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RESEARCH ARTICLE

Influence of soil physical properties and vegetation coverage at different slope aspects in a reclaimed dump

Jian Pan[1] · Zhongke Bai[1,2] · Yingui Cao[1,2] · Wei Zhou[1,2] · Jinman Wang[1,2]

Abstract Vegetation coverage is an important parameter for affecting soil erosion and the physical and chemical properties of soil. To analyze the mutual influence between vegetation coverage and soil quality at different slope aspects in a reclaimed dump, fitting analyses were built between the normalized difference vegetation index and soil physical properties at each slope aspect. Twenty six quadrats were sampled in slope-platform alternate mode. Each quadrat was 10 m × 10 m. Vegetation index and soil physical properties were measured and calculated. Through curve fitting analysis, the results showed that soil bulk density has a negative correlation with the vegetation index on shady and half shady slopes, sunny slopes, and half sunny slopes. Soil porosity has a positive correlation with the vegetation index on shady and half shady slopes, sunny slope, and half sunny slope. The soil mass water content has a concave function relationship with the vegetation index on shady and half shady slopes and has a quadratic function relationship with the vegetation index on sunny and half sunny slopes, with the parabola moving upwards. The soil gravel content has a linear relationship with the vegetation index on shady and half shady slopes, and the image has a negative slope with a quadratic function relationship to the vegetation index on sunny slope and half sunny slope, with the parabola moving downwards. Due to differences among hydrothermal conditions, the relationship between vegetation coverage and soil quality indicators at different slope aspects is different; therefore, reasonable improvement of soil quality indicators on sunny and half sunny slopes could help plants to grow. These findings feed into a reference document that sets out how vegetation and soil quality may be improved in mining areas.

Keywords Reclamation · Vegetation coverage · Soil physical property · Slope aspect · Reclaimed dump · Succession · Land restoration

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Introduction

The affected area has to be reclaimed, with the goal of achieving a level of ecological capability equivalent to that existing prior to disturbance (Sloan et al. 2016). Soil reconstitution is a key part of the process of land reclamation (Cao et al. 2015). When compared with natural soils, reconstituted soil tends to have lower fertility as well as substantial differences in physical and chemical properties, such as high soil pH, increased salinity, and compaction in the overburden (Farnden et al. 2013). So it is significant to choose the plants such as *Robinia pseudoacacia*, *Hippophae rhamnoides*, *Caragana korshinskii*, *Populus alba var. pyramidalis*, *Ulmus pumila*, *Robinia pseudoacacia*, and *Elaeagnus angustifolia* that are resistant to reconstituted soil with drought, salinity pollution, and adverse physicochemical properties. The criteria of plant species selection should adhere to ecological suitability and should be mainly to native herbs or shrubs which are adaptable and root developed with good slope protection effect (Zhang et al. 2013). On the other hand, those alien species or varieties

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proved to have been successful after years of introduction and acclimatization are not been excluded (Chen et al. 2014). In turn, thus formed vegetation coverage is an important parameter affecting soil erosion and the physical and chemical properties of soil (Biro et al. 2013; Mekuria and Aynekulu 2013; Montenegro et al. 2013). It can even be used as an indicator to evaluate land reclamation and vegetation recovery in opencast coal mining areas (Cao et al. 2016; Frouz et al. 2013; Mukhopadhyay et al. 2016). By quantitatively describing the vegetation-soil relationship, we can provide guidelines for land reclamation work in similar opencast mining areas.

Currently, many studies have revealed the interaction mechanisms between soil and vegetation from different angles. Liu et al. (2010) researched a *Calycanthus chinensis* community in Dalei Mountain, Zhejiang and found that the strongest correlation was between species diversity and the organic matter content of soil. Research conducted by Yuan et al. (2015) showed that soil nutrition and soil moisture content are the key factors affecting changes in plant species composition, richness, diversity, and succession on China's Loess Plateau. From the perspective of the relationship between reconstituted soil quality and vegetation recovery on damaged lands, some species have shown tolerance to particular soil properties' characteristic of reclaimed sites, such as salinity (Lilles et al. 2012). Seedlings of these species often exhibit transplant stress and grow slowly for several years after field transplanting (Martens et al. 2006). Through research on a reclaimed mine site, Bauman et al. (2015) found that the soil properties changed after long-term re-vegetation, and it was difficult for vegetation to recover after large-scale soil disturbances due to surface mining for coal. The research of Toktar et al. (2016) showed that during an ecological restoration activity performed on a phosphate mine in Kokdzhon, Zhambyl region, soil properties degrade, and plant engraftment was low because the test area, made by a quarry-hole, was first filled with the earthy material of a dump and then leveled. Ren et al. (2010) found that different types and breeding of artificial vegetation affected soil nutrient status in abandoned quarries to different extents. Li et al. (2016) compared the responses of soil nitrogen storage at different vegetation degradation gradients and found the highly significant regression correlation between the maximum values of the normalized difference vegetation index (NDVI) and the natural logarithm of precipitation on a pixel spatial series.

From the research introduction, we can find that soil reconstitution and vegetation recovery are important to mine reclamation research and practice (Bai et al. 2000; Cao et al. 2015). The formation process of reconstituted soil affects the rate of vegetation recovery, and vegetation succession feeds back into the quality of reconstituted soil (Kamp et al. 2009). The constructed small mounds of sand or topsoil mix could improve the establishment and survival of seeds of prairie plants (Biederman and Whisenant 2011). Furthermore, Hough-Snee et al. (2011) conclude that mounding can have relatively long-term effects on plant community development, even in highly disturbed, minimally maintained restoration projects. We can better understand the relationship between reconstituted soil and vegetation in dumps by analyzing the dynamic variation processes between reconstituted soil and reconstructed vegetation.

However, existing research rarely analyzes the relationship between reconstituted soil quality and vegetation recovery from the perspective of slope aspect in the dump. Slope aspect could determine surface hydrothermal structure and affect vegetation cover by changing moisture content (Sun et al. 2015; Wang et al., 2016). The South Dump in the Pingshuo mine of Shanxi, China was chosen as the study area in which to investigate this relationship. Based on mathematical statistical methods, the main objectives of this research are to (1) analyze the correlation between reclaimed soil physical properties and the corresponding vegetation index (the quantitative expression of vegetation cover) on different slope aspects (2) reveal the interaction mechanisms between soil and vegetation in a reclaimed dump, in order to provide guidelines for restoring vegetation and improving soil quality in mining areas with similar soil and climate characteristics.

