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Evaluating relationships between soil chemical properties and vegetation cover at different slope aspects in a reclaimed dump

Xiaoyang Liu[1] · Yingui Cao[1,2] · Zhongke Bai[1,2] · Jinman Wang[1,2] · Wei Zhou[1,2]

Abstract

Conducting research about the relationships between soil chemical properties and vegetation coverage at different slope aspects is especially important in reconstructed ecosystems of vulnerable ecological regions. This study was conducted in the first reclaimed dump within the Pingshuo mining area of Shanxi Province, China, to analyze patterns of soil chemical properties (soil organic matter (SOM), soil total nitrogen (STN), soil available phosphorus (SAP) and soil available potassium (SAp) and vegetation coverage (NDVI) and their correlations at different slope aspects. In the reclaimed dump, 26 quadrats were established along four slope aspects (i.e., shady, semi-shady, sunny and semi-sunny slopes). There was no significant difference in SOM or STN among different slope aspects, while SAP differed between shady slopes compared to semi-shady, sunny and semi-sunny slopes; SAP differed significantly between semi-shady and semi-sunny slopes. The NDVI of semi-sunny slopes differed significantly from that of the other three aspects. There was variation in the relationships between NDVI and soil chemical properties, depending on the slope aspects. The logarithm of SOM and NDVI was related linearly on shady and semi-shady slopes, while NDVI was inversely related to the natural logarithm of the logarithm of SOM on sunny and semi-sunny slopes. STN and NDVI had a first-order function relationship on shady and semi-shady slopes, yet a quadratic function relationship on sunny and semi-sunny slopes. The relationships between SAP and NDVI were inverse on all types of slopes. On shady and semi-shady slopes, NDVI had a quadratic relationship with the logarithm of SAp, but it was well fitted by using a cubic function on sunny and semi-sunny slopes. The sensitivity coefficients of soil chemical properties and NDVI were different, and soil chemical properties changed differently depending on changes in NDVI at different slope aspects.

Keywords Land reclamation · Vegetation coverage · Ecological restoration · Soil chemical properties · Open-pit coal mine · Reclaimed dump · Slope aspect

Introduction

Mining activities generally lead to the destruction of vast amounts of land, vegetation and microbial communities (Sheoran et al. 2010) and cause environmental contamination (Mokhtari et al. 2015). Restoring degraded ecosystems within landscapes that have been mined is an effective method of land reclamation (Cao et al. 2015). Soil quality improvement and vegetation restoration are the core objectives of the reclamation process (Cao et al. 2016). Nutrient cycling processes via soil and vegetation satisfy the nutrient demands for life that underpins all other ecological services (Press 2006), so soil chemical properties and vegetation cover are two of the most important factors that reflect the quality of land reclamation, such as in coal mining areas. It is therefore important for researchers to evaluate the relationships between soil chemical properties and vegetation cover, in order to keep the ecosystems of reclaimed dumps stable and healthy.

Numerous studies have attempted to explain the relationships between soil chemical properties and vegetation

✉ Yingui Cao
caoyingui1982@126.com

✉ Zhongke Bai
baizk@cugb.edu.cn

[1] School of Land Science and Technology, China University of Geosciences (Beijing), Haidian District, Beijing 100083, People's Republic of China

[2] Key Laboratory of Land Consolidation and Rehabilitation, Ministry of Land and Resources, Beijing 100035, People's Republic of China

cover, which are especially complex in reclaimed dumps within fragile ecosystems (Cao et al. 2016; Zhang et al. 2016). Vegetation cover can improve some soil properties (Bronick and Lal 2005; Puigdefabregas 2005; Ruiz-Colmenero et al. 2013), while simultaneously minimizing erosion (Cammeraat and Imeson 1999; Holwerda et al. 2010) and the dissemination of contaminants (Mendez and Maier 2008). In turn, soils facilitate the establishment of vegetation. For example, the soil seed bank is generally viewed as an important factor that influences vegetation restoration (Kalamees et al. 2012). The relationships between soil chemical properties and vegetation coverage on different slope aspects are expected to be even more complex. Numerous studies indicate that different distributions of soil chemical properties and vegetation coverage are related to topographic positions (Sidari et al. 2008; Nadal-Romero et al. 2014; Lozano-Garcia et al. 2016); slope aspect complicates such correlations because it affects microclimates by changing distributions of precipitation and temperature (Sternberg and Shoshany 2001; Ghosh et al. 2014). Most existing results are based on naturally formed ecosystems, with few analyses of the relationships between soil chemical properties and vegetation cover in reclaimed dumps within mining areas. Therefore, we studied the relationships between soil chemical properties and vegetation cover on different slope aspects in a dump using statistic method and fitting analysis. By concentrating sampling in the same dump with the same reclamation time, reclamation techniques, management measures and other potential factors, we hypothesized that slope aspects would exert the most important influence on soil chemistry and vegetation coverage.

Materials and methods

Study area

This study was carried out in the reclaimed dump of the Antaibao open-cast coal mine (Fig. 1) in Shanxi Province, China. The location experiences a typical, temperate arid and semiarid continental monsoon climate, with average annual temperature 4.8–7.8 °C and 428.2–449.0 mm of average annual precipitation. It is an ecologically fragile area with low vegetation coverage and a great number of gullies because of serious erosion by wind and water.

