Global Ecology and Conservation 4 (2015) 255–263

Contents lists available at ScienceDirect

Global Ecology and Conservation

journal homepage: www.elsevier.com/locate/gecco

Original research article

Vegetation succession and soil infiltration characteristics under different aged refuse dumps at the Heidaigou opencast coal mine

Huang Lei *, Zhang Peng [1], Hu Yigang [1], Zhao Yang [1]

Shapotou Desert Research and Experimental Station, Cold and Arid Regions Environmental and Engineering Research Institute, CAS, Lanzhou 730000, China
Key Laboratory of Stress Physiology and Ecology in Cold and Arid Regions Gansu Province, Lanzhou 730000, China

ARTICLE INFO

Article history:
Received 16 April 2015
Received in revised form 24 June 2015
Accepted 10 July 2015
Available online 28 July 2015

Keywords:
Vegetation succession
Refuse dumps
Infiltration rate
Soil bulk density
Open-pit coal mine

ABSTRACT

Vegetation succession and soil infiltration characteristics under five different restoration models of refuse dumps including different-aged revegetated sites (1995, 1998, 2003 and 2005) in the northern, eastern and western open-pit coal mine dump and a reference site with native vegetation, which had never been damaged by coal mining activities on the Heidaigou Open Cut Coal Mine were studied. Changes in the plant species, soil properties and infiltration rates were evaluated at the different refuse dumps. The results indicated that the number of herbaceous species, plant cover, biomass, fine particles, and total N, P and SOM increased significantly with increasing site age. However, the number of shrub species decreased since revegetation, its cover increased from 17% to 41% initially and subsequently decreased to the present level of 4%. The natural vegetation community and the northern refuse dump had the highest cumulative infiltration rates of 3.96 and 2.89 cm s^{-1} in contrast to the eastern and western refuse dumps and the abandoned land, where the highest cumulative infiltration rates were 1.26, 1.04 and 0.88 cm s^{-1}, respectively. A multiple linear regression analysis indicated that the infiltration rate was primarily determined by the silt percentage, SOM, plant coverage and the variation in soil bulk density. Our results provide new ideas regarding future soil erosion controls and sustainable development at open-pit coal mine refuse dumps.

1. Introduction

Coal is the primary source of energy in China (Lam, 2005). Furthermore, there is an increase in the demand for coal production to meet the requirements of industry; therefore, many open-cast mines have been exploited, such as the Heidaigou opencast coal mine, which is the largest opencast coal mine in China with an annual output of 20 million tons (Liu and Fan, 2002). However, increased mining may lead to a larger amount of coal refuse, resulting in serious environmental problems and causing drastic soil disturbances (Wang et al., 2014). Opencast mining involves the displacement of large amounts of excess material (mine waste) from coal mining activities, and this anthropogenic change in soil structure has a profound impact on rainfall infiltration, the stability by surface weathering, groundwater or surface-water seepage, toe erosion and

---

* Correspondence to: Donggang West Road, 320. Lanzhou, Gansu, China. Tel.: +86 0931 8277921.
E-mail addresses: mathecology@163.com (L. Huang), zhangp1419@163.com (P. Zhang), huyig@lzb.ac.cn (Y. Hu), Zhaoyang66@126.com (Y. Zhao).

[1] Tel.: +86 0931 4967187.

http://dx.doi.org/10.1016/j.gecco.2015.07.006

slope modification (Kainthola et al., 2011). Especially in the transition zones between arid and semi-arid regions with fragile environments. Therefore, a series of vegetation restoration projects, such as tree planting, agricultural reclamation, building botanical gardens, were conducted at these coal mine refuse dumps (Bradshaw, 1997; Ma et al., 2007; Huang and Liu, 2013). This has played a large role in controlling soil erosion, land degradation and desertification, as well as in cultivating agricultural activities, such as cash crops and animal husbandry (Radeloff et al., 2000; Wang et al., 2013; Wei et al., 2013; Henry, 2014; de Paula et al., 2015). However, it remains unclear how these plants proceed through vegetation succession and whether they eventually become as stable as natural vegetation communities (represented by plant diversity, soil infiltration, etc.); this is still a challenge for ecologists due to the difficulty of monitoring various soil parameters over time.

In this study, a ''space for time'' substitution was used as an effective approach to study changes over time (Sparling et al., 2003; Li et al., 2007). The three refuse dumps (northern, eastern and western open-pit coal mine dumps at the Heidaigou open-pit coal mine) initiated vegetation reconstruction in 1995, 1998 and 2003 and offer an ideal opportunity to study the processes of vegetation succession in extreme environments because the soil conditions before coal mining are largely driven by geomorphological processes. Vegetation succession commences after the establishment of artificial vegetation, and monitoring the same site over time is considered the most reliable way to measure change (Powlson et al., 1998). Data from permanent experimental plots of artificial vegetation of different ages were used to quantitatively describe vegetation changes associated with changes in soil infiltration. The aim of this work was to understand the nature of changes to the artificial vegetation succession and soil infiltration over a long period of time in order to improve our knowledge of the rehabilitation of refuse dumps with soil structure changes. Our particular objectives were as follows: (1) to examine changes to the species composition, plant cover, and biomass of plant species in artificial vegetation systems at various refuse dumps and (2) to assess variations in soil infiltration and its influencing factors. This study will help elucidate our understanding of vegetation reconstruction and soil and water conservation in opencast coal mining regions.

