3–5 m. For *S. psammophila* and *P. simonii* areas, soil samples were collected about 15 cm away from the main plant trunk, while for *A. ordosica*, soil samples were collected from under the grass.

Four representative strains for each of the three different types of vegetation were selected for water infiltration field experiments.

2.3 Measurement methods

Soil bulk density was measured by the ring knife method. Specifically, the ring knife was inserted into the ground to obtain a soil core, which was then placed into a sterile plastic bag, and sealing to preserve for lab drying. The weight of drying soil was soil bulk density.

The soil infiltration experiment was conducted using the double-ring infiltrometer method. The inner ring employed Markov bottles to supply water automatically, while the outer ring added water manually every few seconds to maintain the water level flush with the inner ring. In addition, another ring was embedded in the inner ring with a diameter of 24 cm and height of 20 cm, which was suspended in the inner ring to prevent contact with the soil surface. The soil infiltration rate tends to become smaller over time. The infiltration time depended on when the soil infiltration approached stability, ranging from 60 to 90 min depending on the vegetation.

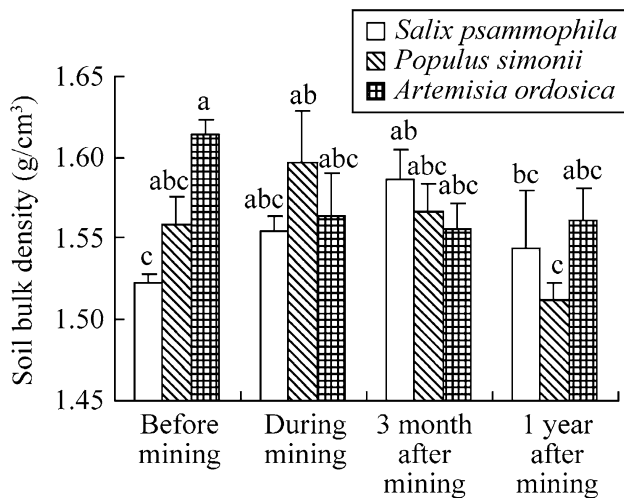


Fig. 2 Changes in soil bulk density during different stages of mining subsidence

The soil water infiltration process can be described by the Kostiakov equation, which can be used to fit the infiltration characteristics. The equations are shown below.

$$K_t = a \times t^{-b} \quad (1)$$

where K_t is the instantaneous infiltration rate (cm/min); t is the infiltration time in min; a and b are empirical parameters that reflect the initial infiltration rate and the rate of decrease in the infiltration rate, respectively.

Immediately before and after the infiltration test was conducted, soil samples were also collected at depths of 10, 30, 50, 70 and 90 cm to test the soil water content.

2.4 Statistical analysis

Data were analyzed by Microsoft Excel and SPSS. Multiple linear regression analysis among soil permeability, soil bulk density and mining time under different vegetation patterns was conducted, and the soil permeability mathematical model was set.

The experimental data were also subjected to differential analyses using SAS. The level of significance was set at 5 %.

3 Results and analysis

3.1 Soil bulk density under different vegetation types

As shown in Fig. 2, the soil bulk density appeared to have a tendency of $A. ordosica > P. simonii > S. psammophila$ in the period before mining. Soil bulk density is the weight of the solid particle size per unit volume of soil, including pores, under natural structure. The density is dependent on

the mineral composition, soil texture, humus, structure, elastic conditions and other factors. Generally, when the content of soil organic matter is low, the bulk density is high, and vice versa. The results of the present study indicate that planting *P. simonii* and *S. psammophila* could improve soil porosity and reduce soil bulk density.

During mining and 3 months after mining the surface soil bulk density there were changes in the presence of different vegetation types, with increases being observed in *S. psammophila* and *P. simonii* areas, and decreases in *A. ordosica* plots. If soil is compacted and soil particles are adhesive, the soil bulk density will increase and vice versa. The increases in the soil density around *S. psammophila* and *P. simonii* may indicate an increased risk of soil desertification. The differences between *S. psammophila*, *P. simonii* and *A. ordosica* may be caused by the distribution of roots and biological crusts. It is well known that the root distribution of *A. ordosica* is shallower than that of *S. psammophila* and *P. simonii*, and that land with *A. ordosica* was covered by soil biological crusts. The shallower root distribution and soil biological crusts may reduce soil desertification trends and improve soil porosity, thereby decreasing the soil bulk density. The results also showed that mining subsidence changed the original soil conditions, and the differences in surface soil bulk density between vegetation types became smaller.