Materials and methods

Study area

Pingshuo mine (111° 58′–112° 30′ E, 39° 23′–39° 37′ N) has a total area of 375.12 km^2 and is located in Shuozhou city, Shanxi province, in the eastern part of the Loess Plateau, China (Fig. 1). The study area has a temperate semi-arid continental monsoon climate. Annual precipitation is 428.2–449.0 mm with annual evaporation of 1786.6–2598.0 mm. The average temperature is 6.3 °C with frost-free period of about 115–130 days and the annual average wind speed of 3.4 m/s. Zonal vegetation in Pingshuo mine is dry steppe type (Li et al. 2010). However, due to a long history of cultivation, natural secondary forest has been wiped out. It is also now rare to encounter large areas of grassland species. The main native vegetation is *Miscanthus*, *Stipa krylovii Roshev*, *Agropyron cristatum*, *Thymus mongolicus Ronn*, and *Lespedeza davurica*. In the study area, 98 plant species have been planted experimentally for controlling soil erosion, rapid ripening of soil, stabilizing soil structure, and forming a self-regulating healthy ecosystem as soon as possible; of which 60 species now have self-sustaining populations (Cao et al. 2013).

As the first large opencast coal mine in Pingshuo mine, the An Taibao (ATB) opencast mine was built in 1985. Located at south of the ATB opencast mine, the South Dump, used as an
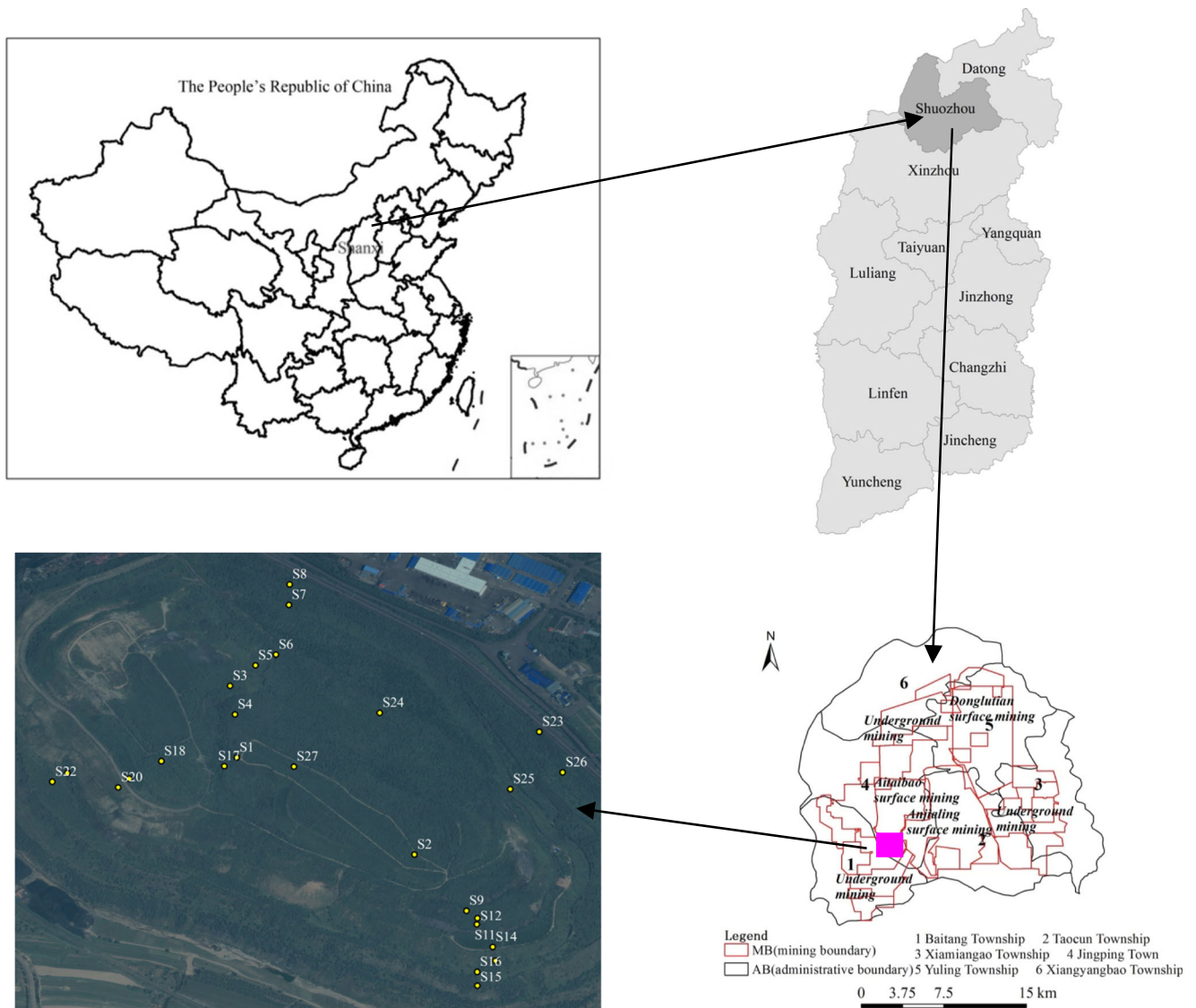
Fig. 1 Location diagram showing the distribution of sampling points and the relationship between Pingshuo mine and Shanxi Province, one province in Northern China. Pingshuo mine is composed of three opencast mines and three underground mines. The South Dump is located in No. 1 underground mine. There are 27 sampling points that are distributed in the South Dump as shown in a remote sensing map. Part of this figure is quoted from Zhang et al. 2016

open dump from 1985 to 1989, is 1360–1465 m high with slopes of 20°–40° and a surface casing of 100 cm. The ground surface is mainly covered by loess, laterite, and red-loess. Beginning in 1990, the dump was reclaimed with a vegetation arrangement mode of grass-shrub-arbor, and its reclamation area is approximately 180 km². The dump reclamation technology includes three aspects: (a) landform remolding (construction process of dump basement, subject, platform, slope, and drainage canal and casting process of reactor appearance ground); (b) soil rebuilding (rapid increase soil fertility technology); (c) vegetation reconstruction (technology of introducing pioneer plant, technology of matching grass-shrub-arbor, technology of constructing community).

Soil sampling

After 20 years of reclamation, the physical properties of reconstructed soils at the South Dump have changed significantly as a whole, and soil bulk density is decreased, soil porosity is increased, and soil mass water content quality is improved (Cao et al. 2015). Most of the physicochemical properties of woodland at the South Dump were better than those of the undamaged woodlands (Cao et al. 2013).

We designed the sampling plan according to the slope aspects, site conditions, and area of dump. The number of quadrats was planned by covering all the basic slope and platforms from the top to the foot of the slope and combining with the

accessibility. Because it was difficult to access the quadrat of S_{10}, then we chose the new quadrat near the S_{10}, and the new quadrat was numbered S_{11}, the rest of the numbers were changed accordingly. Sampling was conducted in early July 2014 in 26 quadrats along four slope aspects (sunny slope, shady slope, half sunny slope, half shady slope, as shown in Fig. 2). All 26 quadrats were sampled in slope-platform alternate mode. The inclinations of slope quadrats are between 35° - 45°, and the inclinations of platform quadrats are between 0° - 2°. Each quadrat was 10 m × 10 m at the platform and had a guaranteed 10 m × 10 m vertical projection area at slope with a 10-m width and a variable length based on the slope. Each quadrat was labeled with a nail stake at the corner and located with the center's coordinates using GPS. Figure 1 shows the distribution of each quadrat in the dump.