2. Materials and methods

2.1. Study area

The Heidaigou open-pit coal mine is located in the middle of the Zhungeer coal field in the Inner Mongolia Autonomous Region of China, and it ranks as the third largest coal mine based on its reserves. The altitude at the site is 1025–1302 m, and the geographical coordinates are $39°43' \sim 39°49'$N and $111°13 \sim 111°20'$E. The Heidaigou coal mine occupies a total area of 5124 ha, and the waste-dumps occupy more than 629 ha of the total area. The site is in a temperate continental arid climate zone that is cold in winter, dry and windy in spring, hot in summer, and mild and pleasant in autumn. The annual average temperature is 7.2 °C, the average annual rainfall is 426.3 mm, decreasing predominantly between June and September, and the precipitation during this period accounts for approximately 60%–70% of the total. The average annual evaporation is 1943.6 mm, and the relative humidity is 58%. The wind is mostly calm, flowing in a north-northwest direction at an average speed of 2.2 m/s. The coal mine is situated in a typical steppe ecological region, with Stipa species comprising the main vegetation.

The mine has six refuse dumps, which are known as the Northern, Eastern, Western, Internal, East Yanbang, and Yinwan dumps. Those dumps are located at a site away from the coal bearing area or it can be internal-dumps created by in-pit dumping concurrent to the creation of voids by extraction of coal (Adibee et al., 2013). The soils of overburden dumps are physically, nutritionally and biologically poor, which usually consists of a mixture of coarse grained particles to rock fragments grading to fine grained particles, causes geotechnical and environmental problems on disposal. As seen in Fig. 1(A) and (B), topography of the area is undulating, reclamation and re-vegetation for surface coal-mine disturbances have induced the bare mound to sustainable and healthy arable-land ecosystems, although the natural succession on the soil is also a very slow process. And the weathered materials would be stable with vegetation succession and they got mixed with organic materials which resulted in an improvement in material's physical properties that facilitate a more favorable condition for the growth of plants. Three of the refuse dumps (Northern, Eastern and Western), along with one abandoned land site that none reclamations activities have been carried out and implemented completely natural recovery, and a control site of natural vegetation communities were chosen for this study. The zonal vegetation at the refuse dumps is warm temperate grassland with low sparse vegetation with an average coverage of at most 30%. The natural plant community has been fully destroyed. The three refuse dumps are in different stages of reclamation and contain a range of vegetation. The basic characteristics of the five sites are shown in Table 1. A range of reclamations techniques available to coal mine reclamation. Trees (such as *Robinia pseudoacacia, Pinus tabulaeformis, Populus simonii*), shrubs (such as *Tamarix chinensis, Caragana mirophylla, Hippophae rhamnoides, Artemisia gmelinii, Armeniaca sibirica, Artemisia giraldii*) and grasses (such as *Stipa bungeana, Bothriochloa ischaemum, Pennisetum centrasiaticum, Lespedeza potaniniiv, Corispermum tylocarpum, Astragalus meliltoides, Thermopsis lanceolata, Leymus secalinus, Medicago sativa, Calamagrostis epigejos, Cleistogenes quarrosa* et al.) were selected as the main reclaimed plants. Among which the main plantation configurations were trees, shrubs, grasses, trees + shrubs, trees + grasses, shrubs + grasses and trees + shrubs + grasses. In the monoculture plantation configurations, its suitable cultivated distance of plantlets and rows is 2 m × 3 m and 1 m × 1 m for trees and shrubs, respectively. The grasses were planted together, and for some other mixed plantation configurations, the densities of planting spacing was 1 m × 2 m, 3 m × 3 m and 2 m × 2 m for the trees + shrubs, trees + grasses, shrubs + grasses configuration, respectively. In the trees + shrubs + grasses configuration, inter-planting grasses around 1 m away from shrubs and trees at the densities of 1 m × 2 m, 1 m × 3 m, respectively.

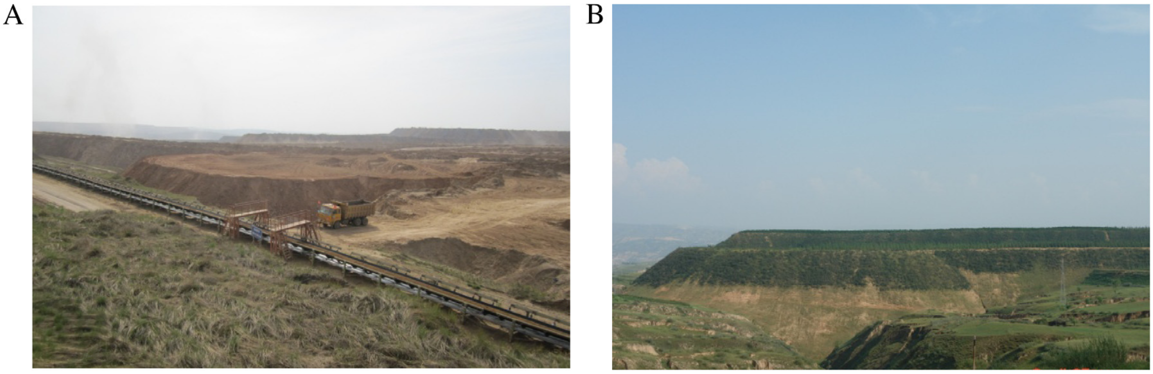

Fig. 1. View of the refuse dump before (A) and after (B) the re-vegetation at the Heidaigou opencast coal mine.

Table 1
Basic information about the sample plots.