Along with mining subsidence age increasing, the soil body almost became stable for 1 year after mining. During the relatively stable period, surface soil bulk density became lower for *A. ordosica* and *P. simonii* relative to the period before mining. For sandy soil, while the soil bulk density is smaller, it will contain less coarse sand and more organic matter and vice versa. The results showed that mining subsidence reduced the average surface soil bulk density of the subsided area, which was probably due to the development of water flowing through the fractured zone. The differences between *P. simonii*, *A. ordosica* and *S. psammophila* areas indicated that vegetation types had a significant effect on soil bulk density. *A. ordosica* and *P. simonii* may be more helpful than *S. psammophila* at decreasing soil bulk density in sandy areas subjected to mining associated subsidence. The effects of *A. ordosica* are likely due to its shallower root distribution and the presence of soil biological crusts, while those of *P. simonii* are likely due to the leaf litter layers. Indeed, these factors all benefit the water distribution of the soil surface layer, which can be helpful for surface soil ecological recovery.

3.2 Soil infiltration characteristics under different vegetation types

Soil permeability is one of the most important soil physical characteristics influencing the water infiltration

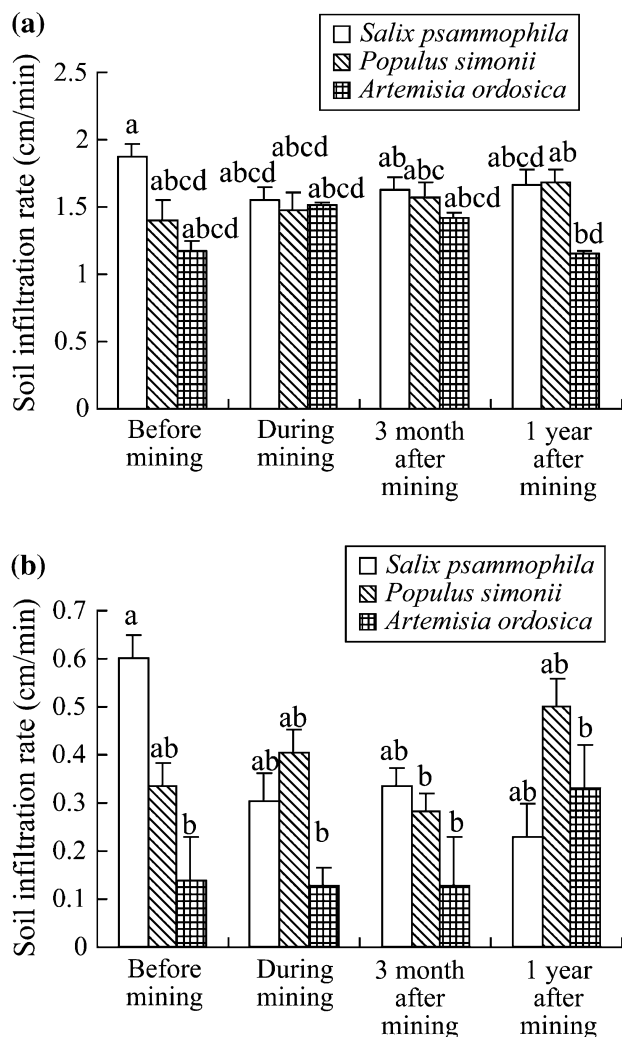


Fig. 3 Soil infiltration rate under different vegetation types: **a** initial soil infiltration rate and **b** steady soil infiltration rate

rate, and main indicators for soil permeability are the initial infiltration rate and the steady infiltration rate. This study considered the first 5 min to be the initial infiltration time and the moment when the permeation amount per unit of time reached stabilization to be the steady infiltration time.

