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Effects of vegetation on runoff and soil erosion on reclaimed land in an opencast coal-mine dump in a loess area

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ABSTRACT

Vegetation reconstruction on opencast coal-mine dumps is an effective way to reduce runoff and soil erosion and is a key to restoring ecosystems in ecologically sensitive regions. To investigate the effects of vegetation on runoff and erosion, a field experiment involving eight erosion plots was conducted on a dump at the Antaibao opencast coal mine in, Shanxi Province. The plots were divided into two location groups, platforms and slopes. Each plot was planted with a typical vegetation pattern. The volumes of runoff and soil erosion during each rainfall event were recorded during the rainy season. The results showed that plots on the platforms experienced a larger volume of runoff than plots on the slopes, while the slope plots generated a larger value of soil erosion than the platform plots. Vegetation restoration has different impacts on runoff and soil erosion. A plot covered with 1-year-old *Robinia pseudoacacia* and *Hippophae rhamnoides* was most effective in terms of soil conservation; the plots covered with 5-year-old mixed legume plants and 5-year-old mixed grass-shrub-arbor forest were most effective overall in preventing both runoff and soil erosion. Over the long term, vegetation can increase soil organic matter, improve soil physical properties and soil anti-erodibility, and reduce runoff and erosion to a safe level. This study provides a theoretical basis and technical support for land reclamation and soil and water conservation in vulnerable ecological mining regions of a loess plateau.

1. Introduction

As one of the most important mainstay industries in the energy source market, opencast coal mines are primarily located in the vulnerable environments of northwestern China, such as Shanxi Province, Inner Mongolia, Gansu Province, Ningxia Province and Shaanxi Province. As the climates of these regions become warmer and more dry, the regions suffer greater soil and water losses, thus threatening local terrestrial ecosystems (Sun et al., 2013; Wang et al., 2013b). With the incentive of rapid economic development, extensive areas of mining are emerging in these regions. Opencast mining is an efficient and cost-effective mode for the exploitation of mineral resources. However, this modern mining technology can have a large impact on the surrounding landscape by eliminating vegetation and permanently altering topography, soils and subsurface geological structures, resulting in accelerated runoff and soil erosion compared with the local mean for natural surfaces (Zhao et al., 2013; Wang et al., 2014b). Waste dumps constitute the land most damaged by opencast mining. Runoff causes soil erosion, a selective process that sweeps away fine materials, and nutrients, from sloped lands, strongly impacting on the long-term development of waste dumps (Polyakov and Lal, 2004). The magnitude of erosion is highly dependent on rainfall characteristics, surface properties and topographic features (Puigdefabregas et al., 1999). As a result, land used for waste dumps becomes less fertile and more depleted in nutrients over time. Runoff and soil erosion hinder vegetative restoration in dumps, further inducing runoff and soil erosion and leading to a more severe threat to the stability of local ecosystems and economic development (Evans et al., 2004; Biemelt et al., 2005). It therefore follows that vegetation restoration is necessary for waste dump reclamation, ecological restoration and the long-term stability of engineered post-mining landforms (Miao and Marrs, 2000; Sever and Makineci, 2009; Bao et al., 2012; Drazic et al., 2012).

Many researchers have analyzed the effects of various types of vegetation on soil and water conservation, and the different ways vegetation can constrain soil loss and improve environmental conditions (Bochet et al., 1999). It has been found that vegetation structure (canopy cover, sapling density, litter depth, and woody debris) may be a main factor influencing soil and water loss. Multiply stratified areas are more advantageous than mono-stratified areas in respect to soil and water conservation (Casermeiro et al., 2004), and natural forests are superior to plantations for their diversities in structure and species. Pure trees

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(e.g., *Pinus massoniana* Lamb, without any grass and shrub under the canopy) show a positive effect of trees on soil and water conservation, accounting for approximately 70% and 55% of the total effect (from 2007 to 2010), respectively, during rainfall events with relatively higher rainfall depths, stronger intensities and shorter durations, whereas negative effects occurred during rainfall events with lower rainfall depths, weaker intensities and longer durations (Cao et al., 2008; Gu et al., 2013). Vegetation fractional coverage (VFC) which means the percentage of vegetation vertical projection area covering a workshop area, is an important parameter for reflecting community structure and was typically reported to be negatively correlated with soil and water loss (Krummelbein et al., 2010; Zuo et al., 2010; Zhang et al., 2011). The type and significance of the relationships varied depending on the conditions in which soil and water loss occurred. The relationships may be obvious in surface areas that are homogenous in terms of their vegetative cover but not in larger and heterogeneous areas, where surface geology varies (Braud et al., 2001). There are complex interactions between plants and soil properties. Plants can improve soil properties, and soil properties will, in return, affect plants. Considered as one of the more important indicators of soil erosion, soil structure is closely related to the process of water and soil erosion through good physical properties (such as high water storage capacity, bulk density, and porosity) to increase water infiltration. In addition, organic carbon increases the formation of soil aggregates, which then reduce runoff and soil loss (Deuchars et al., 1999; Casermeiro et al., 2004). Soil with higher silt and soil organic matter content can increase soil infiltration and soil aggregates, resulting in good structural stability and leading to reduced runoff and erosion (Zheng et al., 2008; Wu et al., 2010). However, the soil organic matter content of loess on the study mining area is generally low and its texture alters slightly, so the variation of particle-size distribution among which silt and clay contents mainly determine the soil erodibility. Soil resistance to erosion gets enhanced with increasing clay content. With increasing silt content increasing, soils are more apt to undergo erosion (Zhang et al., 2001). According to the above authors, vegetation plays an important role in water and soil erosion control. Vegetation cover can reduce the kinetic energy of raindrops. Vegetation covered plots and the litter layer protect soil surfaces, increase soil surface roughness, impede overland flow and increase infiltrating time. Vegetation root development can improve soil physical properties (e.g., soil strength, shear strength, structural stability and aggregate stability), which are closely related to soil erodibility, resulting in a contribution to soil loss control (Gao et al., 2009). The majority of recent field experiments and rainfall simulations have mainly focused on natural landforms and disturbed farmlands (Calvo-Cases et al., 2003; Hartanto et al., 2003; Biemelt et al., 2005; Cao et al., 2008; Shi et al., 2010; El Kateb et al., 2013) and have revealed the mechanism of the influence of vegetation on runoff and soil erosion and provided methods for similar research on mining landscape remediation. While fewer studies have focused on mining reclamation land, Z. Miao outlined the principles and approaches to ecological restoration and land reclamation in open-cast mines on the Loess Plateau of China (Miao and Marrs, 2000). The most common, efficient and practical way to conserve water and soil is to use biological methods by creating a diverse vegetation as soon as possible (Miao and Marrs, 2000; Josa et al., 2012; Xu, 2012). As the only source of soil organic carbon in artificial reclaimed sites, restored plants affect soil-forming processes. Differences in plant type result in different organic matter and organic carbon content, which mainly trigger for the change in the physical structure, chemical properties and microbiological properties of soil. And long-term reclamation can bring direct positive effects upon soil conservation (Dragovich and Patterson, 1995; Fu et al., 2010; Williamson et al., 2011; Zhao et al., 2013). This study contributes to the understanding of runoff generation and soil loss from a dump in mining areas on the Loess Plateau of China. The specific objectives of this experiment were to compare the ratio of runoff and soil losses for different aspects (1) among different plant systems, (2) on different landforms between flat platforms and steep slopes, and (3) under various rainfall event types on the dump, and to explain the mechanism of the effects of vegetation on water and soil conservation as well as the long-term influence of vegetation on environmental conditions.