The study area is approximately 186 ha, and the elevation of the dump is 1360–1465 m. It received coal mine soils and wastes from 1985 to 1989 and was reclaimed with a mix of fast-growing vegetation species (herb–shrub–arbor) from 1992 to 1995. The dominant plant species in the dump include *Pinus tabuliformis*, *Ulmus pumila*, *Robinia pseudoacacia*, *Medicago sativa* and *Hippophae rhamnoides*. The dominant soil types are loess, laterite and red loess, and the average thickness of surface soil in the dump is ~ 100 cm.
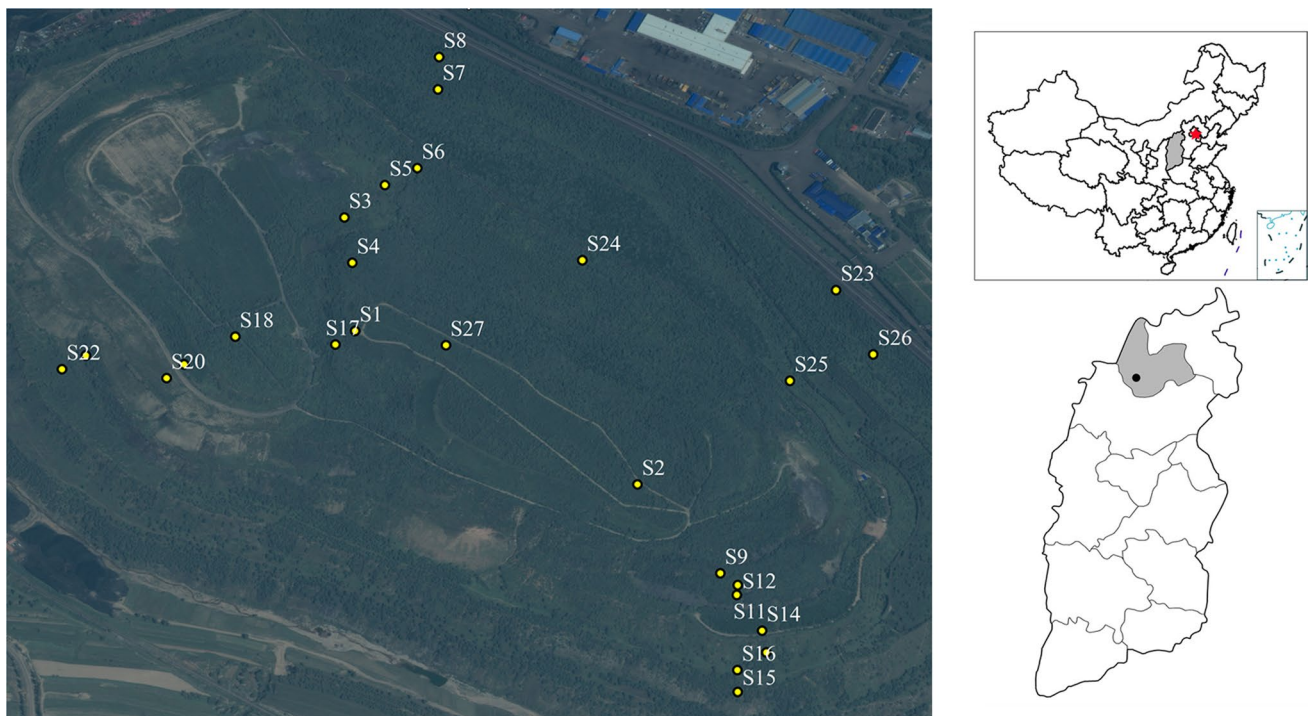
Fig. 1 Study area and sampling quadrats in a reclaimed dump within a coal mining area of Shanxi, China

Soil sampling and data sources

We designed the sampling plan according to the slope aspects, site conditions and total area of the dump. The number of quadrats ($N = 26$) was determined to cover all the basic slopes and platforms from the top to the foot of the dump, while also considering accessibility. Because it was difficult to access the quadrat S_{10}, we chose a new quadrat nearby and numbered it S_{11}; the remaining numbers were changed accordingly. Sampling was conducted in early July 2014, with the quadrats distributed along four slope aspects (shady, semi-shady, sunny or semi-sunny slopes; Fig. 1). Inclinations were $35°−45°$ for quadrats in the slopes and $0°−2°$ for quadrats in the platforms. Each quadrat was $10\,m \times 10\,m$ at the platform and had a guaranteed $10\,m \times 10\,m$ vertical projection area at the slope, with a 10 m width and a variable length based on the slope. Each quadrat was labeled with stakes at the corners and located with the coordinates of its center using GPS. Figure 1 shows the distribution of each quadrat in the dump. A five-point sampling method was used in the quadrats. Surface soil samples (0–10 cm) were collected with an earth-boring auger, mixed and stored in cloth bags and serially numbered ($N = 26$).

All samples were air-dried, crushed and sieved through a 2-mm polyethylene sieve, before the analysis of the soil chemical properties. Soil organic matter (SOM) was determined with an oil bath $K_2Cr_2O_7$ volumetric method, soil total nitrogen (STN) was measured with the semi-micro-Kjeldahl method, soil available phosphorus (SAP) was measured with an adapted Olsen method, and soil available potassium (SAp) was measured with a 1.0 mol/L NH_4OAc extraction and flame photometry (Bao 2000).