Site	Northern	Eastern	Western	Abandoned land	Natural vegetation community
The elevation of the plane (m)	1275	1275	1260	1275	1172
Area of occupied land (h m^2)	197	210	170	15	–
Year reclamation began	1995	1998	2003	2005	–

2.2. Sampling method and data collection

For plant species, three quadrats were established at each of the five experimental sites at the Heidaigou open-pit coal mine, totaling 15 quadrats. The shrubland survey area was 10 m × 10 m, whereas the herb plot was 1 m × 1 m. The species richness (number of species per quadrat), shrub cover, herbaceous cover, biomass and height for each species in the artificial vegetation communities were measured in different refuse dumps, the abandoned land site and a control site of natural vegetation. In addition, the coverage of biological soil crusts was measured using a point sampling frame (2.5 cm × 2.5 cm grid; 169 points per 30 cm × 30 cm quadrat). Prior to sampling, the soil surface was sprayed with deionized water to make the biological soil crust components more readily visible. At each quadrat, the total coverage was estimated as the proportion of the 169 points occupied by the visible component of the crusts (Li et al., 2007). Because there were no historical data regarding the changes to most soil properties over the 20 years of revegetation, we used a "space for time" substitution approach that involved sampling sites of differing ages. The soil sampling sites were the same as those in the plant observation plots, and three replicate soil samples were taken from the different-aged sites at a depth of 0–50 cm during the 2013 growing season. Air-dried soil samples were sieved through a 2-mm screen and used for further analysis. The particle size was assessed with a pipette method, and the soil bulk density was determined by inserting a metallic core (0.05 m in depth and diameter) into the soil. The soil organic matter (SOM) was measured using the $K_2Cr_2O_7$ method (Nelson and Sommers, 1975). The total N was measured using the Kjeltec system with a 1026 Distilling Unit (Tecator AB, Höganäs, Sweden). Phosphorus and potassium were measured using standard methods for observation and analysis developed by the Chinese Ecosystem Research Network (CERN) (Liu, 1996).

A Mini-disc Infiltrometer (MDI, Decagon Devices, Inc., Pullman, WA, USA) was used for assessing the relative infiltration rate. An MDI is a 32.7-cm long, 3-cm diameter hard plastic tube, which is graduated up to 100 ml. A chamber barrier is positioned approximately 5-cm below the top of the tube, creating a separate compartment that controls air suction. A 1-cm wide steel tube passes from above the stopper to the bottom of the tube, above a stainless-steel porous disk (4.5 cm diameter). Another steel tube protrudes from the top, allowing for air to escape when the disk is placed on the soil. When the two compartments of the MDI are filled with water, it produces tension, allowing the water to stay in place and not flow out of the disk. When the disk is placed on the soil, the water is pulled through the disk due to capillarity, thereby infiltrating the soil. The inner steel tube allows air to escape from the lower compartment into the upper compartment in a bubble, which then escapes from the top of the MDI through the other steel tube. The time until infiltration (bubbles rise into the tube) and the amount of infiltration over time are recorded (Glenn and Finley, 2010). Prior to MDI placement, the litter, small branches, residues and coarse mineral particles were carefully removed from the soil surface. In cases in which the measured area was irregular, a thin layer of fine silica was applied to the soil surface (Gordillo-Rivero et al., 2013). Infiltration was performed with a negative pressure head $h0 = -2$ cm with the MDI, and the water volume was manually recorded at 1 min until steady state conditions were reached. Each sample piece was only used for one measurement. Three replicates were performed at the fixed pressure head. The infiltration rate was calculated from a graph of the cumulative infiltration as a function of the square root of time, where the slope represented the infiltration rate (i, cm s^{-1}).

The correlations between the infiltration rate, the vegetative features and the soil parameters were determined using Pearson's correlation analysis. A linear stepwise regression was used to determine the relationships. The statistical analyses were performed using the SPSS 13.0 (SPSS Inc., Chicago, IL, USA) and Origin 7.0 (OriginLab, Northampton, MA, USA) software.

3. Results

3.1. Changes in plant species richness, coverage herbaceous biomass and biological soil crust cover

The number of herbaceous species that were present increased linearly over time (Fig. 2(A)) and 10 species (such as *Stipa bungeana, Bothriochloa ischaemum, Pennisetum centrasiaticum, Lespedeza potaniniiv, Corispermum tylocarpum, Astragalus meliltoides, Thermopsis lanceolata, Leymus secalinus, Medicago sativa, Calamagrostis epigejos*) were identified as having been established since revegetation in 1995a on the northern refuse dump. In the initial stages, the increasing number of herbs was not obvious; however, over time the number of herbaceous species became significantly higher on the abandoned land and in the natural vegetation areas compared with the other refuse dumps. Among these, *Medicago sativa* and *Leymus secalinus* were the dominant annual species and mainly appeared on the abandoned land (2005a) and at the western refuse dump (2003a) as seen in Table 2. The perennial grass species, such as *Astragalus meliltoides, Thermopsis lanceolata, Pennisetum centrasiaticum, Bothriochloa ischaemum, Bothriochloa ischaemum, Corispermum tylocarpum, Artemisia giraldii, Calamagrostis epigejos* and *Setaria virirdis* mainly appeared in natural vegetation areas, and at the eastern (1998a) and northern (1995a) refuse dumps. However, the shrubs exhibited the opposite trend, the planted shrubs, such as *Tamarix chinensis, Caragana mirophylla, Hippophae rhamnoides, Artemisia arenaria* and *Armeniaca sibirica* grew rapidly and established themselves at the refuse dumps from the beginning. They reached a coverage of 33% over a period of 15 years at the eastern refuse dump (1998a), but the shrub cover then gradually decreased (Fig. 2(B)); only *Caragana mirophylla* or *Hippophae rhamnoides* remained in the eastern refuse dump (1998a) leveling off at a lower coverage of 4% (Fig. 2(B)). No new woody species were found to have germinated and established naturally in the revegetation areas after the 18-year succession period. In the revegetation areas, a linear increasing tendency of coverage and biomass of herbaceous species was found over time. Furthermore, the biomass of the naturally established species increased from 0.15 kg m^{-2} in the 8-year-old vegetation to 0.64 kg m^{-2} in the 18-year-old vegetation (Fig. 2(C)). With vegetation succession, the biological soil crusts (BSCs), such as the cyanobacteria, green algae, lichens, mosses and other organisms that are closely integrated with particles of the surface soil, gradually formed and developed with an apparent increase in coverage during the initial stage from 41% on the abounded land (2005a) to 70% at the eastern refuse dump (1998a); however, at the northern refuse dump (1995a) and in the natural vegetation areas, the mean coverage of BSCs was less than 30% (Fig. 2(D)).