As shown in Fig. 3a, the initial soil infiltration rate showed a tendency of *S. psammophila* > *P. simonii* > *A. ordosica* in the period before mining, indicating a negative correlation with the soil bulk density. In the period during mining and 3 months after mining, there were no significant differences among different vegetation types. These results indicate that mining subsidence changed the original soil physical structure and reallocated the proportion of sand and sandy loam, minimizing the differences caused by different vegetation types. When compared with the period before mining, the initial infiltration rate of *S. psammophila*

and *A. ordosica* plots at 1 year after mining showed no significant changes, while that of *P. simonii* plots increased. Based on the above study, after coal mining disturbance, the soil bulk density in the root distribution layer became lower in *P. simonii*, so the initial infiltration rate of *P. simonii* increased.

As shown in Fig. 3b, during the period before mining, the steady soil infiltration rate showed a similar variation trend as the initial soil infiltration rate, while in the period 1 year after mining, the steady soil infiltration rate showed a negative relationship with soil bulk density, occurring in the following order: *P. simonii* > *A. ordosica* > *S. psammophila*. This may have been due to differences in root spatial distribution and the content of clay particles and organic matters owing to the soil biological crusts around *A. ordosica* and the leaf litter layers under *P. simonii*, the same as soil bulk density. The results also showed that coal mining increased the average initial infiltration rate and decreased the average steady infiltration rate, but that these changes were not significant.

3.3 Soil infiltration depth under different vegetation types

Soil infiltration depth is associated with soil moisture, soil bulk density, soil structure, and the impact of herbaceous plants, root distribution, litter cover and other factors. Infiltration depth is an important indicator of soil infiltration ability as well as soil water conservation and anti-erosion ability. A greater soil infiltration depth indicates that there is more water precipitating into the soil, increasing the discharge and flux of interflow and groundwater runoff and reducing surface runoff losses and surface erosion. Additionally, infiltration depth can reflect water movement in the soil better than water infiltration rate and therefore can be helpful for groundwater management, soil erosion prediction and flood forecasting. Many studies of soil water infiltration have been conducted domestically and globally. Eldridge et al. (2000) found that the removal of the crusts in all three landscapes influences resource flows, particularly the redistribution of runoff water, which is essential for maintenance of desert soil surface patterning. The farming–grazing transitional zone was investigated by Lu et al. (2008), who found that bio-crust clearly impedes water infiltration. Furthermore, they found that bio-crust coverage is negatively correlated with infiltration depth (Lu et al. 2008).

Comparison of the water infiltration depths for the three different vegetation types revealed that the water infiltration depths of *S. psammophila*, *P. simonii* and *A. ordosica* were 50, 60 and 30, respectively (Fig. 4). The difference between *A. ordosica*, *S. psammophila* and *P. simonii* was obvious. For *S. psammophila* and *P. simonii*, soil water was evenly distributed at a depth of 0–60 cm, as well as a