Regional vegetation cover parameters are measured directly with remotely sensed images, which can reflect vegetation trends at different spatial scales. Studies have shown that the normalized difference vegetation index (NDVI) provides a good indication, so it has been used frequently for assessing vegetation cover (Do et al. 2014; Detsch et al. 2016; Zewdie et al. 2017). Locations with high NDVI also tend to have high tree crown density or high herb coverage (Bao et al. 2013; Qi et al. 2000; Zhang et al. 2016).

We used remotely sensed images from the satellite SPOT-6 (Shibao Satellite Imagery Corporation in Beijing, China), and the sensor was Reference 3D. The date of the image is July 14th, 2015, and spatial resolution was 6 m. The data for NDVI value of each quadrat were extracted from the remote sense image using formula (1) (Deering 1978).

$$NDVI = (NIR − R)/(NIR + R) \tag{1}$$

where NIR represents near-infrared band reflectance values, and R represents red band reflectance values.

Statistical methods

We employed multiple statistical methods to assess potential differences and relationships between soil chemical properties and vegetation cover on the different slope aspects, using the software SPSS 19.0 (SPSS, Chicago, IL, USA). Soil chemical properties and NDVI were compared among slope aspects using one-way ANOVA ($\alpha = 0.05$ for soil chemical properties and $\alpha = 0.1$ for NDVI). An F test was performed to detect differences in soil chemical properties and NDVI.

Fitting analysis was used to reflect the relationships between soil chemical properties and NDVI. One-way ANOVA was also used after the fitting to confirm the significance of the regression equations. The slope of best fit between soil chemical property and NDVI has been used frequently to reflect sensitivity. We also adopted this sensitivity coefficient, which was calculated using formula (2) (Zhang et al. 2005):

$$S = \Delta y/\Delta x \tag{2}$$

where Δy is the change of soil chemical property, Δx is the change of NDVI, and S is the sensitivity coefficient.

Results and analysis

Relationship between SOM and NDVI

There were no significant differences in soil organic matter (SOM) among all slope aspects or in NDVI on shady, semi-shady and sunny slopes (Fig. 2), although there was a general trend that the SOM at shady slopes were higher than that at sunny slopes. However, NDVI of semi-sunny slopes differed significantly from that of the other slopes (Fig. 2), suggesting that SOM and NDVI had different sensitivities to slope aspects. Kutiel and Lavee (1999) similarly found that SOM did not differ between northern and southern slopes in a Mediterranean region. Therefore, the fitting relationships between SOM and NDVI were built at shady and semi-shady slopes, sunny and semi-sunny slopes (Fig. 2).

On shady and semi-shady slopes, the average value of SOM was 46.43 g/kg, more than double the value on corresponding slopes of a hilly area in Sichuan province, China (Deng et al. 2013). The average value of NDVI was 0.65 in our study. NDVI and the logarithm of SOM were linearly related (Fig. 3a), with log SOM tending to decline as NDVI increased. That agrees with related previous studies showing that the distributions of soil chemical properties are greatly influenced by sunlight (Yang et al. 2014). On shady and semi-shady slopes, due to lower availability of solar radiation, the ground temperature was low and the conversion rate of litter to SOM slowed down (He et al. 2004; Zheng et al. 2014), while vegetation grew well and

Fig. 2 Differences in soil chemical properties and NDVI at different slope aspects
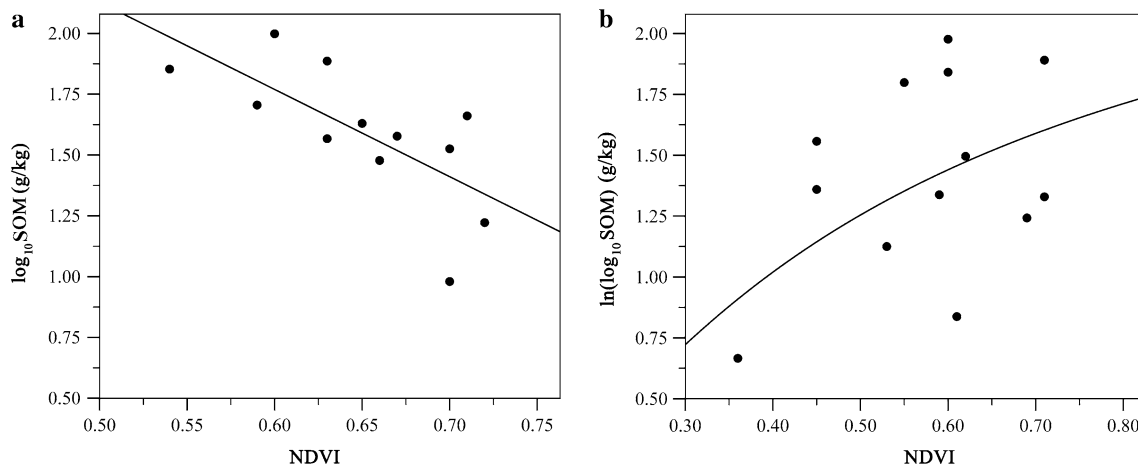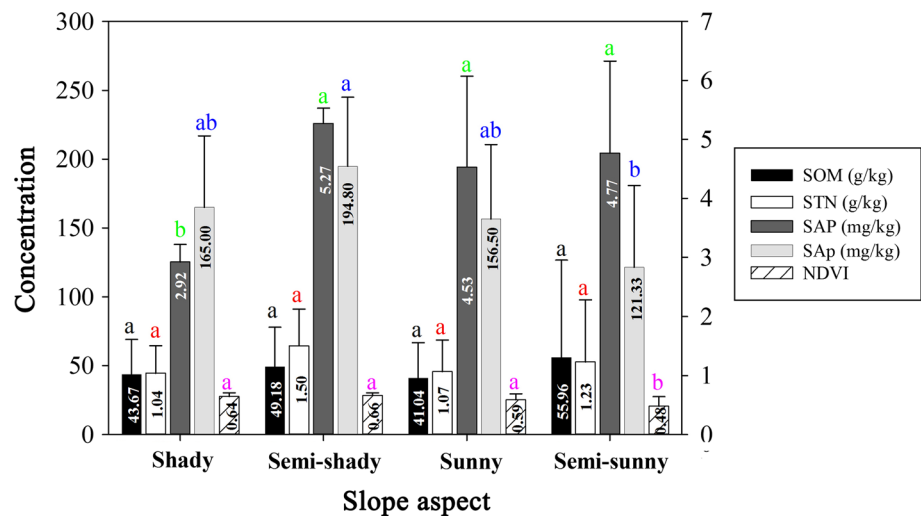
Fig. 3 Relationships between SOM and NDVI at different slope aspects: **a** on shady and semi-shady slopes: $\log_{10}^{SOM} = -3.59$ NDVI $+ 3.92$ $(9.55 \leq SOM \leq 99.63, n = 12, \text{Sig.} = 0.011)$; **b** on sunny and semi-sunny slopes: $\ln^{(\log_{10}SOM)} = -0.41/NDVI + 1.06$ $(4.63 \leq SOM \leq 94.72, n = 13, \text{Sig.} = 0.076)$

