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Spatial Distribution and Regulating Factors of Soil Nutrient Stocks in Afforested Dump of Pingshuo Opencast Coalmine, China

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Abstract: Determining the regulating factors of soil nutrient variations can guide the implementation of land reclamation measures in opencast coalmine regions. In this study, 132 soil samples were collected at 22 sample sites in the South Dump of Pingshuo opencast coalmine, and soil physicochemical properties were separately measured to obtain the related soil information. Geostatistical analyses were employed to analyze the spatial distribution patterns of soil organic carbon stocks (SOCD), total nitrogen stocks (TND), available phosphorus stocks (APD), and available potassium stocks (AKD) at 0–60 cm. The results showed that the spatial distributions of these soil nutrient stocks were characterized by moderate (TND) to strong (SOCD, APD, and AKD) spatial dependence. Meanwhile, the values of SOCD (16.4–60.1 Mg ha^{-1}) and TND (1.9–15.5 Mg ha^{-1}) were much higher than those of APD (0.022–0.095 Mg ha^{-1}) and AKD (0.31–1.40 Mg ha^{-1}). The statistical analyses indicated that the influence of afforestation on SOCD, TND, APD, and AKD was not significant, and the dynamic variations of soil nutrient contents were mainly regulated by soil pH in the South Dump. The findings of this study can provide some scientific guidance for soil nutrient management in the opencast coalmine regions of similar ecosystems.

Keywords: soil nutrient stocks; opencast mining; land reclamation; Loess Plateau

1. Introduction

The cost-effective opencast mining is a widely employed exploitation method for mineral resources all over the world, the high-intensity and large-scale mining activities of which have caused severe damages to the ecosystems of original mining regions [1–3]. Moreover, most of China's opencast coalmine is distributed in the ecologically fragile regions of Loess Plateau, where the local soils are mainly characterized by poor structure and low soil fertility [4–6]. Land reclamation has been proven to be the most effective method for the restoration of the ecological environment in opencast coalmine regions, which mainly comprises revegetation, soil reconstruction, and landform remodeling [7]. Soil fertility is an essential indicator for land reclamation quality, which can be directly reflected by soil nutrient contents [1,8]. Moreover, soil nutrient conditions also determine the spatial vegetation configurations in degraded opencast coalmine regions [1,9]. Therefore, it is of great significance to explore the spatial distribution patterns and regulating factors of soil nutrient stocks in the reclaimed land of opencast coalmine regions.

Soil organic carbon (SOC), total nitrogen (TN), available phosphorus (AP), and potassium (AK) are necessary macronutrients for the growth and productivity of vegetation, which can significantly regulate terrestrial functions by influencing soil physicochemical properties and the activities of soil microorganisms [10–12]. Generally, soil nutrient stocks are determined by the balance between organic matter input from regional biota and the losses from vegetation utilization and microbial respiration [13,14]. Previous studies have reported that the biogeochemical cycling of SOC, TN AP, and AK was greatly affected by natural processes (e.g., decomposition, leaching, and adsorption/desorption) and anthropogenic activities (e.g., fertilization, weeding, and afforestation) [15–17]. For instance, He et al. [18] explored the succession of soil C, N, P, and K stocks in Masson pine ecosystems and they found that the plantations of Masson pine significantly altered soil nutrient stocks and that soil physicochemical properties were the dominant influencing factors for these variations. Li et al. [19] found that the contents of SOC, TN, AN, and AK in woodland were much higher than those in grassland, shrubland, and cropland, but land-use types did not significantly affect other soil nutrient contents (e.g., TP and TK); they also drew the conclusion that climate factors, soil texture, and pH induced the variations of soil nutrient contents. The conclusions of regional-scale studies might contrast with each other due to the difference in climate, geological background, and soil conditions [20], which highlights the significance of regional studies into different ecosystems. Different from natural soils, reclaimed soils are much more heterogeneous and compact due to the irregular mixing of different materials (e.g., plant residues, fly ash, and soil particles) and the compaction of it by heavy machinery [21,22]. However, most studies were carried out in natural ecosystems, whose findings cannot directly guide the land reclamation practice in the ecosystems of opencast coalmine. Moreover, most studies only estimated the stocks of SOC (SOCD), TN (TND), AP (APD), and AK (AKD) at 0–20 cm, while recent studies revealed that soil nutrient stocks in deep soil horizon are also obviously influenced by anthropogenic and natural disturbances [23–25]. Therefore, more studies are required to explore the variations and influencing factors of the SOCD, TND APD, and AKD in deep soil horizons.