A five-point sampling method was used in quadrat: after removal of the foliage at the surface, the samples of soil bulk density at 0-10 cm depth were collected by ring knife. Near the ring knife sample collection point, surface soil samples at 0-10 cm depth were collected with an earth-boring auger, and mixed, stored in cloth bags, and serially numbered. In total, we collected 130 cutting ring soil samples and 26 mixed earth-boring auger soil samples.

Testing soil physical properties

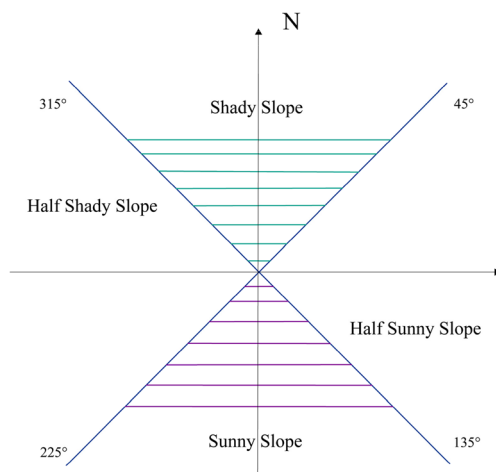Ring knife samples collected in the field were immediately weighed, and their wet weight was recorded. In the lab,

ring knife samples were placed in a 105 °C oven three times and baked for 8 h to a constant weight, and then their soil bulk density (SBD), soil porosity (SP) and soil mass water content (SMWC) was calculated. Mixed surface soil samples were air-dried in the lab, divided into five and passed through a 2-mm sieve to separate gravel and fine earth, and then their soil gravel content (SGC) was weighed and calculated. The calculations of soil bulk density, soil porosity, soil mass water content, and soil gravel content were made using internationally accepted methods (Zornoza et al. 2007), and their computational formulae were detailed as following formulae (1)–(4) (Bao 2005).

$$SBD = \frac{W_1}{V} \tag{1}$$

$$SP = \left(1 - \frac{BD}{2.65}\right) \times 100 \tag{2}$$

$$SMWC = \frac{W_2}{W_1} \times 100 \tag{3}$$

$$SGC = \frac{W_4}{W_3} \times 100 \tag{4}$$

SBD represents soil bulk density (g/cm^3), SP represents soil porosity (%), SMWC represents soil mass water content (%), W_1 represents dry soil weight (g), W_2 represents water weight (g), V represents volume of ring knife (cm^3), SGC represents soil gravel content (g), W_3 represents gravel and fine earth weight, and W_4 represents gravel weight.

NDVI calculation

The vegetation types in each quadrat are also presented in Table 1. There are four arbor modes, including *Acacia*, *Aspen×Chinese pine×Elm*, *Acacia×Elm*, *Acacia×Chinese pine×Elm*. The arbors were planted almost in the same time and seldom disturbed in order for ecological restoration. The main shrub in each quadrat is *Caragana*. The main grasses in each quadrat are *Miscanthus*, *A. cristatum*, and *S. krylovii Roshev*.

As an important mean of obtaining regional vegetation coverage parameters, remote sensing images can reflect vegetation covering information and trends on different spatial scales. It is more direct to estimate vegetation coverage using remote sensing images than it is to use visual estimation or instrument measurement (O'Brien 1989). Studies have shown that the normalized difference vegetation index (NDVI) can reflect the vegetation coverage well, that is, the place with high NDVI is also the place with high tree crown density or high herb coverage (Qi et al. 2000; Bao et al. 2013; Zhang

Fig. 2 The schematic diagram shows the four directions of slope. According to the intensity of solar radiation, the slope aspects in the Northern Hemisphere can be divided into shady slope, half shady slope, sunny slope, and half sunny slope. If north is 0° and the number of degree is increasing in a clockwise direction, thus, shady slope is 0–45° and 315–360° and sunny slope is from 135 to 225°. Half shady slope is 45–90° and 270–315°, and the rest is half sunny slope

Table 1　Conditions, soil's physical and chemical properties, and NDVI values in each quadrat

Quadrat number	Site conditions	Slope aspects	Vegetation types	SBD (g/cm³)	SP (%)	SMWC (%)	SGC (%)	STN (g/kg)	SOM (g/kg)	SAP (mg/kg)	SAK (mg/kg)	NDVI
S_1	Platform	Shady slope	Acacia×Elm	1.32	50.23	6.05	0.00	0.77	76.97	2.84	197	0.63
S_2	Platform	Sunny slope	Acacia×Elm	1.51	42.84	8.05	35.68	0.70	77.68	2.97	147	0.71
S_3	Platform	Shady slope	Acacia×Elm	1.39	47.38	6.49	30.38	0.48	9.55	3.28	120	0.70
S_4	Slope	Shady slope	Acacia	1.54	41.73	7.32	49.75	1.55	50.74	3.18	121	0.59
S_5	Slope	Shady slope	Acacia	1.27	52.01	6.94	1.04	0.61	16.68	3.11	142	0.72
S_6	Platform	Shady slope	Acacia×Elm	1.18	55.50	6.21	35.88	1.73	71.29	2.73	197	0.54
S_7	Slope	Shady slope	Acacia×Elm	1.33	49.76	3.44	11.24	1.06	37.80	2.42	124	0.67
S_8	Platform	Shady slope	Acacia×Elm	1.38	47.76	7.36	38.26	1.07	42.66	2.90	254	0.65
S_9	Slope	Sunny slope	Acacia	1.60	39.67	8.12	39.84	0.78	21.33	5.18	158	0.71
S_{11}	Slope	Sunny slope	Acacia	1.52	42.50	3.76	72.35	0.87	36.06	4.15	137	0.45
S_{12}	Platform	Sunny slope	Acacia×Elm	1.46	44.75	4.58	58.50	2.03	69.32	4.66	259	0.60
S_{13}	Slope	Sunny slope	Acacia×Elm	1.44	45.71	5.97	44.91	1.14	31.29	5.46	176	0.62
S_{14}	Platform	Sunny slope	Apricot×Chinese pine	1.26	52.54	6.20	0.00	0.38	6.88	2.56	61	0.61
S_{15}	Slope	Sunny slope	Acacia×Elm	1.52	42.66	4.62	74.96	1.66	62.87	7.42	152	0.55
S_{16}	Platform	Sunny slope	Acacia	1.56	41.11	4.27	32.37	0.96	22.87	3.87	162	0.45
S_{17}	Slope	Half sunny slope	Acacia×Elm	1.25	52.90	7.63	43.85	2.01	94.72	3.66	193	0.60
S_{18}	Platform	Half sunny slope	Acacia×Elm	1.20	54.55	6.69	32.24	0.81	17.47	3.87	140	0.69
S_{19}	Slope	Half sunny slope	Caragana	1.28	34.42	4.10	5.60	0.52	13.33	3.39	95	0.53
S_{20}	Platform	Half sunny slope	Aspen×Chinese pine×Elm	1.49	43.89	6.85	0.00	0.28	4.63	5.73	62	0.36
S_{21}	Slope	Half sunny slope	Acacia×Elm	1.01	61.76	5.70	55.90	3.00	183.83	4.49	56	0.45
S_{22}	Platform	Half sunny slope	Acacia×Elm	1.26	52.41	7.60	3.74	0.75	21.75	7.46	182	0.26
S_{23}	Slope	Half shady slope	Acacia×Chinese pine×elm	1.58	40.55	7.16	61.16	2.60	99.63	5.25	274	0.60
S_{24}	Platform	Half shady slope	Acacia×Elm	1.37	48.12	7.22	14.11	1.21	33.54	5.01	211	0.70
S_{25}	Slope	Half shady slope	Acacia×Elm	1.20	54.90	6.57	9.58	1.24	36.91	5.60	148	0.63
S_{26}	Platform	Half shady slope	Acacia×Elm	1.39	47.60	7.78	5.87	1.08	30.03	5.04	161	0.66
S_{27}	Slope	Half shady slope	Acacia×Chinese pine×Elm	1.15	56.42	8.33	12.12	1.39	45.80	5.46	180	0.71