consumed much more soil nutrients. The consumption of SOM was greater than its generation (Qin et al. 2008).

On sunny and semi-sunny slopes, the average value of SOM was 48.50 g/kg, and the average value of NDVI was 0.54. NDVI was inversely related with the natural logarithm of the logarithm of SOM (Fig. 3b). As NDVI increased, SOM showed an increasing trend, indicating a positive correlation in agreement with previous studies that SOM is higher on sunny and semi-sunny slopes than on shady and semi-shady slopes (Guo et al. 2003; Fan et al. 2014). On sunny and semi-sunny slopes, SOM decomposition was quicker because of the dry soil conditions (Zheng et al. 2014). SOM is entirely supplemented by litter: faster-growing, denser vegetation can provide more litter, which ensures the supply of SOM (Austin and Vivanco 2006; Dou et al. 2012).

The sensitivity coefficients of SOM to NDVI were -0.002 on shady and semi-shady slopes and 0.01 on sunny and semi-sunny slopes. Thus, SOM was more sensitive to NDVI on sunny and semi-sunny slopes than on shady and semi-shady slopes. This indicated that if NDVI or vegetation coverage increased moderately, the increase in SOM would be more obvious on sunny and semi-sunny slopes.

Relationships between STN and NDVI

There were no significant differences between different slope aspects for soil total nitrogen (STN) (Fig. 2), which followed the pattern of SOM distribution due to the fact that most nitrogen forms part of SOM (Ganuza and Almendros 2003). There were also no differences in NDVI on shady, semi-shady and sunny slopes, while NDVI of those aspects was

significantly different from sunny slopes (Fig. 2). In view of this, the fitting relationships between STN and NDVI were established at shady and semi-sunny slopes, and sunny and semi-sunny slopes, respectively (Fig. 4).

On shady and semi-shady slopes, the average value of STN was 1.27 g/kg, which was much higher than that of soils on a loess plateau in Hengshan County (Lian et al. 2008). The average value of NDVI was 0.65. Similar to the relationship between SOM and NDVI, STN and NDVI also showed a first-order function relationship at these two slope aspects: as NDVI increased, STN tended to decrease (Fig. 4a). On the one hand, nitrogen in soil comes mainly from the mineralization of SOM. Shady and semi-shady slopes are less affected by solar radiation, so the decomposition rate of SOM mineralization decreases due to insufficient sunlight (Yang et al. 2014). On the other hand, vegetation is lush and vegetation coverage is high on shady and semi-shady slopes, where vegetation growth increases due to the absorption of nitrogen from soils (Wang et al. 2001; Qin et al. 2008).

The relationship between STN and NDVI on sunny and semi-sunny slopes was best expressed as a quadratic function. With an increase in NDVI, STN showed a trend of first increasing and then decreasing (Fig. 4b). On sunny and semi-sunny slopes, the average value of STN was 1.15 g/kg and the average value of NDVI was 0.54, and both measures were lower than those on shady and semi-shady slopes. When the NDVI was < 0.53, STN showed an increasing trend as NDVI increased. On sunny and semi-sunny slopes, the mineralization rate of SOM was relatively high. When vegetation cover is moderate, the consumption rate of nitrogen is slightly lower than the mineralization rate of SOM (Liu et al. 2010), so STN increases. When NDVI exceeded 0.53, STN decreased as NDVI increased. Due to the high

amount of vegetation cover, the sunlight was blocked, which influences the mineralization and decomposition of SOM (Yang et al. 2014). Meanwhile, the consumption of nitrogen from soils was high due to the lush vegetation on these slopes (Wang et al. 2001; Qin et al. 2008).