The soil nutrient management in reclaimed lands requires accurate spatial distribution patterns of soil nutrient stocks and deep understandings of the regulating factors for soil nutrient content variations [10]. Afforestation has been frequently employed for the reclamation of opencast coalmine regions because trees own a strong ability to increase soil organic matter (SOM) content and improve the activities of soil microorganisms [26]. The effects of afforestation modes and soil physicochemical properties on the recovery of reclaimed soil nutrients remain controversial and should be separately examined to provide some insight for the land reclamation in opencast coalmine regions. Therefore, the main objectives of this study were to: (1) estimate the nutrient stocks based on soil nutrient contents, soil bulk density, and soil layer thickness in different soil horizons; (2) present and analyze the spatial distribution characteristics of SOCD, TND, APD, and AKD at 0–60 cm based on the ordinary Kriging interpolation method and geostatistical analyses; (3) explore how afforestation and soil properties regulate the variations of soil nutrients in reclaimed soil profiles.

2. Materials and Methods

2.1. Study Area

This study was carried out in the South Dump of Pingshuo opencast coalmine that is located in the north of Shanxi Province and east of the Loess Plateau (39°23′–39°37′ N, 112°11′–113°30′ E) (Figure 1). The Loess Plateau has suffered from extensive mining, cultivation, and deforestation in recent years, where the ecological environment is increasingly threatened by desertification, declining soil fertility, land degradation, and high-intensity soil erosion [27]. Moreover, more than two-thirds of China's coal resource is distributed across the Loess Plateau and opencast mining has inevitably caused damages to local ecosystems [28], for which the Chinese Government has initiated many ecological restoration or land reclamation programs to improve the natural environment in these regions. It has been more than 30 years since the South Dump was reclaimed, and the local ecosystem has been greatly improved. More studies should be carried out to extract the effective land reclamation measures used (e.g., vegetation configuration modes, soil reconstruction methods, and landform remodeling schemes) and fully understand the mechanisms by which these measures influence the evolution path of mining ecosystems.