3.2. Changes in the soil texture, nutrients, bulk density and infiltration rate

Fig. 3 indicate that the soil properties changed markedly after the establishment of plants on refuse dumps. With an increase in the revegetated age the percentage of silt and clay particles in the soil significantly increased, the content of the coarse sand particles decreased and tended to gradually change into the soil texture of the natural vegetation zone (Fig. 3(A)). And the difference of soil texture at each refuse dumps was significant ($P < 0.05$). The total contents of SOM, N, P and K in the sand also increased with vegetation succession; in particular, the increase in the SOM was more significant ($P < 0.05$) (Fig. 3(B)). However the soil nutrient content in the revegetated refuse dumps was still low as compared with the natural vegetation district. Due to the soil structure being destroyed, the soil bulk density at different layers was analyzed. Fig. 4(A) illustrates the soil bulk density at different layers that decreased with increasing revegetated ages, but the rate of decrease was lower than that obtained for the above-mentioned characteristics of plant species. For instance, the average soil bulk density decreased from 1.56 in 8-year-old vegetation on the abounded land (2005a) to 1.24 for 18-year-old vegetation at the northern refuse dump (1995a). The variation in the soil bulk density between the different soil layers became smaller with vegetation succession (Fig. 4(A)), and the recovery was more rapid in the early stages than in the later stages, although it almost reached the level of the natural vegetation site. A plot of the cumulative infiltration from the mini disc infiltrometer is shown in Fig. 4(B). The natural vegetation community and the northern refuse dump (1995a) had the highest cumulative infiltration rates of 3.96 and 2.89 cm s^{-1} when compared with the eastern (1998a) and western (2003a) refuse dumps and the abandoned land (2005a), where the highest infiltration rates were 1.26, 1.04 and 0.88 cm s^{-1}, respectively. The infiltration rates on the abandoned land, the western, eastern and northern refuse dumps and the natural vegetation community were 0.004, 0.007, 0.012, 0.015 and 0.023 cm s^{-1}, respectively.

3.3. Correlation between the infiltration rate and the plant features and soil parameters

A correlation analysis (Table S1, see Appendix A) indicated that the infiltration rate was significantly positively correlated with the silt %, SOM, N, K, herbaceous cover and herbaceous biomass at a 0.01 level, but was only weakly correlated with the other soil parameters, including the clay %, P and herbaceous richness. Conversely, the infiltration rate was highly negatively correlated with the sand % and other parameters, such as the variation in the soil bulk density, shrub richness, shrub coverage and BSCs coverage. The variation in the soil bulk density was mainly affected by the shrub and herbaceous

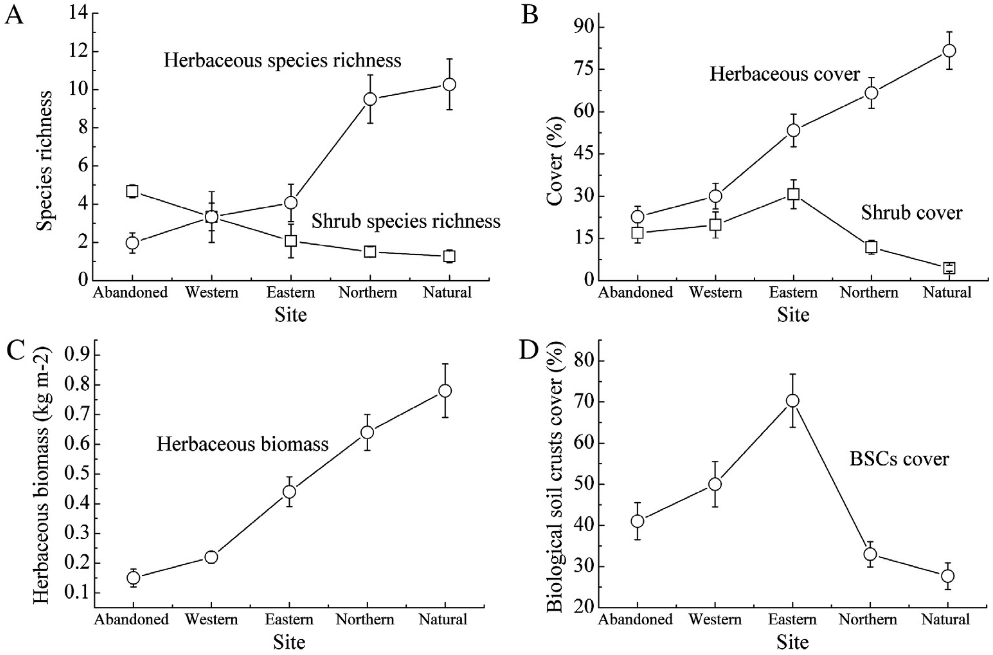

Fig. 2. Changes in the species richness (A), coverage (shrub and herb) (B), herbaceous biomass (mean) (C) and biological soil crust cover (D) after revegetation at the different sites.