The sensitivity coefficient of STN to NDVI was − 0.16 on shady and semi-shady slopes, and the absolute value of the sensitivity coefficient was 0.17 on sunny and semi-sunny slopes. That is, the sensitivity of STN to NDVI was higher on sunny and semi-sunny slopes than on shady and semi-shady slopes. We can also conclude that if vegetation cover or NDVI increased moderately, the corresponding increase of STN on sunny and semi-sunny slopes would be more obvious.
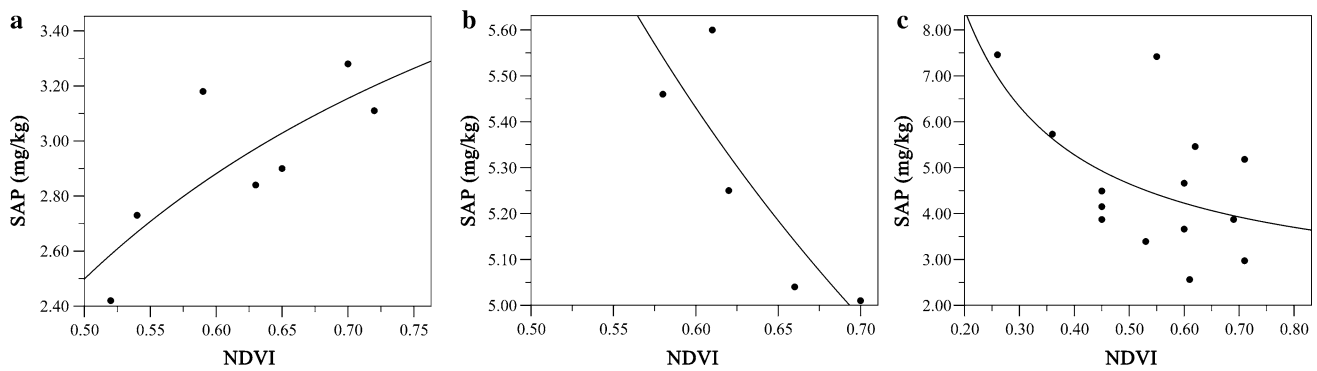
Relationships between SAP and NDVI

There was a significant difference in soil available phosphorus (SAP) between shady slopes compared to semi-shady, sunny and semi-sunny slopes, while NDVI of semi-sunny slopes differed significantly from that of the other three types (Fig. 2). In view of this, the fitting relationships between SAP and NDVI were established from shady and semi-shady slopes, and sunny and semi-sunny slopes, respectively (Fig. 5).

Based on the fitting analysis, the relationship between SAP and NDVI had an inverse function for all slope aspects. On shady slopes, the average SAP was 2.92 mg/kg and the average NDVI was 0.64. SAP and NDVI were inversely related (Fig. 5a): as NDVI increased, SAP increased. The vegetation cover on shady slopes was high, and the sampling area was characteristic with the gentle slope. The leaching effect of rainwater was relatively weak, so SAP can be retained in the soils as much as possible (Yang et al. 2014).
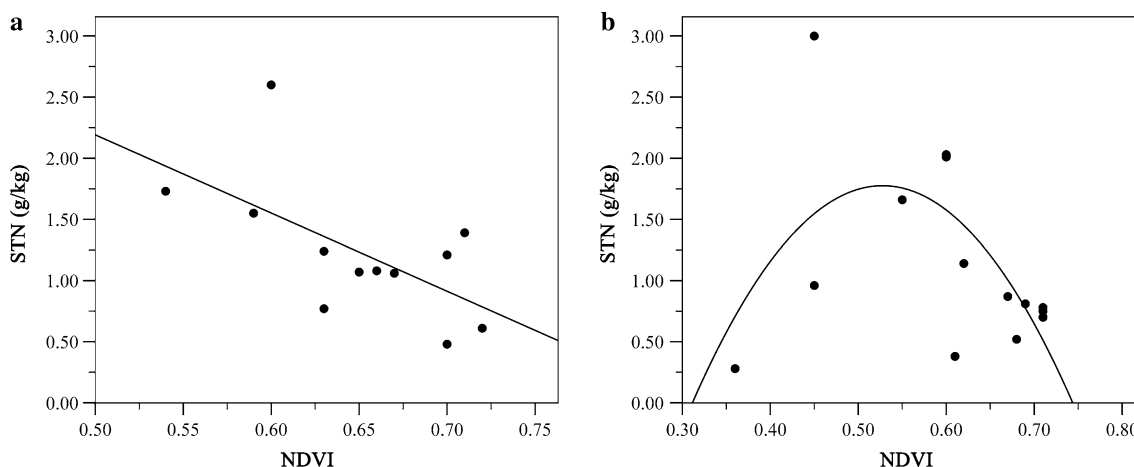
Fig. 4 Relationships between STN and NDVI at different slope aspects: **a** on shady and semi-shady slopes: STN = − 6.40 NDVI + 5.39 (0.48 ≤ TN ≤ 2.60, n = 12, Sig. = 0.031); **b** on sunny and semi-sunny slopes: STN = − 37.99 NDVI^2 + 40.09 NDVI − 8.80 (0.28 ≤ TN ≤ 3.00, n = 14, Sig. = 0.072)

Fig. 5 Relationships between SAP and NDVI at different slope aspects: **a** on shady slopes: SAP = − 1.15/NDVI + 4.79 (2.42 ≤ SAP ≤ 3.28, $n = 7$, Sig. = 0.035); **b** on semi-shady slopes: SAP = 1.92/NDVI + 2.23 (5.01 ≤ SAP ≤ 5.60, $n = 5$, Sig. = 0.067); **c** on sunny and semi-sunny slopes: SAP = 1.26/NDVI + 2.12 (2.56 ≤ SAP ≤ 7.46, $n = 14$, Sig. = 0.037)

On semi-shady slopes, the average SAP was 5.27 mg/kg, and the average NDVI was 0.66. SAP and NDVI were negatively correlated: as NDVI increased, SAP showed a decreasing trend (Fig. 5b). The slope was high and steep on this aspect, although the vegetation cover was high, so the loss of SAP persisted due to leaching by rainwater. In addition, vegetation grew well: with high vegetation cover on semi-shady slopes, the SAP demand for vegetation growth increased, especially during the period of rapid vegetative growth, and the supply of phosphorus lagged behind the consumption of phosphorus in soils (Chen et al. 2012; Wang et al. 2012).