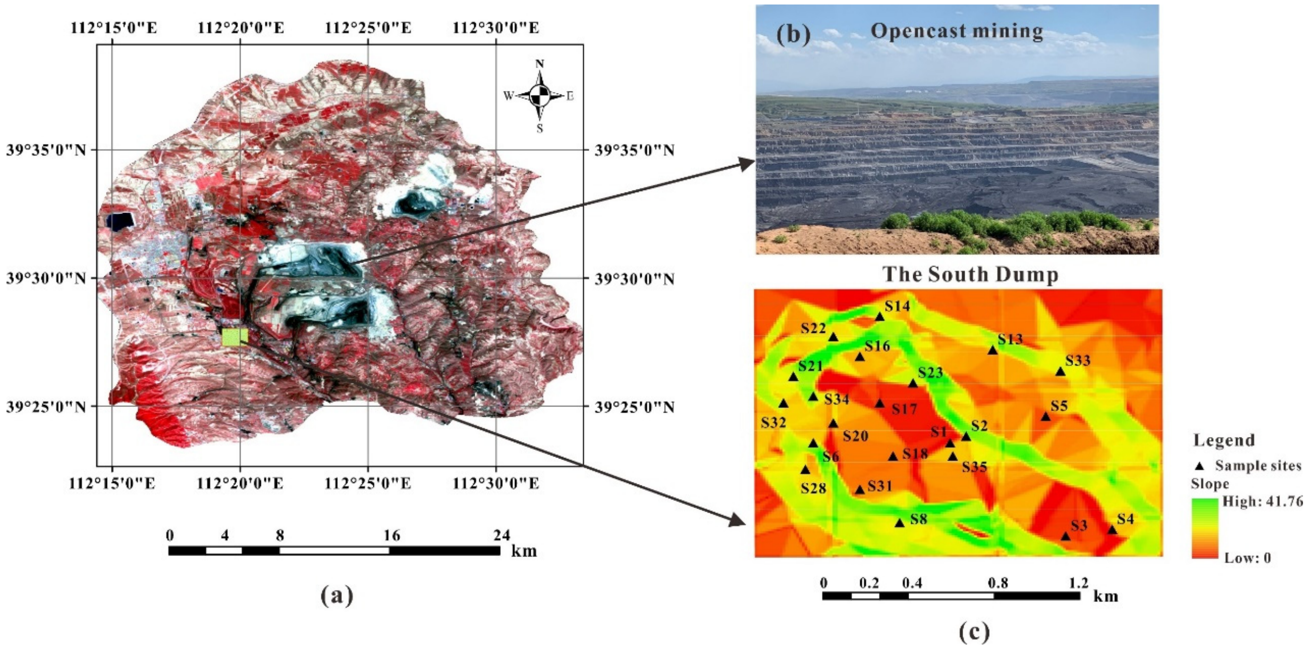

Figure 1. Location of Pingshuo opencast coalmine (**a**), current conditions of opencast mining (**b**), and slope characteristics across the South Dump (**c**).

The South Dump is dominated by a typical semi-arid and arid continental monsoon climate, where the average annual precipitation is about 450 mm (196–757 mm) and the average annual temperature is 4.8–7.8 °C, with the highest temperature of 34.5 °C and lowest temperature of −27.3 °C [1]. Moreover, most rainfall (>65%) is unevenly distributed from June to September, and the average annual evaporation (2160 mm) is much higher than rainfall [21,28]. The main reconstructed soil is classified as chestnut brown soil with low-content organic matter and poor soil structure, making it difficult for the land reclamation in the study area [29]. Afforestation has been initiated since the 1990s to increase the surface vegetation coverage rate in the South Dump and a multilevel ecological landscape has been constructed by planting various vegetation species, such as *Ulmus pumila*, *Robinia pseudoacacia*, *Pinus tabuliformis*, and *Elymus Dahuricus Turcz* [30].

2.2. Sampling and Analysis

In May and August 2018, 22 representative soil profiles were randomly dug across the South Dump (Figure 2) and soil samples were collected in different soil horizons (0–10, 10–20, 20–30, 30–40, 40–50, and 50–60 cm). Overall, these soil profiles were dug in the forest land (sites S1, S2, S4, S5, S6, S8, S14, S18, S20, S21, S22, S32, S33, and S34) and the non-forest land (sites S3, S13, S16, S17, S23, S28, S31, and S35), respectively. Before soil physicochemical properties were measured, all soil samples were sufficiently air-dried in an oven and additional materials (e.g., plant residues and unwanted gravels) were removed by a 2 mm sieve. Soil texture was quantitively determined using a laser particle size analyzer with the precision of 1% (i.e., Longbench Mastersizer 2000; Malvern Instrument, Malvern, England) while soil pH was measured by a pH meter with the precision of 0.05 [31–33]. The soil organic matter (SOM) and TN contents were determined based on the wet oxidation method ($KMnO_4$) and the Kjeldahl method [28,34,35], respectively. Soil AP was extracted by the sodium bicarbonate solution ($NaHCO_3$) and measured through Olsen's bicarbonate method, while soil AK was extracted by the ammonium acetate solution (NH_4OAc) and measured through the atomic absorption spectroscopic analysis [36]. Soil bulk density and herbaceous biomass have been reported in our previous studies [21,30]. Most experiments were performed in Beijing Academy of Agriculture and Forestry Sciences.