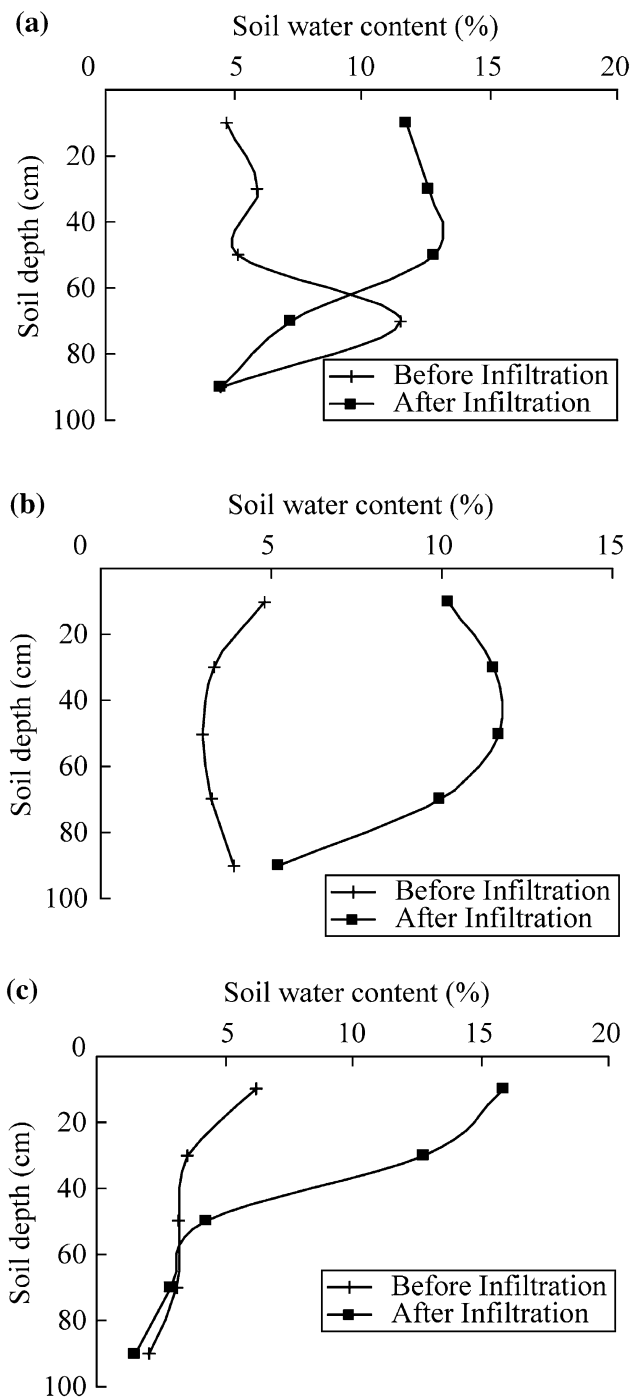


Fig. 4 Soil infiltration depth for different vegetation types: **a** *Salix psammophila*, **b** *Populus simonii* and **c** *Artemisia ordosica*

higher soil water content. At 60–80 cm, the soil water content showed a significant decrease. However, the soil water content of *A. ordosica* acted differently, reaching the maximum value at a depth of 0–20 cm, which was obviously higher than that of areas planted with *S. psammophila* and *P. simonii*. Additionally, in areas planted with *A. ordosica* the soil water content began to decrease at

20–40 cm, which was obviously shallower than that of *S. psammophila* and *P. simonii*. A significant decrease was observed at depths greater than 50 cm. These findings indicate that, in areas planted with *A. ordosica*, the soil water gathered relatively easily on the land surface instead of moving downward. The lack of water penetration in deep soil does not benefit soil water conservation, especially in desert regions with high evaporation. It was found that the deeper infiltration depth, at the same temperature, the longer time for sandy soil holding water, which can be used by plants for longer.

Salix psammophila, *P. simonii*, and *A. ordosica* represent trees, shrubs and grass, respectively. It has been suggested that full use of trees, shrubs, grass and their root characteristics be made by combining deep developed root systems and shallow developed root systems together into a multi-level solid collocation of tree–shrub–grass mode. This mode can be better than the single arrangement for water conversation and vegetation recovery.

3.4 Infiltration models for different vegetation types

For the further investigation of the soil infiltration characteristics under different vegetation types in the study area, the Kostiakov equation were used to fit the infiltration characteristics (Table 3).

The value of parameter a in the Kostiakov equation ranged from 1.105 to 1.852 in the study area. This value, which is related to soil bulk density, was highest in *S. psammophila* land of the period during mining, and smallest in *A. ordosica* land at 1 year after mining. Parameter b, which reflects the decreasing rate of infiltration, ranged from 0.285 to 0.612. The initial soil infiltration rate of *S. psammophila* and *P. simonii* was higher, while that of *A. ordosica* soil was lower.

Infiltration rates under the three different vegetation types were also simulated by Kostiakov equation, which produced results consistent with those of the experiment.