2. Materials and methods

2.1. Study area

The experimental plots are located at the South Dump of the Antaibao (ATB) opencast coal mine, with geographic coordinates of 112° 10′ 58″–113° 30′ E, 39° 37′ N (Fig. 1) in Pingshuo, Shanxi Province, which is the largest opencast coal mining area in China. This area has a typical temperate arid to semi-arid continental monsoon climate and a fragile ecological environment. The annual mean temperature range is 5.4 °C–13.8 °C, and the total annual precipitation averages 426.7 mm, with 75%–90% occurring during the rainy season (June–September). The average annual effective evaporation, however, is approximately 2160 mm, almost 5 times greater than the amount of precipitation (Li et al., 2013). The study area, located east of the Loess Plateau where there are the older landforms (Fig. 2a), was once primarily a landscape of forests and prairies, whereas now it is covered in loess soil. However, during the past 200 years, the primary vegetation has been damaged by long-term human disturbance and climate change, leading to chronic water and soil erosion.

The ATB opencast coal mine has an area of 376 km^2 and has been mined for over 30 years (1985–2007). The specific study area was located in the South Dump of the ATB mine. The South Dump was used from 1985 to 1989, and reclamation began here in 1992, making it one of the earliest reclamation areas of the ATB opencast coal mine. The dump has a stepped design with a maximum step height of 50 m, a main step gradient of 35%–40%, a platform width of 50 m and a final height of 100–140 m. Because it was formed by piling waste soil and rocks throughout the mining process, the dump is an artificial landform significantly different from the original topography (Fig. 2b, c, d). According to previous research and the long-term records of the Shanxi Province Hydrology Calculation Manual on sediment and discharge at Dongyulin and Luozhuang Hydrological Station during the rainy season, dumps without reclamation had soil erosion totaling 15,060 $t \cdot km^{-2} \cdot a^{-1}$, or a 33% greater erosion rate than the original Loess Plateau landform, which has a typical soil erosion rate of 10,120 $t \cdot km^{-2} \cdot a^{-1}$ (The Bureau of Shanxi Province, 2011). After approximately 10 years of re-vegetation measures, the soil erosion of a dump can be reduced to 3438 $t \cdot km^{-2} \cdot a^{-1}$, or 194% less than that of the original Loess Plateau landform (Lv et al., 2003).

2.2. Experiment design

With the acknowledgment of the significance of vegetation to water and soil conservation and ecological restoration in an opencast mine area of loess area, a field experiment was needed to evaluate and explain the effects of vegetation on water and soil conservation, following the dominant vegetation configuration patterns, slope gradients and soil bulk densities of the study area. In the process of piling waste soils and rocks, the platforms were rolled flat using large-scale machines, while the slopes were formed without rolling. Therefore, the platform is characterized by a high bulk density (the average value range is 1.5–1.9 $g \cdot cm^{-3}$, 0.2–0.84 $g \cdot cm^{-3}$ larger than the original landform) and a flat surface, and the slopes are composed of loose soils and rocks (bulk density range is 0.9–1.2 $g \cdot cm^{-3}$) with high gradients (Wei et al., 2001). Four plots were set up on the platform, and the additional four plots were located on the slopes. Soil on these plots is composed of loessial soil, and the soil is silt loam according to the FAO soil classification system (Wang et al., 2014a). The effects of vegetation on runoff and soil erosion were analyzed. The detailed conditions of the two groups of study plots are shown in Table 1. The vegetation configuration types