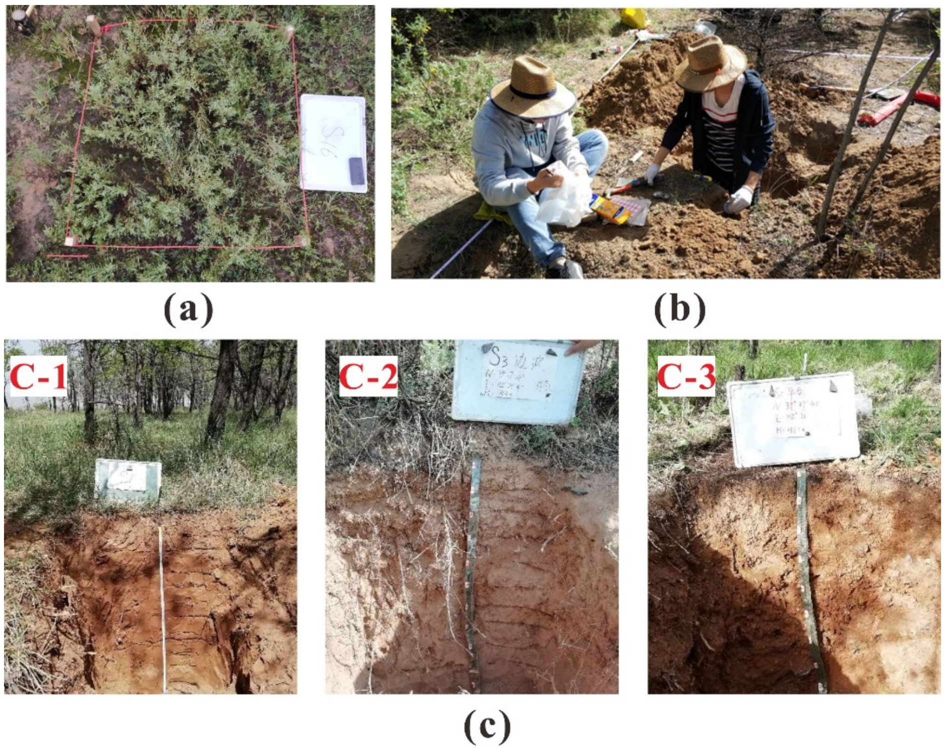

Figure 2. Some field photos of selected quadrat (**a**), soil profile excavation (**b**), and sampled soil profiles (**c**).

2.3. Calculation of Reclaimed Soil Nutrient Stock

The stocks of soil nutrients (i.e., SOC, TN, AP, and AK) were calculated based on the following equation [27,37,38]:

$$NTSD_h = \sum_{i=1}^{n} \frac{NTS_i \times \beta_i \times t_i \times \left(1 - \delta_i \times 10^{-2}\right)}{10} \quad (1)$$

where $NTSD_h$ represents the total amount of soil nutrients at 0-h cm per unit area (Mg ha^{-1}); n refers to the number of soil layers and i represents the i_{th} soil layer; NTS_i, β_i, $t_{i,}$ and δ_i refer to soil nutrient contents (g kg^{-1}), soil bulk density (g cm^{-3}), thickness (cm) of the i_{th} soil layer, and the percentage (%) of coarse particles (>2 mm), respectively. Since the soil particles of loess in China are always smaller than 2 mm, the value of δ is normally considered as 0 [27,39]. In this study, the reclaimed soil nutrient stocks at 0–60 cm were calculated based on these measured soil properties.

2.4. Geostatistical Analysis

Geostatistical methods can be employed to present the spatially continuous distribution of soil nutrients based on some discrete points through optimal interpolation, which was established on the spatial autocorrelation principle [27,40–42]. In this study, the preferentially considered ordinary Kriging interpolation (OK) was adopted to describe the spatial distribution characteristics of different soil nutrient stocks at 0–60 cm. The optimal input parameters of OK should be determined by the application of a semivariogram function, the formula of which is shown as follows [1,21]:

$$\gamma(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} [H(x_i) - H(x_i + 1)]^2 \quad (2)$$

where $\gamma(h)$ is the semivariogram function value, $N(h)$ denotes the total number of data pairs at different sample sites, and $H(x_i)$ represents the value of variable H at the sample site x_i. Moreover, the $C_0/(C + C_0)$ ratio (i.e., Nugget/Sill) is a widely used indicator to quantify the spatial autocorrelation or dependency degree of studied variables [38,43]. According to the $C_0/(C + C_0)$ ratio, the spatial autocorrelation degree could be classified into strong spatial autocorrelation (<25%), moderate spatial autocorrelation (25–75%), or weak spatial autocorrelation (>75%) [15,44].

The cross-validation method has been widely employed to evaluate the reliability of OK interpolation results [38,45,46]. One datum would be considered unknown to construct a variation model based on the data left, and the omitted value would be estimated based on the constructed model. The procedure would be repeated many times to obtain the estimated values at different sample sites and the errors between these actual and estimated values would be calculated to assess the accuracy of the selected interpolation models (e.g., spherical model, linear model, Gaussian model, and exponential model). Here, the absolute mean error (*AME*), mean error (*ME*), and root mean square error (*RMSE*) were selected as the evaluation indices, whose calculation formulae are shown as follows:

$$ME = \frac{1}{n}\sum_{i=1}^{n}(P_i - A_i) \tag{3}$$

$$AME = \frac{1}{n}\sum_{i=1}^{n}|P_i - A_i| \tag{4}$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(P_i - A_i)^2} \tag{5}$$

where n is the number of soil samples, P_i and A_i represent the predicted and actual values, respectively. The geostatistical analyses were achieved in GS^+ 9.0 and the evaluation indices were further calculated in Microsoft Excel 2016.