SBD soil bulk density, *SP* soil porosity, *SMWC* soil mass water content, *SGC* soil gravel content, *STN* soil total nitrogen, *SOM* soil organic matter, *SAP* soil available phosphorus, *SAK* soil available potassium

et al. 2016). The *NDVI* is calculated as formula (5) (Deering 1978).

$$NDVI = (NIR - R) / (NIR + R) \qquad (5)$$

NDVI represents normalized difference vegetation index, *NIR* represents the near infrared band reflectance values, and *R* represents red band reflectance values.

The satellite of the remote sensing image is SPOT6 from Shibao Satellite Imagery Corporation in Beijing, China, and the sensor is Reference 3D. The spatial resolution is 6 m. The date of the image is 14 July 2015. The data of *NDVI* value of each quadrat (Table 1) were extracted from the remote sensing image using formula (5).

Statistical analysis

A one way *ANOVA* was carried out to compare the difference of means of soil physical properties from different slope aspects, and statistical significance was determined at the $P < 0.05$. An *ANOVA* was also carried out to compare vegetation indexes from different slope aspects. Statistical significance was determined at the $P < 0.1$. An *F* test was performed to detect changes in soil physical properties and vegetation

indexes. All statistical evaluations were performed using the Statistic Package for Social Science (SPSS 16.0).

Curve fitting analysis

The relationship between *NDVI* and the physical properties of reclaimed soil at the direction level of the slope was built using curve fitting analysis. This method was used to reveal the difference between vegetation recovery situations on different slope aspects and the physical properties of surface soil. In the process of fitting analysis, *NDVI* was used as the independent variable, and the physical properties of reclaimed soil were used as the dependent variable; the converse was used for individual fitting relationships. Statistic Package for Social Science (SPSS 16.0) was applied and used in curve fitting. After the fitting, the *F* test of *ANOVA* analysis was used to confirm the significance of the regression equations.

Results and analysis

There were five values for each soil physical property in one quadrat, and then the mean of each physical property was calculated. The means of physical and chemical properties of the soil samples in each quadrat are shown in Table 1. The basic statistical indicators of means of soil physical properties are shown in Table 2. The Grubbs critical values are shown in Table 3 (Grubbs 1950). Test results of the physical properties of soil samples show that soil bulk density was between 1.01 and 1.60 g/cm^3, with an average of 1.36 g/cm^3 larger than the original landscape because the original surface soil was replaced by loess parent material; soil porosity was between 39.67 and 61.76%, with an average of 47.83% smaller than the original landscape because the reclaimed dump was compacted; soil mass water content was between 3.44 and 8.33%, with an average of 6.35% larger than the original landscape also because of mechanical compaction, which lead to the reconstructed soil becoming firm, and the infiltration rate being less than the original landscape; and soil gravel content was between 0 and 74.96%, with a variation coefficient of 80.13% because of the irregularity of dumping process. Variable coefficients of the physical properties of soil samples showed that soil bulk density, soil porosity, soil mass water content, and soil gravel content were all at a moderate variability. The variable coefficients of soil bulk density, soil porosity, and soil mass water content were relatively low, at a moderate-weak variability status. However, the variable coefficient of soil gravel content was at an upper-moderate variability status. Using K-S, the test values were all greater than 0.05 and met the test requirements with normal distribution. Using Grubbs test, the test value were all below the critical value except the NDVI value at S$_{22}$ ($n = 25$, $P = 0.95$). The

NDVI value could be supposed as abnormal value. When this value was gotten rid of from the table, there was no other one when we performed Grubbs test again. But due to this place had ever had spontaneous combustion, this abnormal value could be explained. The total soil erosion in coal mining area is 10,120 t/(km^{2}a) (Bai and Tong 1997).

Vegetation coverage and soil bulk density

For soil bulk density, there was no significant difference among soils on the shady slope, half shady slope, and half sunny slope. However, soil bulk density on the sunny slope was significantly different from soils on the shady slope, half shady slope, and half sunny slope ($P \leq 0.05$). For the vegetation index, there was no significant difference among soils on shady slopes, half shady slopes and sunny slopes. However, the vegetation index on half sunny slopes was significantly different from the soils on shady slopes, half shady slopes, and sunny slopes ($P \leq 0.1$). Thus, we built fitting relationships between vegetation index and mean soil bulk density on shady and half shady slopes, sunny slopes, and half sunny slopes (Fig. 3a, b, c).

Three fitting relationships all showed a negative correlation within a certain range of soil bulk density; that is, vegetation cover, as indicated by *NDVI*, decreased along a soil bulk density gradient. On shady and half shady slopes, *VI* and mean *SBD* showed a negative correlation, with the mean *SBD* decreasing while *VI* increased (Fig. 3b). On sunny slopes and half sunny slopes, *VI* and mean *SBD* showed a linear relationship with the mean *SBD* decreasing while *VI* increased (Fig. 3a, c). On shady and half shady slopes, the mean *SBD* was 1.34 g/cm^3, and the mean *VI* was 0.65. On sunny slopes, the mean *SBD* was 1.48 g/cm^3, and the mean *VI* was 0.59. On half sunny slopes, the mean *SBD* was 1.25 g/cm^3, and the mean *VI* was 0.48.