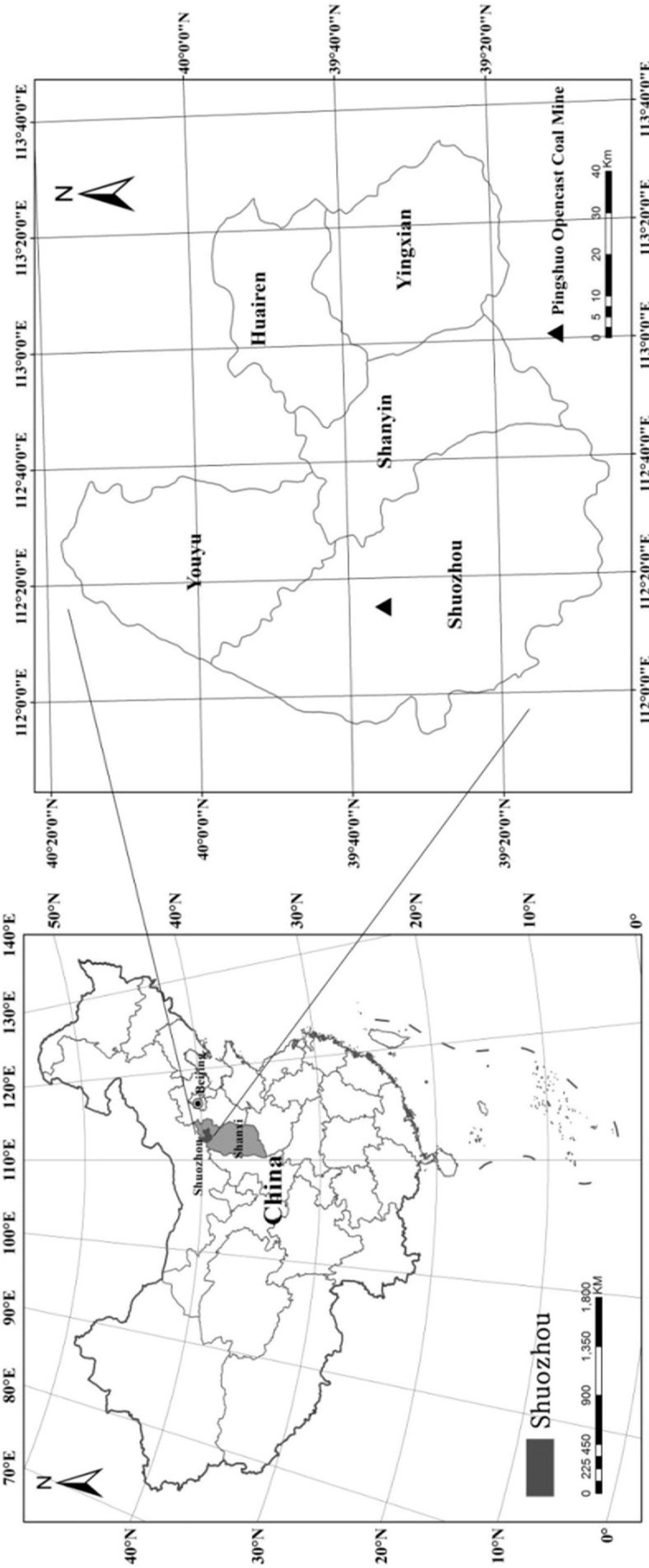

Fig. 1. The study area location.

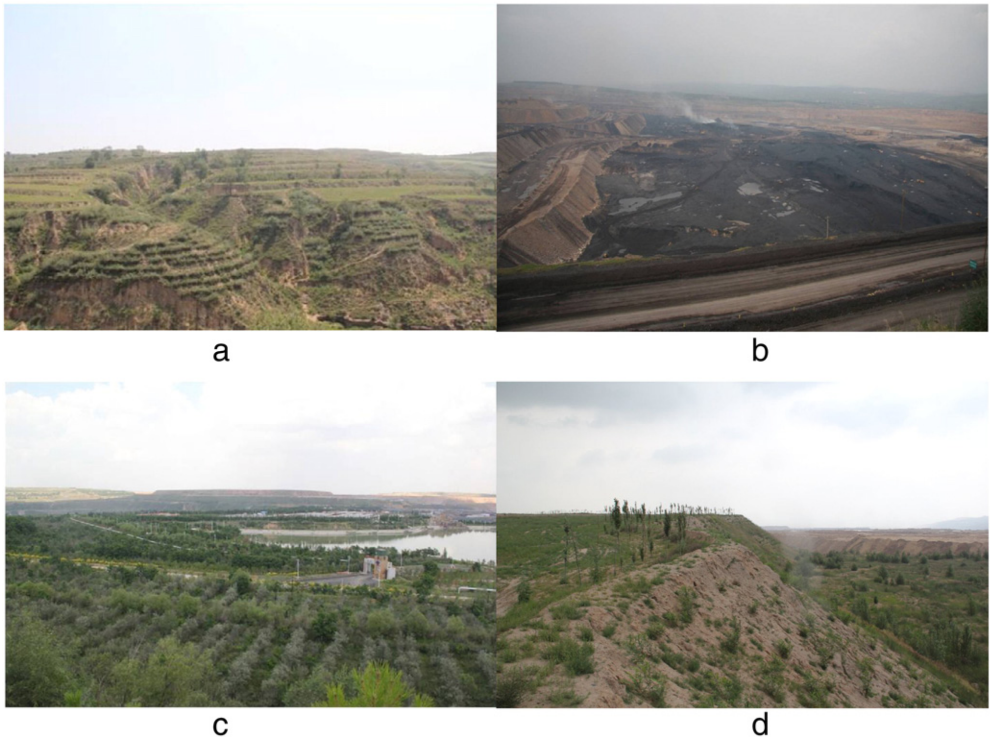

Fig. 2. Main types of geomorphologic landscapes in the ATB opencast mine area (a. The original landform of Pingshuo mine area; b. excavating surface of opencast mining; c. a distant view of the dumps: a dump with re-vegetation, closer; and a dump without any replanting measures started, in the distance; d. a close view of the dump, showing the details of the platform and slope.).

included artificial grass (*Astragalus adsurgens*, *Medicago sativa*, *Melilotus suaveolens*, *Onobrychis viciaefolia*), pure arbor forest (*Robinia pseudoacacia*), mixed arbor–shrub forest (*R. pseudoacacia* × *Hippophae rhamnoides*) and mixed arbor–shrub–grass forest (*R. pseudoacacia* × *Chinese pine* × *Astragalus adsurgens*/*Medicago sativa*/*Melilotus suaveolens*) (Wang et al., 2000; Guo et al., 2005). Vegetation coverage and slope gradients were measured at each runoff plot. The loose-heaped-ground method of soil reconstruction was used on plot 2 on the platform. It is an innovative technology for erosion control and soil reconstruction. On the top platform, loads of soil were heaped up by loosening instead of being rolled (Wei et al., 2001). This method can decrease the compaction of topsoil (in this study, soil bulk density of 1.4 $g \cdot cm^{-3}$ was used as the dividing line) to increase water infiltration while forming pits to accommodate and disperse rainstorm runoff, which creates conditions for fast vegetation recovery.

Each plot on the platform is approximately 100 m^2 in size (5 m in width and 20 m in length) and on the slope ranges from 200 m^2 to 270 m^2 (5 m in width and slope length in length) with length measured in the downhill direction. The plots were bordered with 35-cm-wide cement walls with 20 cm of the walls placed below the soil and 15 cm remaining above the soil surface. This design was used to prevent splashes from the surrounding areas entering the experimental plots and to ensure that the dimensions of the experimental plots were not altered by the wetting and drying of soils. The lowest part of each experimental plot was constructed with an exit (30 × 30 cm) connected to a cement reservoir (2 × 1.5 × 2 m)

Table 1
Description of the runoff plots.