3. Results and Discussion

3.1. Distribution Characteristics of Measured Soil Properties, and Nutrient Stocks

3.1.1. Soil Texture, pH, and Herbaceous Biomass at Different Sample Sites

The soil texture composition, soil pH and herbaceous biomass distributions at different sample sites are shown in Figure 3. The sand contents varied dramatically (12.11–81.42%) when compared with clay or silt contents and most points were distributed at the bottom of the USDA soil texture triangle (Figure 3). Based on the American soil classification scheme, most soil samples can be classified as sandy loam (24.24%), silt loam (26.52%), and loam (40.91%) in the study area. On the other hand, the herbaceous biomass was extremely unevenly distributed at different sample sites, whose coefficient of variation (CV) reached 75.78%. After the long-term afforestation, large amounts of suitable woody species were planted across the South Dump, which greatly improved local ecosystems. The dominant species in the forest land comprised *Robinia pseudoacacia*, *Populus alba*, *Ulmus pumila*, and *Pinus tabulaeformis*, while those in the non-forest land mainly included *Caragana Korshinskii* and *Artemisia Capillaris Thunb*. The mean herbaceous biomass in forest land was 150.56 g m^{-2}, while it was 88.47 g m^{-2} in non-forest land. No significant difference was found between them based on the independent-sample T test, which might result from the high varibaility of herbaceous biomass at different sample sites. Overall, soil pH ranged from 5.7 to 8.4 and most soil samples (96.2%) were alkaline in the study area. Moreover, the vertical variations of soil pH were quite limited in most soil profiles except for sites S1, S2, and S22. Previous studies reported that mining and land reclamation operations would trigger the increase of reclaimed soil pH [47,48], which could account for the alkaline soil environment in this study.