Vegetation coverage and soil porosity

For soil porosity, there was a significant difference between soils on the sunny slope and half sunny slope ($P \leq 0.05$), and there was no significant difference between soils on shady slopes and half shady slopes compared to soils on sunny slopes and half sunny slopes. For the vegetation index, there was no significant difference among soils on the shady slope, half shady slope, and sunny slope. However, the vegetation index on the half sunny slope was significantly different from the soils on the shady slope, half shady slope, and sunny slope ($P \leq 0.1$). Thus, we built fitting relationships between vegetation index and mean soil porosity on shady and half shady slopes, sunny slopes, and half sunny slopes (Fig. 4a, b, c).

Three fitting relationships all showed a positive correlation within a certain range of soil porosity; that is, vegetation covers, as indicated by *NDVI*, increased along a soil porosity

Table 2 Basic statistical indicators of soil physical properties

Statistical indicators	SBD (g/cm³)	SP (%)	SMWC (%)	SGC (%)	NDVI
Average	1.36	47.83	6.35	29.59	0.59
Maximum	1.60	61.76	8.33	74.96	0.26
Minimum	1.01	39.67	3.44	0.00	0.72
Standard deviation	0.15	6.35	1.42	23.71	0.12
Variation coefficient (%)	11.03	13.28	22.36	80.13	20.34
K-S test	0.52	0.47	0.65	0.85	0.95
Progressive significance	0.95	0.98	0.80	0.47	0.33
Dubious value[a]	1.01	61.76	3.44	74.96	0.26
Residual (absolute value)[b]	0.35	13.93	2.91	45.37	0.33
Grubbs test	2.33	2.19	2.05	1.91	2.75

[a] Dubious value is the bigger one of difference between maximum or minimum and average

[b] Residual is equal to dubious value minus average

gradient. On shady and half shady slopes, *VI* and mean *SP* showed a positive correlation, with the mean *SP* increasing while *VI* grew (Fig. 4a). On sunny slopes, *VI* and mean *SP* showed a linear relationship, with the mean *SP* increasing while *VI* grew (Fig. 4b). On half sunny slopes, *VI* and mean *SP* showed a positive correlation, with the mean *SP* increasing while *VI* grew (Fig. 4c). On shady and half shady slopes, the mean *SP* was 49.36%, and the mean *VI* was 0.65. On sunny slopes, the mean *SP* was 43.97%, and the mean *VI* was 0.59. On half sunny slopes, the mean *SP* was 50.00%, and the mean *VI* was 0.48.

Table 3 Grubbs critical values

Number	$P = 0.95$	$P = 0.99$
3	1.135	1.155
4	1.463	1.492
5	1.672	1.749
6	1.822	1.944
7	1.938	2.097
8	2.032	2.231
9	2.110	2.323
10	2.176	2.410
11	2.234	2.485
12	2.285	2.550
13	2.331	2.607
14	2.371	2.659
15	2.409	2.705
16	2.443	2.747
17	2.475	2.785
18	2.504	2.821
19	2.532	2.854
20	2.557	2.884
21	2.580	2.912
22	2.603	2.939
23	2.624	2.963
24	2.644	2.987
25	2.663	3.009
30	2.745	3.103
35	2.811	3.178
40	2.866	3.240
45	2.914	3.292
50	2.956	3.336

Vegetation coverage and soil mass water content

For soil mass water content, there was a significant difference between soils on half shady slopes and sunny slopes ($P \leq 0.05$), but soil mass water content on shady slopes was not significantly different from that on half shady slopes, and soil mass water content on sunny slopes was not significantly different from that on half sunny slopes. For the vegetation index, there was no significant difference among soils on shady slopes, half shady slopes, and sunny slopes. However, the vegetation index on half sunny slopes was significantly different from the soils on shady slopes, half shady slopes, and sunny slopes ($P \leq 0.1$). Thus, we built a fitting relationship between vegetation index and the mean soil mass water content on shady and half shady slopes and sunny and half sunny slopes (Fig. 5a, b).

On shady and half shady slopes, the vegetation index (*VI*) and the mean soil mass water content (*SMWC*) showed a positive correlation; that is, vegetation cover, as indicated by *NDVI*, increased along a soil mass water content gradient (Fig. 5a). On sunny and half sunny slopes, the relationship between soil mass water content and vegetation covers is consistent with a cubic inverted parabola (Fig. 5b). On shady and half shady slopes, the mean *SMWC* was 6.84%, and the mean *VI* was 0.65. On sunny and half sunny slopes, the mean *SMWC* was 6.07%, and the mean *VI* was 0.54.
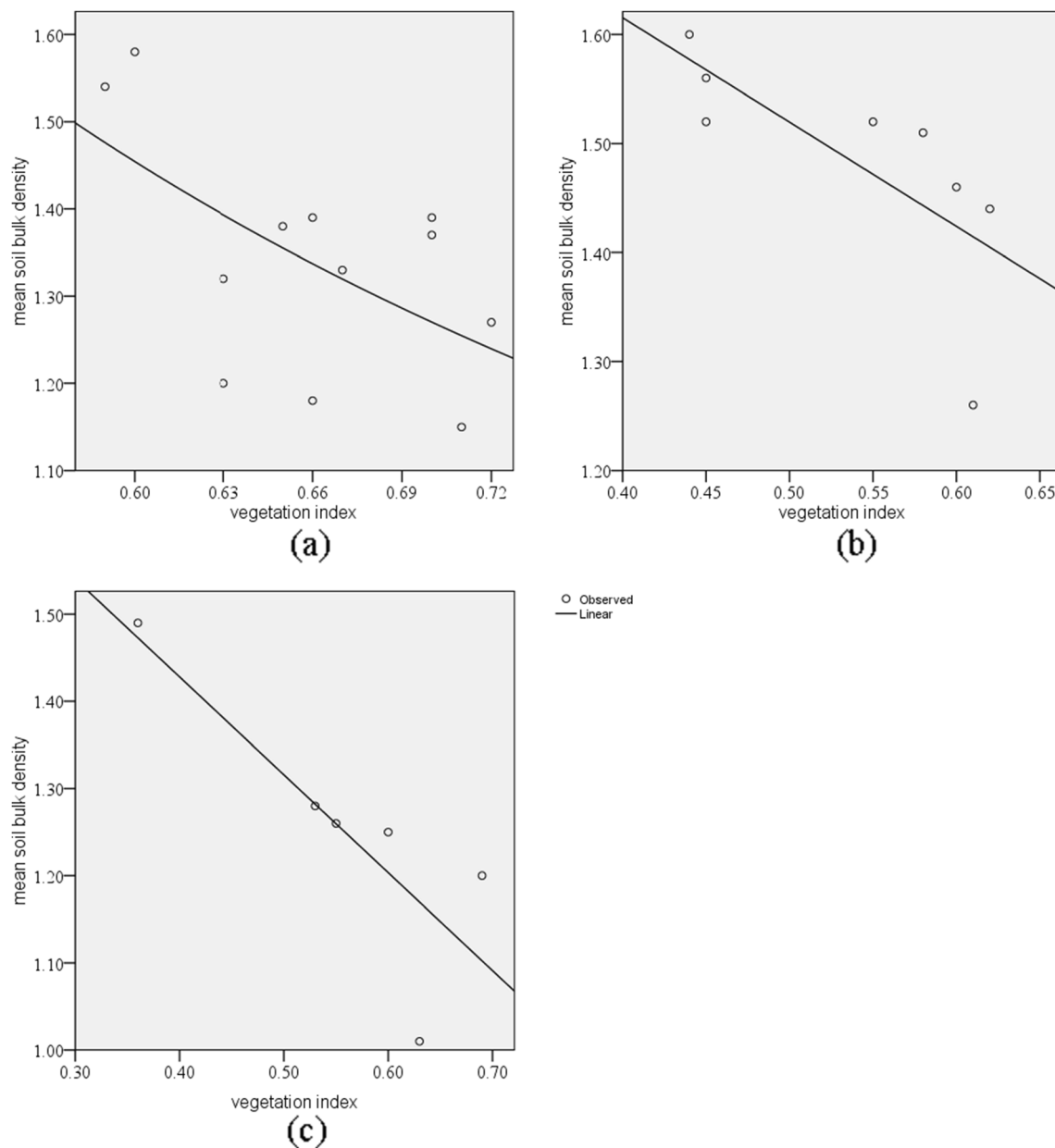
Fig. 3 The relationship between *SBD* and *VI* at different slope aspects: **a** is shady and half shady slopes, **b** is sunny slope, and **c** is half sunny slope. In plot **a**, the regression equation is expressed as $SBD = -0.77/VI + 0.17$ ($1.15 \leq SBD \leq 1.58$, $n = 12$, $P = 0.047$); in plot **b**, $SBD = -0.96VI + 2.00$ ($1.26 \leq SBD \leq 1.60$, $n = 8$, $P = 0.043$); in plot **c**, $SBD = -1.12VI + 1.88$ ($1.01 \leq SBD \leq 1.49$, $n = 6$, $P = 0.042$). *SBD* soil bulk density (g/cm³), *VI* normalized difference vegetation index (*NDVI*)