Site	Layout	Gradient/(°)	Length/m	Width/m	Catchment area/m^2	Total runoff/mm	Total soil erosion /$kg \cdot m^{-2}$
Platform	1#	3°–5°	20	5	100	62.1	1.3
	2#	3–5°	20	5	100	102.2	1.8
	3#	3°–5°	20	5	100	126.7	2.5
	4#	3°–5°	20	5	100	10.7	0.5
Slope	5#	36°–40°	40	5	161.8	17.3	6.4
	6#	36°–40°	54	5	206.83	35.1	25.4
	7#	36°–40°	54	5	206.83	39.1	21.8
	8#	36°–40°	54	5	206.83	46.6	27.6

Site	Layout	Description
Platform	1#	1-year-old *Robinia pseudoacacia* × *Hippophae rhamnoides*; row spacing: 1 m × 1 m
	2#	No vegetation; soil bulk density < 1.4 $g \cdot cm^{-3}$
	3#	No vegetation; soil bulk density > 1.4 $g \cdot cm^{-3}$
	4#	5-year-old mixed legume plants (*Medicago sativa*, *Melilotus suaveolens*; *Onobrychis viciaefolia*); vegetation coverage was 95%
Slope	5#	5-year-old mixed grass-shrub-arbor forest (*Robinia pseudoacacia* × *Chinese pine* × *Astragalus adsurgens*/*Medicago sativa*/*Melilotus suaveolens*); vegetation coverage was 95%
	6#	2-year-old grass (*Astragalus adsurgens*, *Medicago sativa*, *Melilotus suaveolens*); vegetation coverage was 10%
	7#	1-year-old *Robinia pseudoacacia*; row spacing: 1.5 m × 2 m
	8#	No vegetation

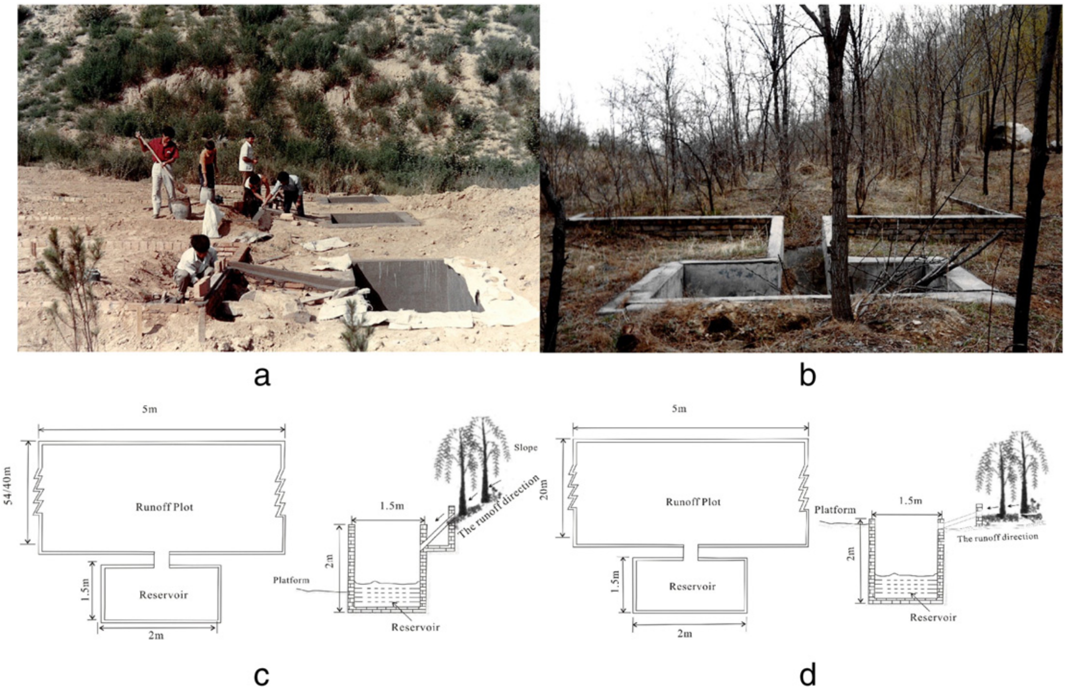

Fig. 3. Pictures for the setting of runoff plot. (a. The construction of field experiment; b. picture for Plot 1 with 1-year-old *Robinia pseudoacacia* × *Hippophae rhamnoides*, row spacing: 1 m × 1 m, which was taken after 6 years of the construction; c. a schematic drawing of plot setting on the platform; and d. a schematic drawing of plot setting in the slope, an upward view and a side view).

(Fig. 3). To minimize the disturbance of surface soil and vegetation, the plots were carefully installed 6 months in advance of the start of the study (Kang et al., 2001).

2.3. Data collection and analysis

A tipping-bucket rain gauge was installed in the study area to collect precipitation data after each rainfall event during the rainy season. In some rainfall events, the precipitation was not enough to generate measurable runoff in the plots, and the records were marked with "0". Therefore, soil loss and runoff discharge were only recorded after each "erosive rainfall." After each rainfall event, the reservoirs were checked. The runoff volume was determined using a measuring cylinder. After adequately mixing the eroded soils using a stick, sediment was collected from the bottom of each reservoir and stored in 8 bottles with a volume of 500 ml for further testing. After transport to the laboratory, the samples were dried in an oven at 105 °C and subsequently weighed to determine the sediment yield. After the collection of rain data and soil and water samples, the reservoirs were cleaned for the following rainfall event.

For a comparison of measurements, the response of plots under different events to water and soil erosion was analyzed with a chi-square test. To show the differences in effects of applying the soil conservation method and replanting vegetation on runoff conservation, a paired sample T-test was applied individually between plots 2 and 3 to analyze the effect of bulk density. Additionally, we compared plots 2 and 3 with 4 and with 1 and compared plot 8 with plots 5, 6 and 7 to analyze the effect of vegetation coverage, using SPSS 19 for Windows (SPSS, Chicago, IL, USA) (Puigdefabregas et al., 1999; Bhattarai et al., 2011; Wang et al., 2013a).