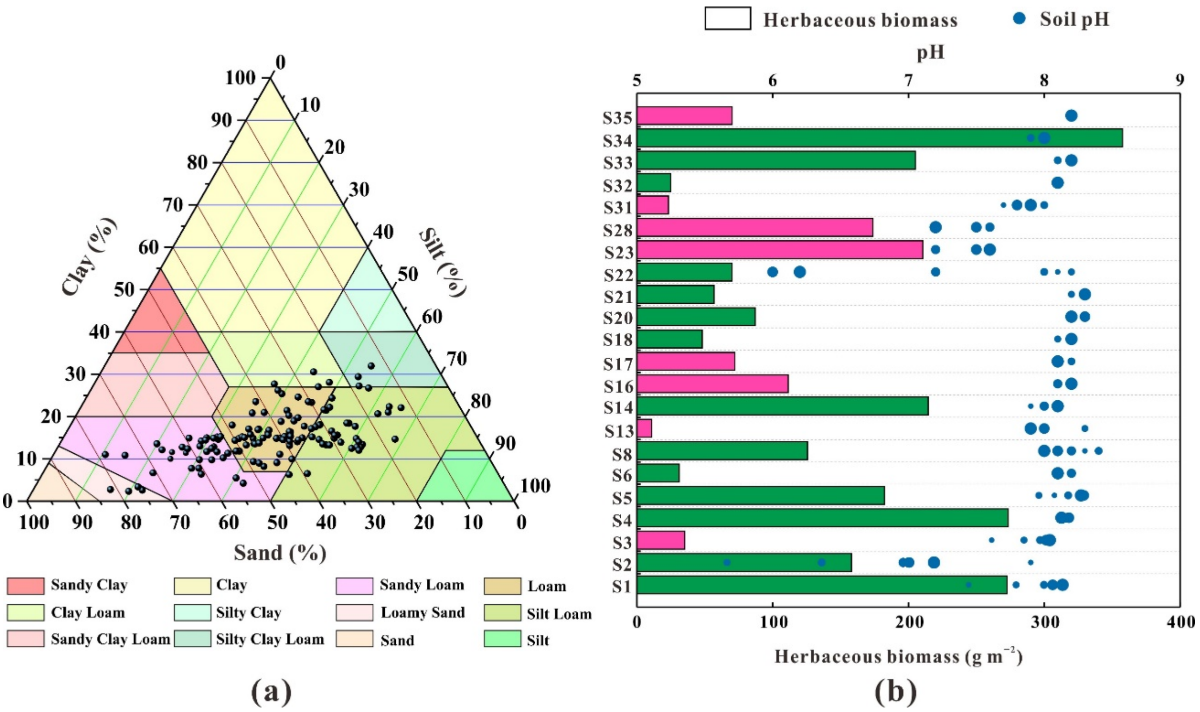

Figure 3. Characteristics of soil texture (**a**), pH and herbaceous biomass (**b**). The soil texture triangle diagram has been reported in our previous study [49]. Soil pH at different depths is displayed by bubble diagrams, where larger bubbles represent the soil samples in deeper horizons. The column in green represents forest land sites, while that in red represents non-forest land sites.

3.1.2. Statistical Characteristics of SOCD, TND, APD, and AKD in Different Soil Horizons

The statistical results of the studied soil nutrient stocks in different soil horizons are shown in Table 1. The SOCD showed extremely strong variability (CV > 250%) at 20–60 cm and seemed to increase with soil depth, which should be mainly attributed to the existence of coal gangue in soil profiles at several sample sites. During the early stages of land reclamation, some coal gangue was inappropriately backfilled in reclaimed soils due to the limitation of theories and techniques [49]. Based on our field observations, the abnormally high SOCD values were always found in the reclaimed soils where coal gangue was distributed, which changed the original distribution characteristics of SOCD and cannot reflect the actual conditions of reclaimed soils [50]. Therefore, the abnormal SOCD data at sample sites S2, S22, and S28 were omitted in the following analyses to avoid the interference of coal gangue. Meanwhile, the average values of TND, APD, and AKD in different soil horizons did not present clear vertical distribution patterns. Moreover, TND was characterized by moderate (0–20 cm) to strong (20–60 cm) variability while APD and AKD were characterized by moderate variability in all soil horizons, indicating that available soil nutrients were less variable than SOC and TN in the reclaimed soils.

3.2. Geostatistical Analyses of the Calculated Nutrient Stocks

3.2.1. Semi-Variogram Analyses

In this study, the stocks of SOC, TN, AP, and AK at 0–60 cm were calculated to examine their spatial distribution patterns across the South Dump. Overall, SOCD and TND conformed to a lognormal distribution while APD and AKD were normally distributed, which met the requirement of semi-variogram analyses. The log-transformed SOCD and TND have been transformed back to their actual values in the following analyses. Semivariograms have always been considered as the optimal analytical method for the spatial variability of soil properties [44], whose parameters are listed in Table 2. The optimal model for SOCD, APD, and AKD is the Gaussian model while that for TND is the Spherical model. The results of R^2 ($\geq$0.58) and RSS ($\leq 2.65 \times 10^{-2}$) indicated that these models were reliable to analyze the spatial variability of the soil nutrient stocks in this study. Meanwhile, the $C_0/(C + C_0)$ ratios of SOCD, APD, and AKD were lower than 18% while that of TND was higher than 25%, which demonstrated that these soil nutrient stocks were characterized by moderate (TND) to strong (SOCD, APD, and AKD) spatial dependence. The results indicated that the spatial distributions of these soil nutrient stocks were mainly influenced by intrinsic factors (e.g., heterogeneity of reclaimed soil, soil pH, surface vegetation configuration, and soil texture) [21,51,52], although extrinsic factors could slightly affect the spatial distribution of TND. The cross-validation was carried out to examine the accuracy of the optimal models, which demonstrated that the interpolated results were reliable and the errors were acceptable (Table 3). Moreover, it should be noted that all *RMSE* values were greater than *AME* values for these models, indicating that the predicted nutrient stocks were slightly underestimated [21].

Table 1. The calculated SOCD, TND, APD, and AKD in different soil horizons.