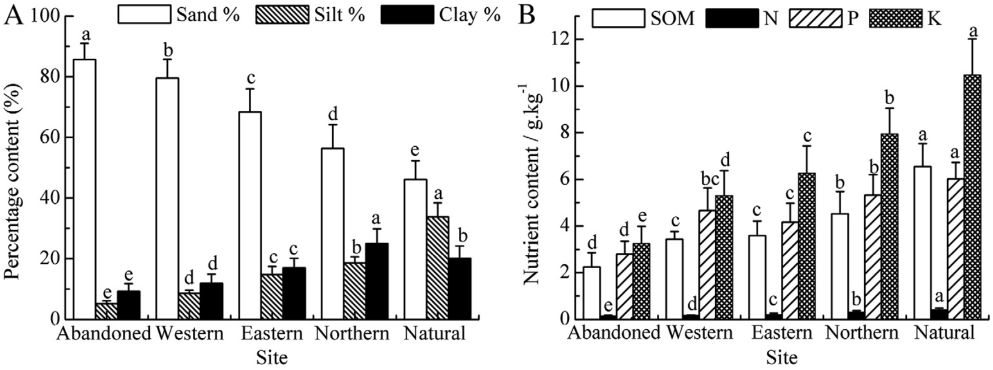

Fig. 3. Changes in the soil texture (A) and soil nutrients (B) at the different vegetative sites.

Table 2
Remaining plant species and its coverage with different refuge dumps and a natural community located in the Heidaigou opencast coal mine.

Site	Remaining plant species of revegetation		Coverage
Abandoned	Shrub	*Tamarix chinensis, Caragana mirophylla, Hippophae rhamnoides, Artemisia arenaria, Armeniaca sibirica*	16.3%
	Grass	*Medicago sativa, Leymus secalinus*	20.5%
Western	Shrub	*Armeniaca sibirica, Hippophae rhamnoides, Caragana mirophylla*	18.7%
	Grass	*Medicago sativa, Leymus secalinus, Astragalus meliltoides*	30.2%
Eastern	Shrub	*Armeniaca sibirica, Caragana mirophylla*	25.4%
	Grass	*Medicago sativa, Leymus secalinus, Astragalus meliltoides, Thermopsis lanceolata*	50.2%
Northern	Shrub	*Caragana mirophylla*	12.4%
	Grass	*Medicago sativa, Leymus secalinus, Astragalus meliltoides, Thermopsis lanceolata, Pennisetum centrasiaticum, Bothriochloa ischaemum, Bothriochloa ischaemum, Corispermum tylocarpum, Artemisia giraldii*	63.5%
Natural	Shrub	*Caragana mirophylla*	4.8%
	Grass	*Medicago sativa, Leymus secalinus, Astragalus meliltoides, Thermopsis lanceolata, Pennisetum centrasiaticum, Bothriochloa ischaemum, Bothriochloa ischaemum, Corispermum tylocarpum, Artemisia giraldii, Calamagrostis epigejos, Setaria virirdis*	80.5%

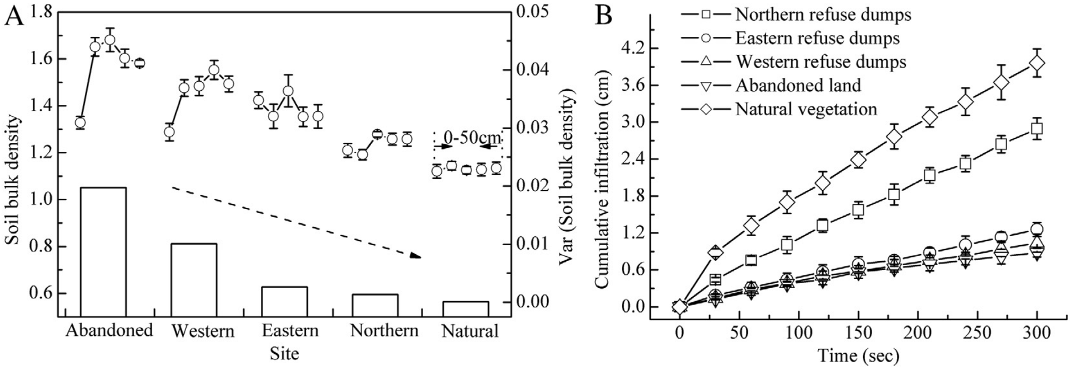

Fig. 4. Changes in the soil bulk density and its variations (A), cumulative infiltration measured with mini-disc infiltrometers (B) at the different vegetative sites.

species richness, and the cover in the plant communities corresponded highly to the proportion of changes in the habitat soil parameters. For the shrub species, the richness and cover were significantly positively correlated with the sand and the variation in the soil bulk silt ($P < 0.05$), but were negatively correlated with the silt, clay and other soil nutrients, such as the SOM, N and P ($P < 0.05$). Similar to the shrub species, there were highly positive relationships between the herbaceous richness, the cover and parameters such as the clay, silt, SOM, N and P content ($P < 0.05$). However, there are significantly negative relationships between the shrub and herbaceous species richness and the cover extent ($P < 0.05$), which indicates that the two communities cannot coexist over a long period of time unless both remain at a relatively stable level of coverage. Changes in the soil texture and soil nutrients were mainly related to the herbaceous species richness, coverage and biomass. Along with vegetation succession, the relationship between the soil texture and soil nutrients also increases. The BSCs coverage was significantly positively correlated with the shrub cover ($P < 0.01$), which indicates that the BSCs would decrease with vegetation succession along with the degeneration of shrubs at the refuse dumps.

Multiple linear regressions of the infiltration rate, the plant features and the soil parameters were programmed using a stepwise regression method, and the optical regression model is shown in the following equation:

$$\text{Infiltration} = 0.007 + 0.003\text{Silt} + 0.002\text{SOM} + 0.008\text{HC} - 0.011\text{Var} - 0.004\text{SC} \qquad R^2 = 0.998$$

where HC indicates the herbaceous coverage, Var indicates the variation in soil bulk density, and SC indicates the shrub coverage.

This equation indicated that the infiltration rate was mainly determined by the silt %, SOM, plant coverage and the variations in the soil bulk density.