Vegetation coverage and soil gravel content

The soil gravel content on the sunny slope was significantly different from that on the shady slope, half shady slope, and half sunny slope ($P \leq 0.05$), and there was no significant difference among soils on the shady slope, half shady slope, and half sunny slope. For the vegetation index, there was no significant difference among soils on the shady slope, half shady slope, and sunny slope. However, the vegetation index on the half sunny slope was significantly different from the

soils on the shady slope, half shady slope, and sunny slope ($P \leq 0.1$). Thus, we built fitting relationships between the vegetation index and the mean soil gravel content on shady and half shady slopes, sunny slopes, and half sunny slopes (Fig. 6a, b, c).

On shady and half shady slopes, the vegetation index (*VI*) and the mean soil gravel content (*SGC*) showed a linear relationship; that is, vegetation cover, as indicated by *NDVI*, increased along a soil gravel content gradient (Fig. 6a). On the sunny slope, the relationship between vegetation cover and
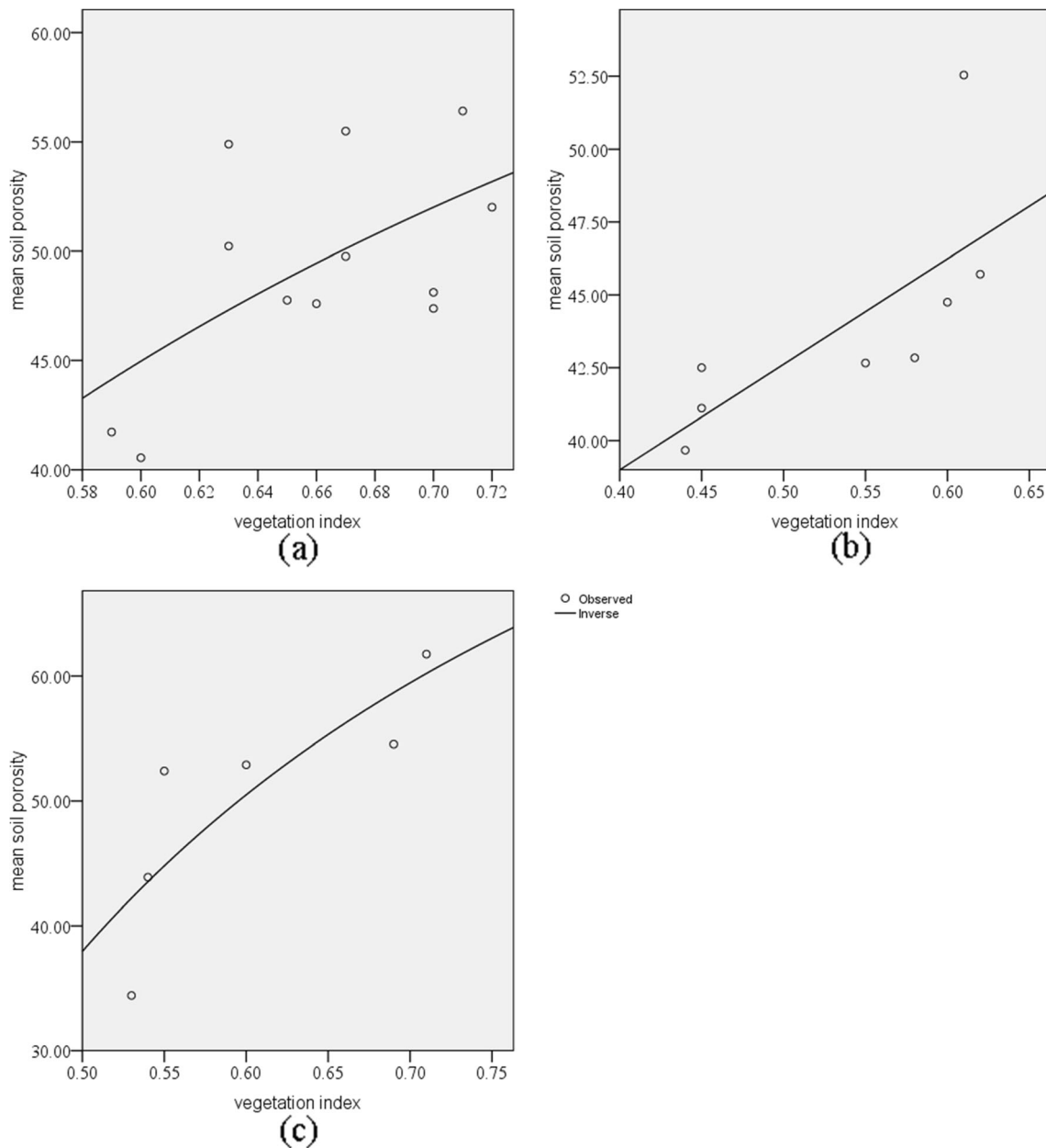
Fig. 4 The relationship between *SP* and *VI* at different slope aspects (**a** is shady and half shady slopes, **b** is sunny slope, and **c** is half sunny slope) are similar. In plot **a**, $SP = -29.59/VI + 94.28$ ($40.55\% \leq SP \leq 56.42\%$, $n = 12$, $P = 0.042$); in plot **b**, $SP = 36.20VI + 24.52$ ($39.67\% \leq SP \leq 52.54\%$, $n = 8$, $P = 0.045$); in plot **c**, $SP = -37.62/VI + 113.19$ ($34.42\% \leq SP \leq 61.76\%$, $n = 6$, $P. = 0.043$). *SP* soil porosity (%), *VI* normalized difference vegetation index (*NDVI*)