3. Results

3.1. Rainfall events

A total of 10 rainfall events were recorded during the rainy season (Fig. 4) with heavier rainfall events distributed in July, and the total precipitation was 331 mm. The precipitation events were classified into non-erosive and erosive events. Considering the influence of the initial soil moisture on water infiltration, the non-erosive events were subdivided into two categories: (1) events that occurred at the beginning of the rainy season (Jun 12–28), and (2) events that occurred in the middle and end of the rainy season (Jul 2–Aug 23). The erosive events were divided into four groups according to precipitation, rainfall intensity and rainfall duration: (1) low precipitation (≥13 mm and <24 mm); (2) high precipitation (≥24 mm and ≤39 mm); (3) a single event with very low rainfall intensity and long duration that occurred on Aug 21–23, with precipitation of 62 mm; and (4) a single rainstorm with the highest precipitation (>50 mm in 24 h) and a strong rainfall intensity.

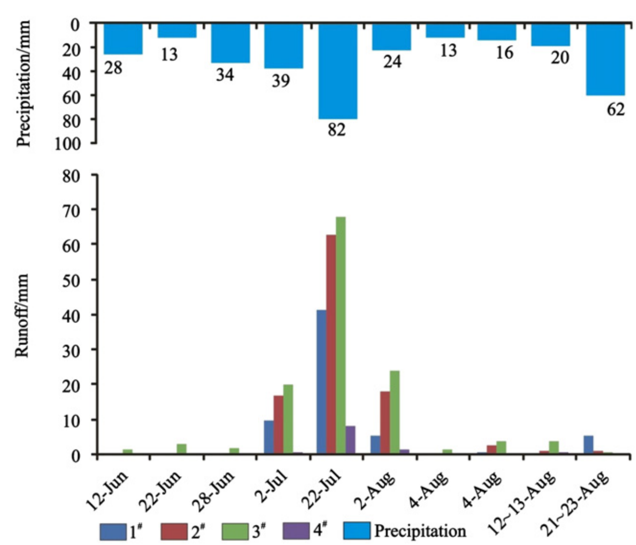

Fig. 4. The generalized differences in runoff response to rainfall events on the platform during the rainy season.

3.2. Runoff response

The generalized differences in runoff response to rainfall events between the platforms and the slopes are shown in Figs. 4 and 5. Because of the effects of initial soil moisture on runoff (Weiler and Naef, 2003; Tramblay et al., 2012), the event on Aug 2 with little precipitation produced a higher runoff than the heavier rainfall events on Jun 12 and Jun 28. High runoff typically coincided with heavy precipitation, and the variation was more obvious for the events after Jul 2. Due to the critical impact of rainfall intensity, the event on Aug 21–23 with a high amount of precipitation (62 mm) yielded a lower runoff than the events on Jul 2 (39 mm), Aug 2 (24 mm), Aug 4 (13 mm; 16 mm) and Aug 12–13 (20 mm). Significant differences under different vegetation patterns for the two plot location groups were comparatively analyzed for different events occurring on Jul 2 and Aug 13 (Table 2). The differences in runoff for the platform group were significant (sig < 0.05) for the precipitation events totalling 39 mm, 82 mm and 20 mm. In the slope group, the difference in runoff between the plots was significant only following the 82-mm precipitation event.

On the platforms, plot 1 (with 1-year-old *R. pseudoacacia* and *Hippophae*) and plot 4 (with 5-year-old mixed legume plants and a vegetation coverage of 95%) had lower runoff volumes than plots 2 and 3, which had bare land cover (Fig. 6). Plots 2 and 3 were both without vegetation but had different bulk densities. Plot 2 (with the loose-heaped-ground method of soil reconstruction) yielded a 19.4%-lower runoff volume, in comparison with plot 3 (without loose-heaped-ground method of soil reconstruction). Plot 4, with a total runoff volume of 10.7 mm, held an advantage over plot 1 in preventing runoff and yielded runoff that was 91.6% less than the runoff from plot 3. The similar variation seen in the platform plots was also found on the slope plots (Fig. 5). Under different vegetation conditions, the overland runoff coefficient was ranked as follows: 8 > 7 > 6 > 5. Plot 5 (5-year-old mixed grass-shrub-arbor forest and vegetation coverage of 95%) with a total runoff volume of 17.3 mm, yielded 62.9% less runoff than plot 8 with bare land. Significant differences (sig < 0.1) in the effects on runoff conservation between plots appeared in the pairs $1^{\#}$ vs $3^{\#}$, $2^{\#}$ vs $3^{\#}$, $3^{\#}$ vs $4^{\#}$ and $7^{\#}$ vs $8^{\#}$ (Table 3).

All other platform plots, except for plot 4, generally generated larger runoff volumes than those on the slopes, whether for the individual rainfall event or the total seasonal amount (Figs. 4–6). The bare platform plot 3 generated a total runoff volume of 126.7 mm, which was almost 3 times the volume of the bare slope plot 8. All of the rainfall events generated a total runoff of 301.6 mm on the platform and 138.1 mm on the slopes, contradicting the expectation that higher runoff accompanies higher gradients.

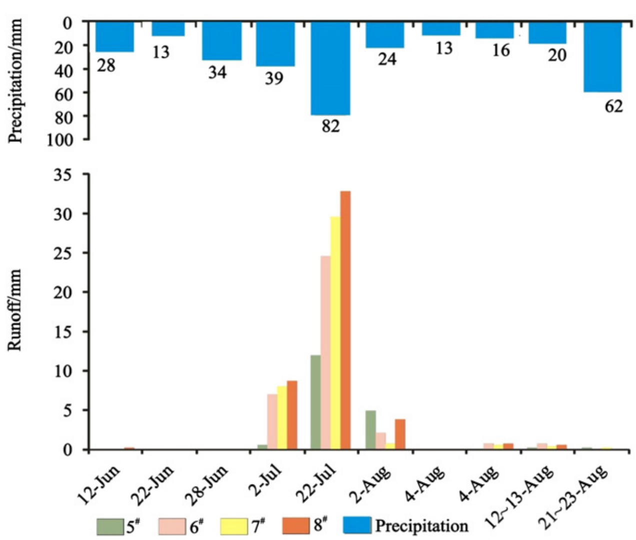

Fig. 5. The generalized differences in runoff response to rainfall events on the slope during the rainy season.