4. Discussion

In the refuse dumps at the Heidaigou opencast coal mine, the original land surface morphology and soil structure were directly damaged by coal mining activities; therefore, a series of ecological engineering projects, such as revegetation or agricultural reclamation have been undertaken in the area (Singh et al., 2002; Fan and Wang, 2009; Zhang et al., 2015). In the early vegetation successional stage, such as on abounded land, there were many annual herbaceous species; due to their adaptability to the harsh environmental conditions of bare land surface and barren soils, these species sprang up quickly and the ground was almost completely covered during the rainy season (Brown et al., 1997; Gutie'rrez et al., 1997). The soil properties at this time mainly reflected a poor soil quality, high sand content and low silt, clay and soil organic matter content and low nitrogen and phosphorus levels. Furthermore, the difference in the soil bulk density between the upper and lower soil layers was obvious (Chang et al., 2011). After a short intense period of competition, such as at the western (2003a) and eastern (1998a) refuse dumps, some of the originally planted shrubs degenerated and perennial herb communities became a major part of the vegetation community; in addition, patchy black biological soil crusts appeared on the soil surface, and this change was accompanied by an increased soil organic matter content, nitrogen and phosphorus, mainly due to the large amount of litter from shrubs, which accumulated approximately 2–4 cm below the shrubs and created favorable conditions for the multiplication and growth of herbaceous plants; the soil quality also improved due to the herbaceous plants because these provided the material inputs of twigs, leaves and dead roots. Furthermore, these plants provided a good habitat for soil microbes, which formed a nourishing cycle between the soil and plants, allowing the revegetated ecosystem to finally succeed into natural vegetation ecosystems (Pickett et al., 2001; Fan et al., 2003; Wang et al., 2014). In particular, at the northern (1995a) refuse dump, the plant features reached almost the same levels as in the natural vegetation site after 18 years of succession.

The soil recovery occurred much slower than the plant recovery. This recovery feature has also been confirmed by other researchers (Sparling et al., 2003; Li et al., 2007). Recovery of topsoil characteristics through establishing sand-binding vegetation in a sand-burial environment in the Tengger Desert was estimated to take between 23 and 245 years. Amongst soil characteristics, recoveries of clay content, topsoil water content, depth of soil and crust, and total salt content need between 70 and 245 years to reach the level of the native desert steppe (Li et al., 2007). The composition of the original soil texture was altered after revegetation mainly due to the large amounts of dead leaves and litter from shrubs that were deposited onto the dump surfaces. The results of this study indicate that a continuous increase in the silt and clay content of surface soils occurs over time during revegetation. Increasing the amount of fine-sized particles in the soil results in improved soil nutrient concentrations, which are more beneficial to herbaceous plants than to deeply rooted shrubs (Li et al., 2004, 2007). A number of studies from arid regions worldwide suggest that the colonization of herbaceous species is positively correlated with soil silt and clay content (Danin et al., 1989; Dodd et al., 2002). Finer-textured soils would enrich the surface with nutrients (Drees, 1993). With the increase in revegetation age the total contents of N, P and K also significantly increased. SOM in the 0–50 cm layer of refuse dumps increased from 2.25 g kg^{-1} at the beginning to about 4.52 g kg^{-1} after 10 years vegetation. N, P, K have increased from 0.15, 2.79, 3.23 g kg^{-1} to 0.29, 5.31 and 7.93 g kg^{-1}, respectively. Although the increase in the topsoil SOM observed in our study occurred slowly, it played an important role in plant colonization and establishment because it acted as a reservoir for essential elements, particularly N and P. The SOM is also considered a source of cation exchange capacity and to enhance soil porosity, improving the infiltration rate of the soil (Bohn et al., 2001). Our stepwise regression analyses support this conclusion. Therefore, improvement to the physicochemical properties of the soil during the 18-year study period created a favorable environment for the germination and establishment of grasses. Biological soil crusts, which are associated with soils that have a higher concentration of finer material at the surface, alter the spatial and temporal distribution of infiltration, rainfall interception at the surface, and the inhibition of water infiltration into deeper soil layers (Li et al., 2000, 2003). This leads to a decline in the deep-rooted shrubs; therefore, shrubs are gradually replaced by annual and perennial herbaceous species over time. The BSCs coverage first increased to its maximum under shrub cover but then decreased 8 years after revegetation at the refuse dumps. This was mainly because shrub coverage can reduce the wind speed near the ground, making the soil surface more stable and conducive to the deposition of minerals and organic matter in the atmosphere. Furthermore, the temperature at the soil surface reduced, and the soil moisture improved; these external environmental conditions prompted the colonization and development of BSCs (Zhao et al., 2009). However, at later revegetation ages, such as on the northern refuse dump, the BSCs cover began to decline because of the low shrub cover, the large number of herb species and the raindrop splash influence (Zhao et al., 2014). This conclusion is a little different from the results of ecological restoration in the Shapotou region, where the BSCs cover continued increasing (Li et al., 2004); the main reason for this was the higher rainfall of 426 mm in our study area, compared with the mean annual rainfall of only 186 mm in the Shapotou region. However, the measured plant and other soil parameters were strongly related to the site age, suggesting that a revegetation approach is effective for enhancing ecosystem recovery after soil destruction at the refuse dumps of open cast coal mines.