soil gravel content is consistent with quadratic parabola (Fig. 6b). On the half sunny slope, vegetation cover and $\log_{10}SGC$ showed a quadratic parabola relationship (Fig. 6c). On shady and half shady slopes, the mean *SGC* was 22.18%, and the mean *VI* was 0.65. Compared with other slope aspects, the mean *SGC* of shady and half shady slopes was the lowest. On the sunny slope, the mean *SGC* was 44.83%, and the mean *VI* was 0.59. On the half sunny slope, the mean *SGC* was 23.56%, and the mean *VI* was 0.48.

Discussion and conclusions

Discussion

Soil bulk density is a basic physical property of soil, and its value reflects the soil's comprehensive properties, including character, construction, and organic matter. Vegetation state is one of the main factors influencing soil bulk density. In this study, we found that the higher the *NDVI*, the lower the mean
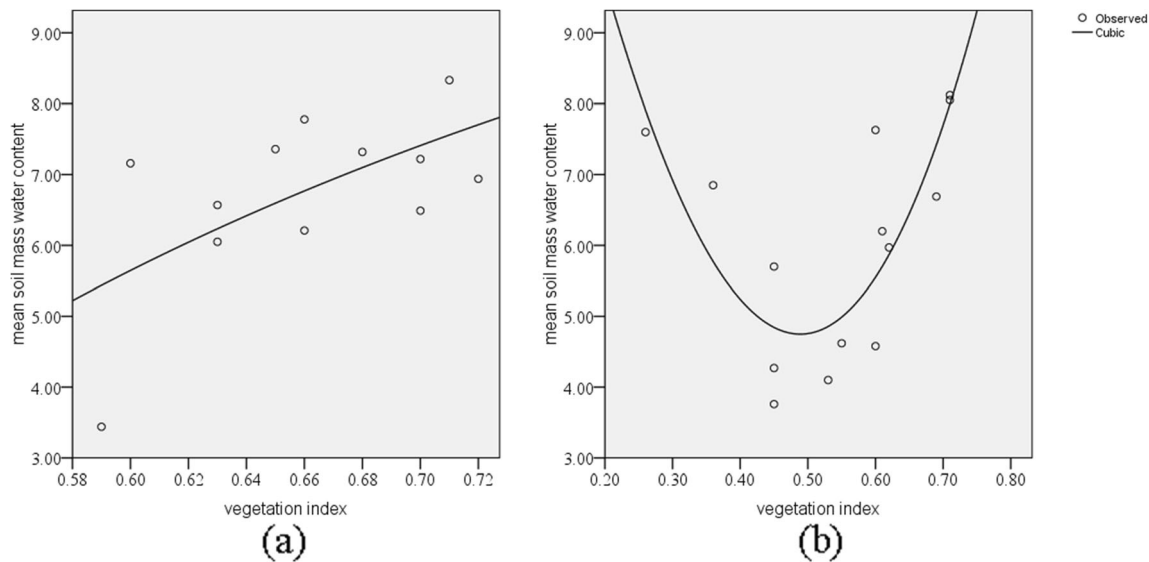
Fig. 5 The relationship between *SMWC* and *VI* at different slope aspects (**a** is shady and half shady slopes; **b** is sunny and half sunny slopes) are different. In plot **a**, $SMWC = -7.41/VI + 18.00$ ($3.44\% \leq SMWC \leq 8.33\%$, $n = 12$, $P = 0.037$); in plot **b**, $SMWC = 13.25VI^3 + 43.95VI^2 - 52.47VI + 18.35$ ($39.67\% \leq SMWC \leq 52.54\%$, $n = 14$, $P = 0.010$). *SMWC* soil mass water content (%), *VI* normalized difference vegetation index (*NDVI*)

soil bulk density. Low soil bulk density is good when vegetation is at root growth, simultaneously enhancing the absorption of soil nutrients through the root system and accelerating the growth of vegetation (Cai et al. 2014). Vegetation growth can reduce soil bulk density; this is especially obvious at depths of 0–10 cm (Lu et al. 2015). Soil bulk density reflects the degree of maturation, and surface soil bulk density is related to surface litter reserves and decomposition on forest lands, which are closely related to vegetation coverage, vegetation growth time, and vegetation configuration mode (Fest et al. 2015). In the South Dump, vegetation growth time and vegetation configuration mode are basically the same; therefore, the effect of these two factors can be excluded. Soil bulk density can reflect the remaining variable, vegetation coverage, directly.

Soil porosity refers to the percentage of soil void compared to the total volume of soil under natural conditions. Fitting relationship between the *NDVI* and the mean soil porosity is the converse of fitting relationship between the *NDVI* and the mean soil bulk density. Soil porosity is affected by soil bulk density: the higher soil bulk density is, the lower soil porosity is. Research conducted by Panettieri et al. (2013) suggests that forests can increase the quantity of soil pores, mainly at the surface layer. Soil porosity has a remarkable positive effect on water, fertilizer, air in the soil, heat conditions, and forestry production, and suitable soil porosity aids vegetation growth. In turn, the larger the area of vegetation growth is, the greater the porosity of the soil is.

Vegetation transpiration influences soil mass water content (Bing et al. 2012). Because of the lack of sunlight and the plant cover on the shady and half shady slope, transpiration

has little effect on improving soil mass water content (Famiglietti et al. 1998). In addition, although high vegetation coverage could help retain and filter rainfall, most moisture evaporates into the atmosphere, which reduces the impact of transpiration (Bing et al. 2012). Research shows that when the vegetation index is less than 0.50, the mean soil mass water content decreases as the vegetation index increases, mainly on the half sunny slope. This is because when vegetation coverage is low and evaporation is intense, surface soil receives direct solar radiation and transpiration; additionally, root growth consumes large amounts of water (Makky et al. 2016; Vanuytrecht et al. 2014). When the vegetation index is > 0.50, the mean soil mass water content increases while the vegetation index grows, mainly on sunny slopes. Although the sunny slope receives most of the solar radiation and their transpiration is the highest, high vegetation coverage on sunny slopes reduces surface evaporation. At the same time, high rainfall on sunny slopes recharges the water supply and promotes the mass water content of soil (Hu et al. 2014).