Similarly, the relationship between SAP and NDVI was described well by an inverse function on sunny and semi-sunny slopes (Fig. 5c). As NDVI increased, SAP decreased. On sunny and semi-sunny slopes, the average SAP was 4.65 mg/kg, and the average NDVI was 0.54. At these slope aspects, quadrats were distributed mainly in areas of middle to high elevation, and middle steep to high steepness of the slopes. The loss of SAP was obvious, especially in areas with low vegetation cover. With the increase in NDVI, the declining rate of SAP in soil slowed down, indicating the enhanced effect of vegetation in intercepting soil erosion (Chen et al. 2012). In addition, the phosphorus supply continued to lag behind phosphorus consumption in soils (Chen et al. 2012; Wang et al. 2012).

The sensitivity coefficients of SAP to NDVI were 0.33, − 0.20 and − 0.14 on shady, semi-shady, and sunny and semi-sunny slopes, respectively. SAP was clearly most sensitive to NDVI on shady slopes, indicating that an increase in vegetation cover or NDVI on shady slopes would further promote the increase of SAP.
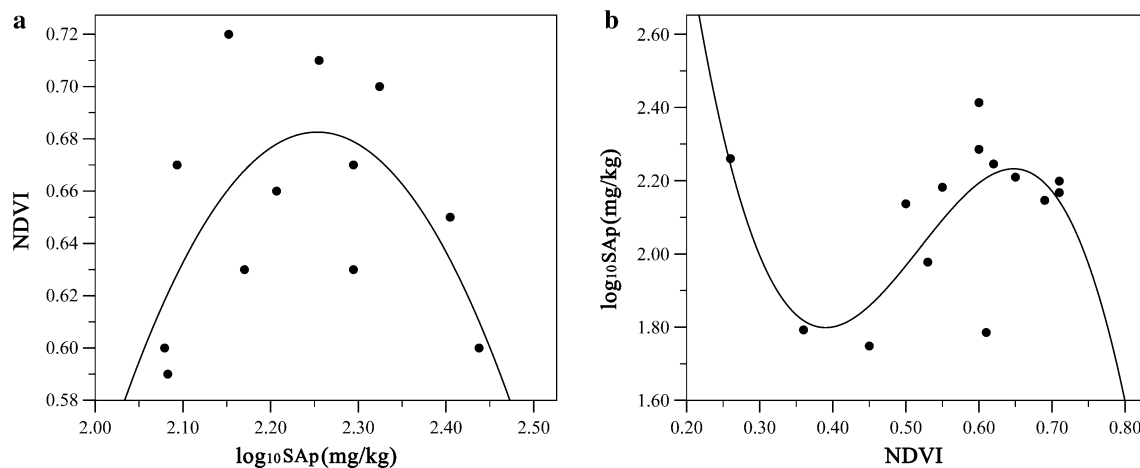
Relationships between SAp and NDVI

Soil available potassium (SAp) at semi-shady slope differed significantly from that at semi-sunny slopes, while there was a significant difference in NDVI between semi-sunny slopes and the other three aspects (Fig. 2). Thus, the fitting relationships between SAp and NDVI were established at shady and semi-shady slopes, and sunny and semi-sunny slopes, respectively (Fig. 6).

On shady and semi-shady slopes, there was a quadratic relationship between NDVI and the logarithm of SAp (Fig. 6a). NDVI first increased and then decreased, with an increased logarithm of SAp. At these slope aspects, the average SAP was 179.90 mg/kg, approximately reaching the average SAp found the four shady slopes of the hilly grassland in the Xilin River Basin, Inner Mongolia, China (Gong et al. 2008). The average value of NDVI was 0.65. When the logarithm of SAp was < 2.25 mg/kg, the well-conserved soil and water were favorable for preventing the loss of SAp in soils due to the high vegetation cover (Liu et al. 2006; Dai et al. 2008). In addition, the vegetation cover was high and the litter on the ground was thick. Rich SOM promotes the enrichment of SAp in soils (Peng et al. 2004; Chen et al. 2014). When the logarithm of SAp exceeded 2.25 mg/kg, as the logarithm of SAp increased, NDVI decreased. In general, SAp and vegetation growth were positively correlated. Lu et al. (2011) found an obvious promotion of vegetation growth when SAp increased, but only when SAp was low; above a certain value, the promoting effect declined.