3.3. Soil erosion response

Sediment concentration in the plots increased linearly at the beginning of a given rainfall event especially in the events at the beginning of the rainy season (Jun 12–28), because it takes time for the soils to get wet. Based on the observation of a rainfall simulation conducted on this study area in 1993, sediment concentrations increased during the first 8–10 min of rainfall (Bai et al., 1998); after approximately 15 min, there was a relatively steady decrease in sediment concentration. Similar to what was observed in the runoff responses of the plots, the soil erosion volumes generated from all plots on Aug 21–23 were smaller than those generated by the events on Jul 2, Aug 2, Aug 4 and Aug 12–13 (Figs. 7 and 8), likely because of the increased rainfall intensity and duration of the earlier events. An analysis of the significant differences in soil erosion was conducted for the events occurring on Jul 2 and Aug 13. The difference in soil erosion among different plots under the precipitation amounts of 39 mm and 82 mm on the platform and the precipitation of 82 mm and 20 mm on the slopes reached statistical significance (sig < 0.05, Table 2).

A separate analysis of both platform and slope plots showed that higher runoff led to higher soil erosion, except in the case of plot 7 (Fig. 6). Plot 7 had a higher runoff volume (39.1 mm) than plot 6 (35 mm), yet it generated lower soil erosion (21.8 $kg \cdot m^{-2}$) than plot 6 (25.4 $kg \cdot m^{-2}$). Whether in the platform group or in the slope group, the soil losses from the plots with vegetation were much lower than the losses from bare land plots. Under different surface conditions, the soil erosions of platform plots were ranked 3 > 2 > 1 > 4. Plot 4 had a cumulative amount of soil erosion volume of 0.5 $kg \cdot m^{-2}$, which is 81.3% lower than the eroded soil collected from plot 3 (no reclamation). Plot 2, using the loose-heaped-ground method of soil reconstruction, had a lower soil erosion volume of 1.8 $kg \cdot m^{-2}$, a decrease of 27.9% compared with plot 3, which did not have the loose-heaped-ground method of soil reconstruction. For different runoff events, the slope plots had relatively high soil erosion volumes. The most serious soil erosion was found on the bare slope plot 8 (27.6 $kg \cdot m^{-2}$), with an eroded soil volume approximately 11 times that of the bare platform plot 3, though plot 8 had a lower runoff volume (Fig. 8). The soil erosion on the slope plots was ranked: 8 > 6 > 7 > 5. Plot 5 generated an amount of soil erosion in the amount of 6.4 $kg \cdot m^{-2}$, which was 76.9% lower than plot 8. Similarly, the pairs $1^{\#}$ vs $2^{\#}$, $1^{\#}$ vs $3^{\#}$, $2^{\#}$ vs $3^{\#}$, $3^{\#}$ vs $4^{\#}$ indicated significant differences (sig < 0.1) in effects on soil conservation from a paired sample T-test (Table 3).

3.4. Runoff and soil erosion generated by typical rainfall events

Fig. 9 shows different functions of plots with various vegetations under two types of rainfall events: the typical rainfall event with precipitation of approximately 39 mm and a rainstorm event with precipitation totalling 82 mm, which might occur once in a one hundred-year period in this area (Chen et al., 2003). The typical rainfall event recorded on Jul 2 induced typical runoff and soil erosion, while the highest precipitation recorded on Jul 22 generated the largest runoff and soil erosion of all of the erosive rainfall events. A clear relationship between vegetation patterns and both runoff and soil erosion was revealed. In the typical rainfall event, platform plot 1 (covered with 1-year-old *R. pseudoacacia* and *Hippophae*) yielded the highest runoff volume. Platform plot 4 (covered with 5-year-old mixed legume plants and having 95% vegetation coverage) and slope plot 5 (covered with 5-year-old mixed grass–shrub–arbor forest and having 95% vegetation coverage) produced very little runoff. None of the plots had significant soil losses; plots 4 and 5 generated very little soil erosion through all of the rainfall events. Plots 4 and 5 more effectively conserved soil than did plots 1, 6 and 7. In the large rainstorm event on Jul 22, all of the plots had a greater

Table 2
A significant difference analysis of runoff and soil erosion among all plots on platforms and slopes was tested under different events (sig < 0.05).

Location		Precipitation	Check value = 0.05 2-tail sig	Location		Precipitation	Check value = 0.05 2-tail sig
Platform 1#/2#/3#/4#	Runoff	P39	0.050	Slope 5#/6#/7#/8#	Runoff	P39	0.069
		P82	0.012			P82	0.045
		P24	0.053			P24	0.105
		P16	0.059			P13	0.391
		P20	0.049			P16	0.15
	Soil erosion	P39	0.029			P20	0.217
		P82	0.025		Soil erosion	P39	0.073
		P24	0.113			P82	0.037
		P13	0.400			P24	0.128
		P16	0.066			P16	0.115
		P20	0.075			P20	0.023

runoff volume than they did following the more typical rainfall event on Jul 2; the ranked order of runoff from all plots is as follows: 1 > 7 > 6 > 5 > 4. Platform plot 1 yielded the largest runoff amount of all of the experimental plots; however, it also had an outstanding function on soil conservation under the largest surface flow. Although plot 7 had a higher runoff volume than plot 6, it had less soil erosion.

4. Discussion

4.1. Function of vegetation on water conservation

The results showed that rainfall levels, dump construction, plot locations and vegetation all influenced runoff and soil erosion. There was significant diversity in the runoff and soil erosion of different situations. This study principally stressed the influence of different vegetation on water and soil erosion among other ecological factors, including canopy cover, litter depth, bulk density, vegetation roots and soil water content (Baumgartl et al., 1998; Hartanto et al., 2003; Lampurlanes and Cantero-Martinez, 2003).

The function of vegetation on water conservation is an ecological service mainly provided through canopy and litter layer interception and through water regulation by the redistribution of precipitation regulated by soil. Precipitation intercepted by vegetation is mostly returned to the atmosphere through evaporation, and water held by the litter layer and soil accounts for approximately 90% of the total precipitation (Tan, 2002). The functions of the litter layer and soil make soil the main body of water conservation. It relieves the competition for water among vegetation in this arid and semi-arid region. The litter layer is also effective in reducing the erosion of surface runoff.