There is a significant difference between *NDVI* and the mean soil gravel content at different slope aspects. On the shady slope and half shady slope, when soil gravel content range is from 1.04 to 61.16%, the logarithm of the mean soil gravel content and the *NDVI* shows an obvious linear relationship. When the *NDVI* is smaller, the logarithm of the mean soil gravel content is greater. On the sunny slope and half sunny slope, the effect of soil gravel content on vegetation coverage is bidirectional, meaning that the soil gravel content within a certain range distribution is beneficial to the growth of vegetation, but not conducive to the growth of vegetation at other distributions. According to this study, analysis demonstrates
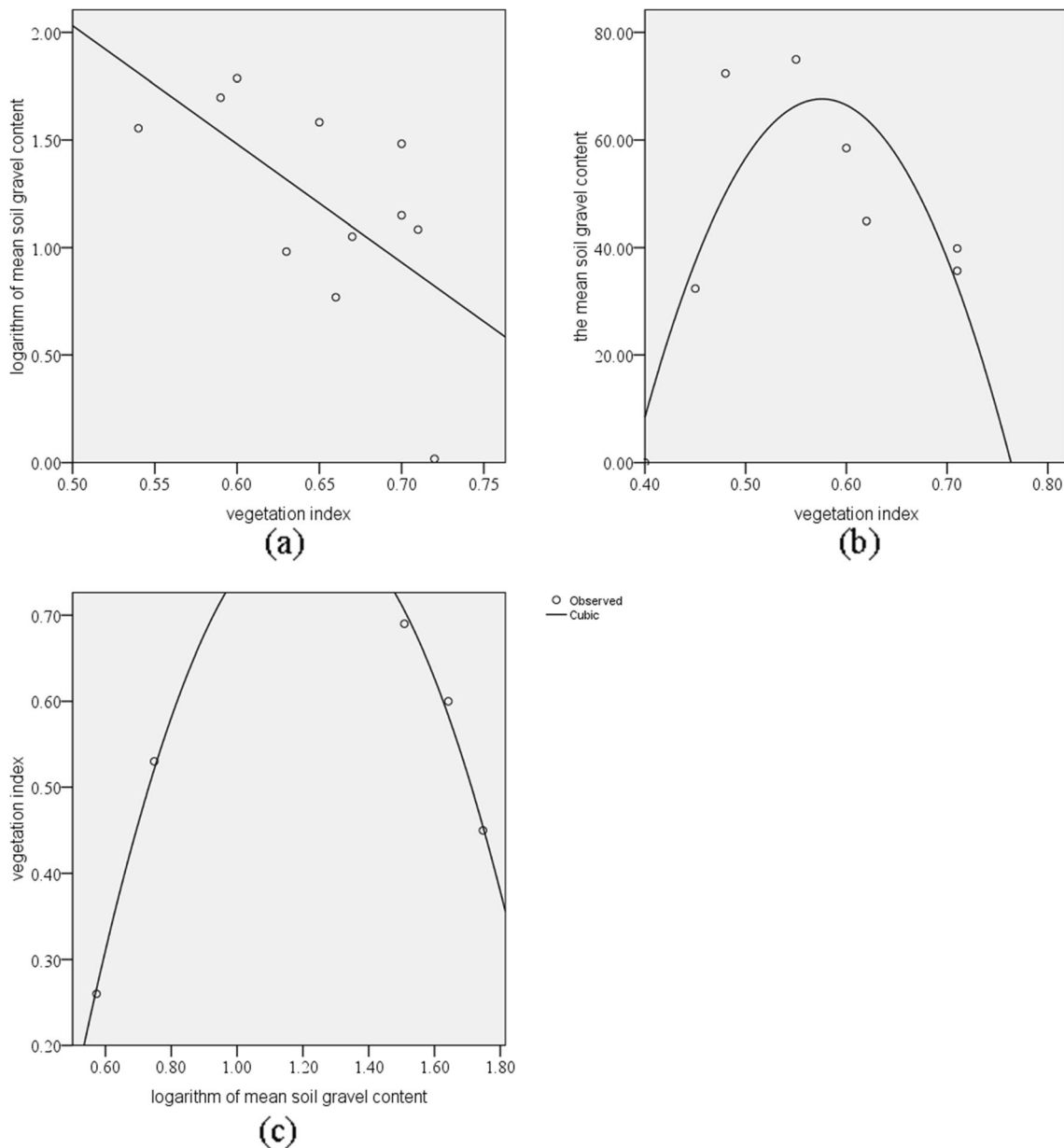
(a)

(b)

○ Observed
— Cubic

(c)

Fig. 6 The relationship between *SGC* of and *VI* at different slope aspects (**a** is shady and half shady slopes, **b** is sunny slope, and **c** is half sunny slope) are different. In plot **a**, $\log_{10}SGC = -5.50VI + 4.78$ ($1.04\% \leq SGC \leq 61.16\%$, $n = 11$, $P = 0.044$); in plot **b**, $SGC = -1918.53VI^2 + 2208.81VI - 568.12$ ($0 \leq SGC \leq 74.96\%$, $n = 8$, $P = 0.040$); in plot c, $VI = -1.30(\log_{10}SGC)^2 + 3.17 \log_{10}SGC - 1.12$ ($3.74\% \leq SGC \leq 55.90\%$, $n = 5$, $P = 0.006$). *SGC* soil gravel content (%), *VI* normalized difference vegetation index (*NDVI*)

vegetation growth is best when the mean gravel content of soil gravel content is 35.00% on the sunny slope. However, vegetation growth is greatest when the mean soil gravel content is 8.27% on half sunny slopes. Although the overall effect is good, a high content of surface soil gravel affects the ability of vegetation to absorb nutrients from the soil (Lawrence and Slater 2007). Conversely, low vegetation coverage could also leave surface soil exposed to water and wind erosion as well as soil texture desertification resulting in an increase of soil gravel content (Arnhold et al. 2015; Rossi and Ares 2016).

Conclusions

Dump vegetation coverage and soil physical properties show a complementary relationship. Fitting relationships showed that soil physical properties influence dump vegetation coverage more obviously; soil physical properties showed clearly positive or negative characteristics when vegetation coverage was high. The characteristics of vegetation coverage and soil physical properties showed a certain discontinuity, and the range of characteristics of certain soil physical properties is different.

The relationship between vegetation coverage and soil physical properties on shady slopes, half shady slopes, sunny slopes, and half sunny slopes is different at different slope aspects. Improving soil physical properties on sunny and half sunny slopes could help plants to grow. In turn, enhancing the growing conditions of plants could also help improve soil quality.

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