On sunny and semi-sunny slopes, the average SAp was 138.92 mg/kg, and the average NDVI was 0.54. The logarithm of SAp and NDVI was well fitted with a cubic function (Fig. 6b). The general trend in variation showed that the logarithm of SAp first increased and then decreased with the increase in NDVI. When NDVI was < 0.38, the logarithm of SAp declined with increased NDVI, which may be attributed to the leaching of SAp due to lower vegetation cover, slightly more rainfall and steeper slope at sunny and semi-sunny slopes (Liu et al. 2006; Dai et al. 2008). When NDVI was between 0.38 and 0.65, SAp was positively correlated with NDVI; at NDVI > 0.65, SAp continued to decrease

Fig. 6 Relationships between SAp and NDVI at different slope aspects: **a** on shady and semi-shady slopes: $NDVI = -2.13(\log_{10}^{SAp})^2 + 9.59(\log_{10}^{SAp}) - 10.12$ ($120 \leq SAp \leq 274$, $n = 12$, Sig. = 0.098); **b** on sunny and semi-sunny slopes: $\log_{10}^{SAp} = -50.87\ NDVI^3 + 79.20\ NDVI^2 - 38.57\ NDVI + 7.81$ ($56 \leq SAp \leq 259$, $n = 14$, Sig. = 0.093)

with the increasing NDVI, which may have been due to the increasing consumption of SAp by vegetation.

The absolute value of sensitivity coefficients of SAp to NDVI was 0.0008 and 0.0013 on shady and semi-shady slopes, and sunny and semi-sunny slopes, respectively. The low sensitivity coefficients on these slope aspects implied that the change of vegetation coverage or NDVI would exert little influence on SAp.

Discussion

Impacts of slope aspects on soil chemical properties and vegetation coverage

The microclimates of different slope aspects exert important influences on both the rate of microbial decomposition and the mineralization of SOM. Slope aspect influences SOM by affecting soil water, soil erosion and sedimentation processes, as well as microclimates and the species composition of vegetation community (Huang et al. 2015). Much research has shown that SOM distribution in topsoil is influenced greatly by slope aspect (Gebrelibanos and Assen 2014; Zhao et al. 2016). However, this was not the case in our study site: although there was a trend for relatively higher SOM on sunny slopes, there was no significant difference among slope aspects. Similar findings of no difference among varying slope aspects have also been reported for certain vegetation types (Sharma et al. 2010), land use types (Huang et al. 2015) and land use changes (Abu-hashim et al. 2016). In general, there are small differences in some soil nutrients among varying slope aspects or no difference in some cases (Kutiel 1992). Higher values of carbon and nitrogen content can be found at places where vegetation cover is high (Jeong

et al. 2017). In this study, the high vegetation fraction that provides abundant litter sources may also help to weaken the variability of SOM among different slope aspects.

STN is an essential nutrient for plant growth and is generally viewed as a limiting nutrient in most ecosystems (Fenn et al. 1998; Splittstoesser 1990). Conditions on shady slopes are more suitable for nitrogen mineralization and the accumulation of organic and inorganic nitrogen (Zhang et al. 2010; Qin et al. 2008). Generally, STN in soils of shady slopes is higher than that of sunny slopes (Sariyildiz et al. 2005). However, some studies have found no difference in STN on sunny versus shady slopes (Khormali et al. 2007; Ajami et al. 2016) and these results are consistent with ours. Our result may be explained by the arid nature due to low rainfall and high potential evaporation, which was supported by the evidence of Kutiel and Lavee's study (Kutiel and Lavee 1999).

Compared with STN, other available nutrients including SAP and SAp are more representative of soil fertility and are more important for vegetation growth (Wang et al. 2014). Variations in precipitation, temperature and insolation among different slope aspects can trigger different soil properties (Fisk et al. 1998). Similar to some other studies (Måren et al. 2015; Chu et al. 2016), SAP and SAp both differed significantly among some slope aspects in this study, which implies that these two nutrients were more sensitive to slope aspects within the dump than were SOM and STN.

Soil water is an important pathway for nutrient absorption by vegetation, and slope aspects affect vegetation through nutrient cycling (Yuan et al. 2015). Due to the higher water content of soils on shady slopes, forests are mainly distributed on shady slopes, while grasses or shrubs occupy sunny slopes (Fang and Guo 2015). Meanwhile, prior studies have revealed that vegetation cover is lower on sunny slopes than

on shady slopes, due to the high water stress on sunny slopes (Marque and Mora 1992; Nyssen and Vermeersch 2010), which was similar to our finding here that the distribution of vegetation varied among slope aspects.

As discussed above, there were no effects of slope aspect on some soil properties (e.g., SOM and STN). This may be because the soil in our unique study area was reconstructed after mining and land reclamation, as human disturbance and mining activities are important factors that greatly affect vegetation and soil properties (Cao et al. 2015; Måren et al. 2015; Huang et al. 2010). In the process of mining and dumping, soils were mixed and compacted by large machinery; after dumping and land reclamation, the artificial terrain was further altered with the creation of platform and side slope formations. Different terrain features created the widely contrasting microclimates across the dump. We have studied the effects of terrain factors on vegetation and found the significant effect of some factors (i.e., elevation and slope) on vegetation in the reclaimed dump (Liu et al. 2016). Among terrain variables, slope length is the principal factor used to calculate soil loss (Adugna et al. 2015). In the artificial dump, the slope length is shortened by landforms, thus reducing soil erosion and complicating the relationships between soil properties and NDVI on the different slope aspects. This may be one important cause of the lower variation of some soil properties (e.g., SOM and STN) among slope aspects.

Specified conditions of fitting analyses between soil chemical properties and NDVI

In this study, the fitting relationships between soil chemical properties and NDVI are based on three specified conditions—slope aspects, ranges of soil chemical properties and the adoption of mathematical methods. The impacts of specified slope aspects on the fitting relationship are indicated in Results and Sect. 4.1.