Infiltration rates are significantly affected by a number of structural, physicochemical, and environmental factors, such as the soil type, vegetation cover, initial soil humidity conditions, soil compaction, etc. (Lewis et al., 2006; Mehta et al., 2008). In this study, water infiltration was strongly dependent on the soil structure; therefore, the poor soil structure was substantially related to the limitation of water infiltration. In general, the infiltration rates markedly reduced with increases in soil bulk density (Abdelmagid et al., 1987). However, for restructured soils, the relationship between the two was complicated, as seen in Fig. 4, thus, we introduced a new variable, namely soil bulk density variation, which represents the degree of soil reorganization. As overburden refuse dumps involves a downward and outward movement of the entire mass of soil. Usually, the bedrock is formed of medium to course grained sandstone clay with ferruginous bands and carbonaceous shales. The soil surface layer is 20 cm thick cultivated loessial soils to very pale brown sandy loam to clay loam with subangular blocky structure. Coal gangue and clay content are found in sub soil. The overburden consists of alluvium loose sand, gravel, shale and sandstone. This soil structure variation would lead to the variation of soil bulk density, both of which connect and also influence each other closely. This variable decreased with vegetation succession mainly due to the hydrologic, chemical, and geo-morphic conditions of the material in the refuse dumps had been developed over time, soil texture and structure becomes more uniform after revegetation. In the natural vegetation community, the layered soil structure was not obvious and the infiltration rate reached its maximum. In addition to the variation in the soil bulk density, the decreasing shrub cover and increasing SOM all increased the soil infiltration rate, particularly in the natural vegetation community with large herbaceous species that produced substantial soil structure and high biological activity, thereby enhancing the soil water infiltration rates (Li et al., 2007). Furthermore, the infiltration rate as taken into account as a major integrated evaluation index of the soil and vegetation ecosystem recovery; the difference in the infiltration rate between the four refuse dumps was not significant, but all of these remained low compared with that obtained in the natural vegetation site. Therefore, we can conclude that, although the recovery of plant features such as species richness, cover and biomass almost reached the level of the natural vegetation communities, a full recovery still requires a long process.

5. Conclusions

On the refuse dumps at the Heidaigou opencast coal mine, changes in the plant species and soil physicochemical properties and their relationship with infiltration rates were examined on different-aged sites using a "space for time" substitution approach. The recovery of the number of herbaceous species, cover, biomass, fine particles, total N, P and SOM increased significantly with increasing revegetation age. However, the number of shrub species decreased and its cover increased initially, but then decreased to a low level. The natural vegetation community and the northern (1995a) refuse dump had the highest cumulative infiltration rate of 3.96 and 2.89 cm s^{-1}, compared with the eastern (1998a) and western (2003a) refuse dumps and the abandoned land (2005a) where the highest cumulative infiltration rate were 1.26, 1.04 and 0.88 cm s^{-1}, respectively. Furthermore, a multiple linear regression analysis indicated that the infiltration rate was mainly determined by the silt %, SOM, plant cover and variation in the soil bulk density. These findings indicate that the vegetation succession and soil infiltration characteristics are positive correlated to the site age, suggesting that a revegetation approach is effective for enhancing ecosystem recovery after soil destruction in refuse dumps at opencast coal mines but that full recovery requires a long process.

Acknowledgments

This work was supported by the CAS Action-plan for Western Development (KZCX2-XB3-13-03), the National Key Basic Research program (2013CB429905) and Chinese National Natural Scientific Foundation (41201084; 31170385).

Appendix A. Supplementary data

Supplementary material related to this article can be found online at http://dx.doi.org/10.1016/j.gecco.2015.07.006.