Due to the techniques of dumping, soil porosity, bulk density and soil infiltration, the platform and slopes show significantly different

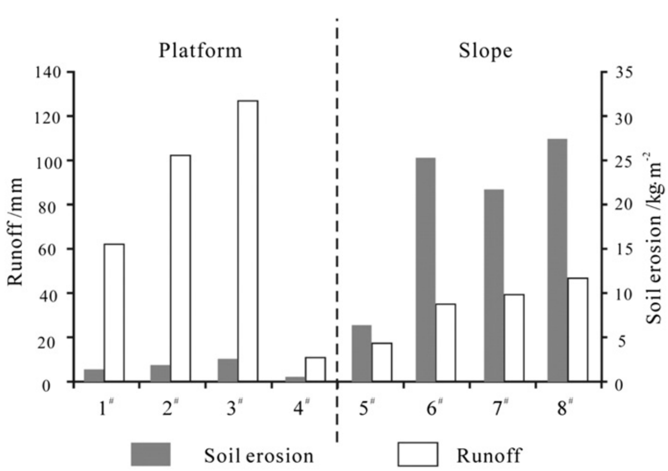

Fig. 6. Total runoff and soil erosion of each plot during the rainy season.

processes at the beginning of the dump reclamation. Soils captured with differing physical properties, such as soil bulk density and porosity, have different capacities of water storage and soil infiltration. Good water storage capacity and infiltration of soil is usually combined with high soil porosity and low bulk density (Yates et al., 2000; Krummelbein et al., 2010; Sasal et al., 2010; Zhao et al., 2013). Because of severe soil disturbance, the soil physical properties and infiltration were dramatically altered. Soil porosity, bulk density and soil on the newly formed platform and the slope of the dump changed to −23.3%, 21.4%, and +3.83%, +3.7% respectively, in comparison with the original grassland, and the soil porosity on the slope is 15.28% higher than that on the platform (Li et al., 2007; Lv and Lu, 2009). Therefore, the runoff volume of plot 8 was less than that of plot 3. The infiltration on the slopes was higher in the initial stages of reclamation. It was observed that after several years of reclamation, the functions of gravitation and roots began to appear, which conforms to the significantly different effects of runoff conservation between plots 7# and 8# (Table 3); soil infiltration decreased to a constant rate, and the gap of soil bulk density between the platform and slope gradually narrowed (Hartanto et al., 2003; Fu et al., 2010). Developed roots can improve soil physical properties, strengthening soil infiltration and reducing surface runoff. However, significant difference can only be found in the pairs involving plots 3# and 7# vs 8# (Table 3). This is mainly because the vegetation on those plots was little and the effect of roots has not been fully reflected. Noticeable effects on improving soil infiltration are predicted to occur after a longer period of growth (Huang et al., 2004; Wang et al., 2012; Zhao et al., 2013).

Within the same plot location, soil porosity, bulk density and soil infiltration are also affected by the vegetation pattern. Soil with large-scale fissures and root holes are characterized by high porosity, high soil infiltration and low soil bulk density. Roots play a critical role in the improvement of soil property and cause the differences in soil water storage capacity among different vegetation types. Fig. 6 shows the overall effect of vegetation on runoff generation. Fig. 9 shows that on the platform, plot 1 (with 1-year-old *R. pseudoacacia* and *Hippophae*) suffered a significantly larger runoff volume than that of plot 4 during the typical rainfall event of Jul 2, and this extent became wider in the subsequent rainstorm events; meanwhile, on the slope, the capacity of vegetation is ranked as follows: 5-year-old mixed grass–shrub–arbor forest > 1-year-old *R. pseudoacacia* > 2-year-old grass. The phenomena fit well with the distribution characteristics and functions of vegetation roots. Grass roots mainly distribute at the shallow layer, roots of trees mainly distribute on deep soil layer, and shrub roots are intermediate. The shallow layer of plot 1, without the benefits of grass roots and combined with the initial soil bulk density, yielded the highest runoff volume. Plot 5, with mixed grass–shrub–arbor, had a rich distribution of roots and the highest water storage capacity. The function of litter layers on the land surface cannot be ignored. They produced a fine water absorption and rainfall interception capacity and improved the surface roughness to limit soils being hit directly by rainfall, thereby reducing

Table 3
A paired sample T-test was applied individually between plots to analyze the significant differences in effects of the soil conservation method and vegetation on water and soil conservation (sig < 0.1, df = 9).

Paired sample T test									
	Location	Pair	t	Check value = 0.1		Location	Pair	t	Check value = 0.1
				2-Tail Sig					2-Tail Sig
Runoff	Platform	1# vs 2#	−1.65	0.13	Soil erosion	Platform	1# vs 2#	−1.902	0.09
		1# vs 3#	−2.168	0.05			1# vs 3#	−1.994	0.08
		1# vs 4#	1.578	0.14			1# vs 4#	1.094	0.30
		2# vs 3#	−3.932	<0.01			2# vs 3#	−1.96	0.08
		2# vs 4#	1.678	0.12			2# vs 4#	1.486	0.17
		3# vs 4#	1.971	<0.01			3# vs 4#	1.856	0.09
	Slope	5# vs 8#	−1.362	0.20		Slope	5# vs 8#	−1.064	0.31
		6# vs 8#	−1.422	0.19			6# vs 8#	−1.306	0.22
		7# vs 8#	−1.797	0.10			7# vs 8#	−1.057	0.32

runoff velocity and weakening runoff erosion on soil (Calvo-Cases et al., 2003; Wu et al., 2004). Although this function is not a significant factor during the rainy season, its importance will emerge in the autumn and winter.