Shelford's law of tolerance indicates that organisms can tolerate a given environmental factor from the upper to lower bound; that is, if one environmental factor is too scarce or too abundant, or is deficient in quality, it becomes the limiting factor to organisms (Shelford 1911). So, based on Shelford's law and the fitting relationships, if the relationship between a soil chemical property and NDVI is positive in the specified range, then the soil chemical property would have an obvious positive effect on vegetation, promoting cover; in contrast, if the relationship is negative in the specified range, it would have a restrictive effect on vegetation. Although there are few published studies about the tolerance range of vegetation cover to soil chemical properties, some results have demonstrated the tolerance of other vegetation variables to soil chemical properties. Some results indicate that species-rich grasslands tend to occur on very infertile

soils (Marrs 1993), and where nutrient concentrations (particularly SAP) increase, it is difficult to re-establish the original grassland communities (Critchley et al. 2002; Başnou et al. 2009). Increasing nutrient supplies (STN, SAP, SAp) usually cause a decline in species richness (Janssens et al. 1998; Critchley et al. 2002; Marini et al. 2007). Besides, soil and vegetation are thought to interact normally with each other under all kinds of environmental conditions (Martinez-Fernandez et al. 1995; El-Ghani and Amer 2003). The semi-shrub *Artemisia ordosica* adapts well to low-nutrient soils and might easily form nutrient islands under its canopy, which fosters their existence (Xie et al. 2015), and there are some similar relationships between SOM, STN, SAP, SAp and NDVI at some specified ranges in this study.

The fitting relationships between soil chemical properties and NDVI were based on the adoption of specified mathematical methods. One is the logarithmic transformation of original data, and the other is the selection of fitting equations. Logarithmic transformation can not only maintain the relative relation among data, but also reduce the difference among data (Gao et al. 2017). There is significant heterogeneity of reclaimed soil chemical properties in our study area (Cao et al. 2016), so it was necessary to use a logarithmic transformation to reduce differences. Further, choosing the proper fitting equations is necessary to characterize the relationships between soil chemical properties and NDVI. The chosen fitting equations can not only satisfy *the assumptions* of the F test, but can also accord with the mechanism that links soil chemical properties and NDVI, and can be similar to the prior studies cited in Results and Sect. 4.1.

Implications for land reclamation techniques and vegetation restoration management

The sensitivities of soil quality indicators to land use types have been analyzed by some researchers. Caravaca et al. (2002) evaluated the effect of land use on the sensitivity indexes for different forms of SOM in a semiarid environment. Raiesi (2017) calculated the sensitivity indexes of soil attributes to land use types in rangelands and croplands. However, little research has been reported about the sensitivity of soil properties to vegetation cover. From calculating the different sensitivity coefficients between soil chemical properties and NDVI, we found that soil chemical properties tended to be more sensitive to NDVI on sunny and semi-sunny slopes than were any other variables except for SAP. It is widely accepted that shady and sunny slopes differ notably in net solar radiation, which drives a series of other ecological differences in factors such as soil temperature, soil water and microbial activities (Beaudette and O'Geen 2009; Dorji et al. 2014). The higher soil temperature on sunny slopes accelerates microbial activity, which accelerates the processes of litter decomposition and transformation, and hence

the return of nutrients from vegetation to soil. This is one important reason why soil chemical properties had higher sensitivity coefficients to vegetation cover on sunny slopes.

The soil vegetation environment is a mutually interacting system. Since soil properties were more sensitive to vegetation cover on sunny slopes, the soil vegetation system there seemed to be more fragile than on other slopes. This suggests that special attention should be paid to sunny slopes during the management practices of land reclamation and vegetation restoration. Soil properties can be improved gradually over time with the establishment of artificial vegetation (Su et al. 2008), but process may be slow, usually taking decades for some soil properties (e.g., SOM) to recover to close to natural levels (Liu et al. 2017). To maintain the stability of soil vegetation systems on sunny slopes, quick establishment of vegetation is the key to the initial stage of land reclamation. Vegetation properties and growth are particularly sensitive to soil moisture in semiarid and arid environments (Magagi and Kerr 2001; Piao et al. 2007), but water levels are generally insufficient in the arid loess plateau area, especially on sunny slopes. Therefore, increasing soil water content (e.g., via drip irrigation technology) in artificial management has proven to be an effective way to keep the soil vegetation system stable on sunny slopes. Additionally, we should take advantage of the sufficient sunlight on sunny slopes and construct vertical ecosystems of grasses, bushes and trees. The good vegetation cover not only effectively utilizes sunlight, but also prevents soil water evaporation, which would help to promote the development of the soil vegetation system in managed landscapes.

Conclusions

Centering on the relationships between soil chemical properties and NDVI, this paper tested the differences of SOM, STN, SAP and SAp at different slope aspects and their fitted relationships with NDVI. We found that SAP and SAp were more sensitive to slope aspects than were SOM and STN. Further, soil chemical properties were more sensitive to NDVI on sunny and semi-sunny slopes. The relationships between soil chemical properties and NDVI as fitted by mathematical equations were complex, and they differed between different soil chemical properties and different slope aspects. The sensitivity coefficients of soil chemical properties to vegetation coverage or NDVI were different, and the soil chemical properties changed differently with changes in vegetation cover or NDVI at different slope aspects. This study may help us to understand the change of soil and vegetation at different slope aspects and provide baseline information to improve techniques for land reclamation and vegetation restoration.

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