3.5 Multiple linear regression models

3.5.1 Multiple linear regression model with main impact factors

To determine which factors had significant effects, three impact factors (time after mining, vegetation types, and surface soil bulk density) were evaluated as independent variables by SPSS linear regression. The estimation equations for soil infiltration rate (initial infiltration rate and steady infiltration rate) are shown in Formulas (2) and (3). After generation of the equations, the relationships between

Table 3 Soil infiltration model under different vegetation types

Vegetation types	Period	Kostiakov equations	
		Equations	R ²
<i>Salix psammophila</i>	Before mining	$K_t = 1.775 t^{-0.285}$	0.962
	During mining	$K_t = 1.852 t^{-0.416}$	0.962
	Three months after mining	$K_t = 1.431 t^{-0.422}$	0.967
	One year after mining	$K_t = 1.633 t^{-0.559}$	0.995
<i>Populus simonii</i>	Before mining	$K_t = 1.367 t^{-0.392}$	0.982
	During mining	$K_t = 1.447 t^{-0.349}$	0.995
	Three months after mining	$K_t = 1.520 t^{-0.482}$	0.987
	One year after mining	$K_t = 1.647 t^{-0.324}$	0.994
<i>Artemisia ordosica</i>	Before mining	$K_t = 1.159 t^{-0.588}$	0.998
	During mining	$K_t = 1.139 t^{-0.612}$	0.998
	Three months after mining	$K_t = 1.381 t^{-0.443}$	0.997
	One year after mining	$K_t = 1.105 t^{-0.347}$	0.982

the soil infiltration rate and the three impact factors were analyzed.

$$Y = -0.019X_1 - 0.147X_2 - 3.359X_3 + 7.089 \tag{2}$$

$$R^2 = 0.865 (p = 0.009)$$

$$Y = -0.023X_1 - 0.068X_2 - 2.302X_3 + 4.095 \tag{3}$$

$$R^2 = 0.677 (p = 0.159)$$

where X_1 , X_2 , and X_3 are the time after mining, vegetation types, and surface soil bulk density, respectively. For X_2 (vegetation types), *S. psammophila* was assigned a value of 1, *P. simonii* 2, and *A. ordosica* 3.

The results showed that the R^2 of the regression model for the soil initial infiltration rate was 0.865, corresponding to a p value of 0.009 ($p < 0.05$). These findings indicate that the linear relationship of the regression model was significant with a high correlation, so a multiple linear regression model could be made. As shown in Table 4, the regression constant value was 7.089 ($p < 0.05$), while the values of the regression coefficient were -0.019 ($p > 0.05$), -0.147 ($p < 0.05$) and -3.359 ($p < 0.05$), respectively, representing remarkably negative correlations

Table 4 Significance of regression coefficients for initial infiltration rate

Model	Unstandardized coefficients		Standardized coefficients	t	Sig.
	B	SE			
(Constant)	7.089	2.252		3.148	0.014
X_1	-0.019	0.033	-0.110	-0.584	0.576
X_2	-0.147	0.046	-0.607	-3.212	0.012
X_3	-3.359	1.442	-0.465	-2.330	0.048

Table 5 Significance of regression coefficients for steady infiltration rate

Model	Unstandardized coefficients		Standardized coefficients	t	Sig.
	B	SE			
(Constant)	4.095	2.325		1.761	0.116
X_1	-0.023	0.034	-0.183	-0.663	0.526
X_2	-0.068	0.047	-0.397	-1.435	0.189
X_3	-2.302	1.489	-0.452	-1.546	0.161

between vegetation types (X_2), soil bulk density (X_3) and initial soil infiltration rate. These findings indicate that vegetation types and soil bulk density had significant effects on soil initial infiltration rate.

For soil steady infiltration rate, the R^2 of the regression model is 0.677, corresponding to a p value of 0.159 ($p > 0.05$). These findings indicate that the linear relationship of the regression model is not significant with moderate correlation, so the equation was invalid. As shown in Table 5, there are negative relationships between impact factors and soil steady infiltration rate similar to the soil initial infiltration rate, but these associations were not significant.

According to the above analysis, the regression model based on the initial infiltration rate and the three impact factors was significant with high correlation. Therefore, Eq. 1 could be used to forecast the initial infiltration rate in the sandy mining subsidence area.