4.2. Erosion durability of soil

Soil erosion has a close relationship with the erosion durability of soil. Soil anti-erodibility reflects the ability of dispersing and suspended soil to resist water; it is affected by many factors, such as the physico-chemical properties of soil, climate, vegetation coverage and litter reserves (Bryan, 2000; Jiao et al., 2012; An et al., 2013). Fig. 6 indicates that plots 4 and 5 had the optimal effects of soil conservation for all of the studied rainfall events, and plot 1 had the least erosion with the strongest runoff during the rainstorm event. The root densities of vegetation types and their change over depth contribute to this phenomenon. The roots of *H. rhamnoides* mainly distribute from 0 to 60 cm depth and its roots density decrease with depth; the roots of *R. pseudoacacia* show less of a decrease with depth and reach depths of approximately 120 cm. The roots of grasses are uniformly distributed across the entire slope and the root distribution depth is similar to *R. pseudoacacia* (Lv et al., 2006). The fixation effect and direct pull effect of roots play an important role in this process of soil conservation from erosion. Water-stable aggregate content was also a major factor affecting soil erosion. Organic matter could offer cement for the formation of water stable aggregates; rotten roots can improve soil organic matter content and tiny roots, especially root hairs, could prevent the soil from dispersing and crushing in the water. The litter layers can effectively increase the content of organic matter in surface soil and increase the content of water stable aggregate (Spaccini et al., 2001; Polyakov and Lal, 2004; Six et al., 2004; Adesodun et al., 2007). Nevertheless, it is a long process. Similar to runoff, significant differences in soil conservation can only be seen with the platform pairs — 1# vs 2#, 1# vs 3# and 3# vs 4# (Table 3). This is probably caused by the amount of runoff and the effects of vegetation on soil structure, soil organic accumulation and soil aggregation were not been obvious over a short time.

4.3. Conclusions and suggestions

The following conclusions can be drawn from our findings:

(1) Platforms experienced a larger volume of runoff than slopes, while slopes generated a larger value of soil erosion than platforms. Water conservation engineering measures should be conducted at the edges of platforms to prevent secondary runoff from flowing toward the slopes.
(2) The re-vegetation of dumps is an effective way to improve soil physical properties, increase soil anti-erodibility, reduce runoff and soil erosion, and improve the stability of ecosystems. Mixed grass–shrub–arbor resulted in an obvious reduction of the effects of runoff and sediment erosion, especially after the large storm event. High vegetation coverage can bring the most effective function on water filtration, sediment conservation and slope protection.

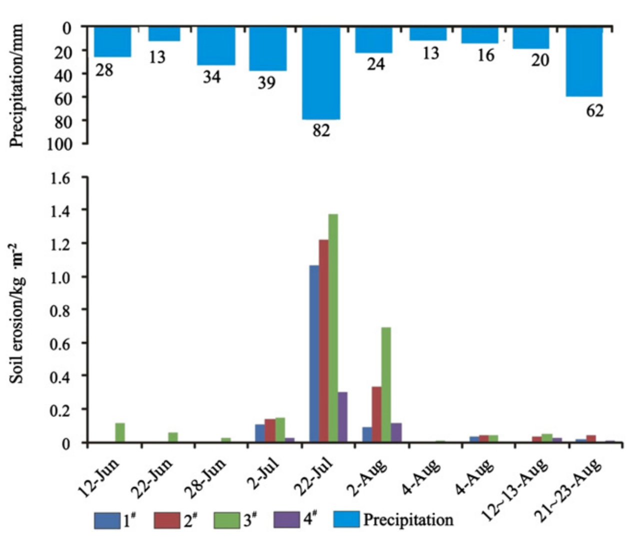

Fig. 7. The generalized differences in soil erosion response to rainfall events on the platform during the rainy season.

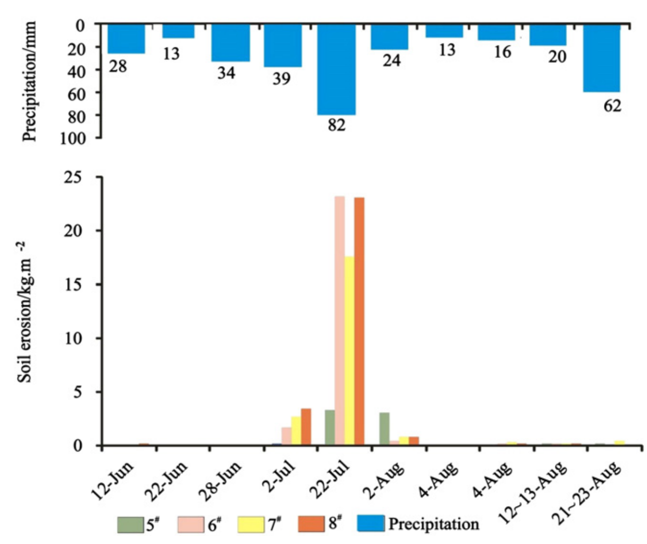

Fig. 8. The generalized differences in soil erosion response to rainfall events on the slope during the rainy season.

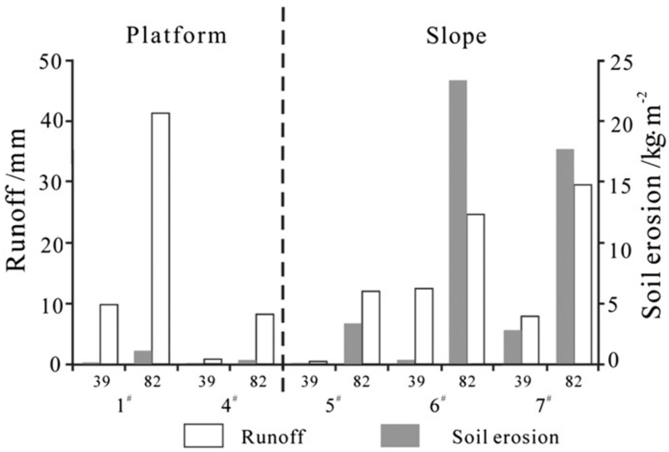

Fig. 9. Different functions of plots with various vegetation under two types of rainfall events: the typical rainfall events with precipitation of approximately 39 mm, and a rainstorm event with precipitation totaling 82 mm.

(3) Using specific data, findings for this reclamated land confirm finding from other studies on the original landform. This work scientifically valued and verified that the principles governing the original landform are also suitable for dumps; vegetation truly has significant effects on local water and soil conservation and ecology restoration, and optimal vegetation under different surface types and habitats was selected.

(4) Land reclamation at the ATB opencast coal mine provides a valuable experience for the control of soil erosion in opencast mining areas. Further research is needed to determine the degree of improvement that vegetation can play on soil porosity, bulk density, soil infiltration and soil anti-erodibility. The relationship between the structure and the function of the artificial vegetation community should also be one of the emphases of future research.

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