References

Abdelmagid, A.H., Schuman, G.E., Hart, R.H., 1987. Soil bulk-density and water infiltration as affected by grazing systems. J. Range Manag. 40, 307–309.
Adibee, N., Osanloo, M., Rahmanpour, M., 2013. Adverse effects of coal mine waste dumps on the environment and their management. Environ. Earth Sci. 70, 1581–1592.
Bohn, H.L., McNeal, B.L., O'Connor, G.A., 2001. Soil Chemistry, third ed. Wiley, New York, pp. 155–171.
Bradshaw, A., 1997. Restoration of mined lands—using natural processes. Ecol. Eng. 8, 255–269.
Brown, J.H., Valone, T.J., Curtin, C.G., 1997. Reorganization of an arid ecosystem in response to recent climate change. Proc. Natl. Acad. Sci. USA 94, 9729–9733.
Chang, J., Wang, J.T., Liu, Y., 2011. Land reclamation research in Heidaigou coal mining area. Shandong Coal Sci. Technol. 3, 94–95.
Danin, A., Bar-Or, Y., Dor, I., Yisraeli, T., 1989. The role of cyanobacteria in stabilization of sand dunes in southern Israel. Ecol. Mediterr. 15, 55–64.
de Paula, M.D., Groeneveld, J., Huth, A., 2015. Tropical forest degradation and recovery in fragmented landscapes-Simulating changes in tree community, forest hydrology and carbon balance. Glob. Ecol. Conserv. 3, 664–677.
Dodd, M.B., Lauenroth, W.K., Burke, I.C., Chapman, P.L., 2002. Association between vegetation patterns and soil texture in the shortgrass steppe. Plant Ecol. 158, 127–137.
Drees, L.R., 1993. Characteristics of aeolian dusts in Niger, West Africa. Geoderma 59, 213–233.
Fan, Y.H., Lu, Z.H., Cheng, J.L., Zhou, Z.X., Wu, G., 2003. Major ecological and environmental problems and the ecological reconstruction technologies of the coal mining areas in China. Acta Ecol. Sin. 23 (10), 2144–2152.
Fan, J.F., Wang, X.L., 2009. Application of waste mushroom on land reclamation in the refuse dump of Haizhou Open-pit Mines. J. Coal Sci. Eng. 15 (1), 72–75.
Glenn, N.F., Finley, C.D., 2010. Fire and vegetation type effects on soil hydrophobicity and infiltration in sagebrush-steppe: I. Field analysis. J. Arid Environ. 74, 653–659.
Gordillo-Rivero, A.J., García-Moreno, J., Jordán, A., Zavala, L.M., Granja-Martins, F.M., 2013. Fire severity and surface rock fragments cause patchy distribution of soil water repellency and infiltration rates after burning. Hydro. Process. http://dx.doi.org/10.1002/hyp.10072.
Gutie'rrez, J.R., Meserve, P.L., Herrera, S., Contreras, L.C., Jaksic, F.M., 1997. Effects of small mammals and vertebrate predators on vegetation in the Chilean semiarid zone. Oecologia 109, 398–406.
Henry, F.H., 2014. Diversity storage: Implications for tropical conservation and restoration. Glob. Ecol. Conserv. 2, 349–358.
Huang, D., Liu, Q.S., 2013. Remote sensing monitoring and effect evaluation on ecological restoration of heidaigou coal mining area. In: International Conference on Remote Sensing, Environment and Transportation Engineering, RSETE 2013. http://dx.doi.org/10.2991/rsete.2013.40.
Kainthola, A., Verma, D., Gupte, S.S., Singh, T.N., 2011. A coal mine dump stability analysis—a case study. Geomaterials 1, 1–13.
Lam, P., 2005. Energy in China: Development and prospects. China Perspect. 59, 14–25.
Lewis, S.A., Wu, J.Q., Robichaud, P.R., 2006. Assessing burn severity and comparing soil water repellency, Hayman Fire, Colorado. Hydro. Process. 20, 1–16.
Li, X.R., Kong, D.S., Tan, H.J., Wang, X.P., 2007. Changes in soil and vegetation following stabilization of dunes in the southeastern fringe of the Tengger Desert, China. Plant Soil 300, 221–231.
Li, X.R., Xiao, H.L., Zhang, J.G., Wang, X.P., 2004. Long-term ecosystem effects of sand-binding vegetation in the Tengger Desert, Northern China. Restor. Ecol. 12, 376–290.
Li, X.R., Zhang, J.G., Wang, X.P., Liu, L.C., 2000. Study on soil microbiotic crust and its influences on sand-fixing vegetation in arid desert region. Acta Bot. Sin. 42, 965–970.
Li, X.R., Zhou, H.Y., Wang, X.P., Zhu, Y.G., O'Conner, P.J., 2003. The effects of re-vegetation on cryptogam species diversity in Tengger Desert, Northern China. Plant Soil 251, 237–245.
Liu, G.S., 1996. Soil Physical and Chemical Analysis and Description of Soil Profiles. Chinese Standard Press, Beijing.
Liu, Z.B., Fan, J.F., 2002. The application of the ecological succession principle on the land reclaimation In the open coal mines. Opencast Min. Technol. 5, 27–30.
Ma, J.J., Li, Q.F., Zhang, S.L., 2007. The correlation among soil microorganism and soil nutrient in different types of mixed stands of *Hippophae Rhamnoides*. J. Arid Land Resour. Environ. 21 (6), 163–167.
Mehta, V.K., Sullivan, P.J., Walter, T.M., Krishnaswamy, J., DeGloria, S.D., 2008. Impacts of disturbance on soil properties in a dry tropical forest in Southern India. Ecohydrology 1 (2), 161–175.
Nelson, D.W., Sommers, L.E., 1975. A rapid and accurate method for estimating organic carbon in soil. Proc. Indian Acad. Sci. 84, 456–462.
Pickett, S.T.A., Cadenasso, M.L., Bartha, S., 2001. Implications from the Buell–Small succession study for vegetation restoration. Appl. Veg. Sci. 4, 41–52.
Powlson, D.S., Smith, P., Coleman, K., Smith, J.U., Glendining, M.J., Korschens, M., Franko, U., 1998. A European network of long-term sites for studies on soil organic matter. Soil Tillage Res. 47, 263–274.
Radeloff, V.R., Mladenoff, D.J., Boyce, M.S., 2000. A historical perspective and future outlook on landscape scale restoration in the Northwest Wisconsin Pine Barrens. Restor. Ecol. 8, 119–126.
Singh, A.N., Raghubanshi, A.S., Singh, J.S., 2002. Plantations as a tool for mine spoil restoration. Curr. Sci. 82, 1436–1441.
Sparling, G., Ross, D., Trustrum, N., Arnold, G., West, A., Speir, T., Schipper, L., 2003. Recovery of topsoil characteristics after landslide erosion in dry hill country of New Zealand, and a test of the space-for-time hypothesis. Soil Biol. Biochem. 35, 1575–1586.
Wang, J.M., Jiao, Z.Z., Bai, Z.K., 2014. Changes in carbon sink value based on RS and GIS in the Heidaigou opencast coal mine. Environ. Earth Sci. 71, 863–871.
Wang, Y., Wang, L., Shao, H.B., 2013. Ecological footprint analysis applied to a coal-consumption county in China. Clean-Soil Air Water 41, 1–10.

Wei, X.R., Huang, M.B., Shao, M.A., Li, L.H., Zhang, X.C., Horton, R., 2013. Shrubs increase soil resources heterogeneity along semiarid grass slopes in the Loess Plateau. J. Arid Environ. 88, 175–183.

Zhang, L., Wang, J.M., Bai, Z.K., Lv, C.J., 2015. Effects of vegetation on runoff and soil erosion on reclaimed land in an opencast coal-mine dump in a loess area. CATENA 128, 44–53.

Zhao, H.L., Guo, Y.R., Zhou, R.L., Zhao, X.Y., 2009. Effects of vegetation cover on physical and chemical properties of bio-crust and under-layer soil in Horqin Sand Land. Chinese J. Appl. Ecol. 20 (7), 1657–1663.

Zhao, Y., Zhang, P., Hu, Y.G., Huang, L., Hu, R., Liu, M.L., 2014. Effect of re-vegetation types on colonization and growth of biological soil crusts of dumping site in open pit coal mine of Heidaigou. Chinese J. Ecol. 33 (2), 269–275.