3.5.2 Multiple linear regression model with soil bulk density in different periods

The changes in soil bulk density appeared to differ in different subsidence stages, leading to changes in the soil

Table 6 Soil infiltration rate with changes in soil bulk density

Vegetation type	Repetition	Soil bulk density				Soil infiltration rate	
		Before mining	During mining	Three months after mining	One year after mining	Initial infiltration rate	Steady infiltration rate
<i>Salix psammophila</i>	1	1.512	1.599	1.606	1.664	1.663	0.227
	2	1.589	1.592	1.634	1.644	1.544	0.300
	3	1.406	1.598	1.550	1.611	1.710	0.491
	4	1.618	1.621	1.621	1.662	1.266	0.155
<i>Populus simonii</i>	1	1.434	1.594	1.567	1.515	1.672	0.498
	2	1.666	1.563	1.503	1.473	1.561	0.289
	3	1.527	1.632	1.573	1.530	1.467	0.401
	4	1.378	1.532	1.545	1.600	1.947	0.486
<i>Artemisia ordosica</i>	1	1.668	1.580	1.430	1.628	1.147	0.327
	2	1.693	1.589	1.620	1.547	1.168	0.137

Table 7 Significance of regression coefficients for initial infiltration rate

Model	Unstandardized coefficients		Standardized coefficients β	t	Sig.
	B	SE			
(Constant)	9.171	2.533		3.621	0.015
X_1	-1.756	0.383	-0.789	-4.584	0.006
X_2	-3.404	1.731	-0.371	-1.966	0.106
X_3	0.787	0.780	0.192	-1.010	0.359
X_4	-0.476	0.665	-0.124	-0.716	0.506

Table 8 Significance of regression coefficients for steady infiltration rate

Model	Unstandardized coefficients		Standardized coefficients β	t	Sig.
	B	SE			
(Constant)	3.425	1.160		2.954	0.032
X_1	-1.022	0.175	-0.873	-5.826	0.002
X_2	0.416	0.793	0.086	0.525	0.622
X_3	-0.906	0.357	-0.419	-2.536	0.052
X_4	-0.476	0.304	-0.235	-1.563	0.179

infiltration rate (Table 6). To identify the effects of soil bulk density on the soil infiltration rate in the mining subsidence area, estimation equations for soil infiltration rate in the relatively stable period 1 year after mining were generated [Formulas (4) and (5)] by linear regression fitting using four impact factors (surface soil bulk density of the period before mining, during mining, 3 months after mining, and 1 year after mining) as dependent variables. The relationship between soil infiltration rate and surface soil bulk density of the period before mining, during mining,

3 months after mining, and 1 year after mining could then be analyzed.

$$Y = -1.756X_1 - 3.404X_2 + 0.787X_3 - 0.476X_4 + 9.171$$

$$R^2 = 0.928 * (p = 0.023)$$
(4)

$$Y = -1.022X_1 + 0.416X_2 - 0.906X_3 - 0.476X_4 + 3.425$$

$$R^2 = 0.946 * (p = 0.012)$$
(5)

where X_1 , X_2 , X_3 , and X_4 are the soil bulk density of the period before mining, during mining, 3 months after mining, and 1 year after mining, respectively, and Y is the soil infiltration rate (initial infiltration rate and steady infiltration rate).

The R^2 of the regression model for the initial infiltration rate and steady infiltration rate was 0.928 and 0.946, corresponding to p values of 0.023 ($p < 0.05$) and 0.012 ($p < 0.05$), respectively, indicating that the linear relationships of the regression model were significant with high correlation. As shown in Tables 7 and 8, the soil bulk density of the period before mining had p values of 0.006 ($p < 0.01$) and 0.002 ($p < 0.01$), indicating that the impact of soil bulk density in the period before mining on the soil infiltration rate was significant.

4 Conclusions

Analysis of soil bulk density and soil infiltration rate for the three different vegetation types during the process of mining revealed that mining subsidence impacts these physical characteristics. Specifically, in the period before mining, *P. simonii* and *S. psammophila* promoted soil

organic matter, reduced soil bulk density, and improved soil porosity and soil infiltration rate. During mining and 3 months after mining, subsidence changed the original soil physical structure, reallocated the proportion of sand and sandy loam, and decreased the differences in surface soil bulk density between different vegetation types. One year after mining, *P. simonii* led to low soil bulk density and high soil infiltration rate. A regression model based on the initial infiltration rate and three impact factors (time after mining, vegetation types, and surface soil bulk density) was significant with a high correlation. Regression models based on the infiltration rate of the relatively stable period and surface soil bulk density of four different periods were significant with high correlations.

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