Depth (cm)	Mean	Median	Maximum	Minimum	CV (%)
SOCD Mg ha^{-1}					
0–10	15.60	9.24	58.19	3.45	99.14
10–20	10.13	4.22	74.88	2.54	169.89
20–30	26.56	3.91	304.63	1.76	259.21
30–40	31.20	3.21	496.49	1.90	339.75
40–50	31.37	2.82	559.12	1.46	378.31
50–60	26.72	3.42	397.62	1.81	323.00
TND Mg ha^{-1}					
0–10	0.79	0.58	1.97	0.35	57.74
10–20	0.53	0.39	1.62	0.25	68.78
20–30	0.73	0.39	5.11	0.19	147.68
30–40	0.81	0.32	8.65	0.18	219.75
40–50	0.83	0.34	9.92	0.17	247.51
50–60	0.72	0.30	6.67	0.20	192.11
APD Mg ha^{-1}					
0–10	0.0056	0.0050	0.0116	0.0026	39.83
10–20	0.0053	0.0042	0.0149	0.0004	63.30
20–30	0.0062	0.0047	0.0149	0.0004	63.83
30–40	0.0074	0.0061	0.0165	0.0018	63.69
40–50	0.0091	0.0072	0.0255	0.0005	60.17
50–60	0.0097	0.0086	0.0303	0.0010	62.42
AKD Mg ha^{-1}					
0–10	0.17	0.14	0.41	0.06	52.12
10–20	0.10	0.09	0.18	0.03	41.63
20–30	0.09	0.08	0.18	0.04	41.98
30–40	0.10	0.09	0.22	0.04	47.09
40–50	0.11	0.10	0.22	0.03	44.37
50–60	0.11	0.10	0.25	0.05	48.10

Table 2. Semi-variogram analyses of SOCD, TND, APD, and AKD at 0–60 cm.

Soil nutrient Stocks	Optimal Model	$C_0/(C + C_0)$ % [a]	R^2 [b]	RSS [c]	A_0/m [d]
SOCD (Mg ha^{-1})	Gaussian	17.05	0.58	2.65×10^{-2}	971.68
TND (Mg ha^{-1})	Spherical	25.60	0.82	1.06×10^{-2}	242.00
APD (Mg ha^{-1})	Gaussian	0.20	0.66	8.28×10^{-8}	171.47
AKD (Mg ha^{-1})	Gaussian	0.14	0.74	9.33×10^{-4}	280.59

[a] Nugget/Sill, spatial heterogeneity ratio; [b] determination coefficient; [c] residual sum of squares; [d] Range, distance of spatial dependency.

Table 3. Cross-validation of OK interpolation for SOCD, TND, APD, and AKD at 0–60 cm.

Soil nutrient Stocks	Optimal Model	*ME*	*AME*	*RMSE*
SOCD (Mg ha^{-1})	Gaussian	-2.56×10^{0}	1.05×10^{1}	1.47×10^{1}
TND (Mg ha^{-1})	Spherical	-1.38×10^{0}	2.69×10^{0}	5.92×10^{0}
APD (Mg ha^{-1})	Gaussian	-1.07×10^{-3}	1.83×10^{-2}	2.25×10^{-2}
AKD (Mg ha^{-1})	Gaussian	-1.21×10^{-2}	1.81×10^{-1}	2.69×10^{-1}

3.2.2. Spatial Distribution Patterns of SOCD, TND, APD, and AKD across South Dump

The spatial distribution maps of SOCD, TND, APD, and AKD are displayed in Figure 4. The stocks of SOC at 0–60 cm ranged from 16.4 to 60.1 Mg ha^{-1} and the high-SOCD regions were mainly distributed in the northeastern areas of the South Dump, which was roughly characterized by a striped distribution pattern (Figure 4). The TND values were lower than 3.7 Mg ha^{-1} in most areas while the high-TND areas were mainly concentrated in the northwestern regions of the South Dump. Available soil nutrients can be directly utilized by vegetation because they are always dissolved in soil solutions [53], for which it was of great significance to explore their spatial distribution characteristics. In this study, the APD values ranged from 0.022 to 0.095 Mg ha^{-1}, while AKD values ranged from 0.31 to 1.40 Mg ha^{-1}, much lower than SOCD and TND. Moreover, most areas were characterized by low APD (<0.051 Mg ha^{-1}) and AKD values (<0.82 Mg ha^{-1}), while several high-APD or high-AKD "points" were sporadically scattered across the South Dump (Figure 4).

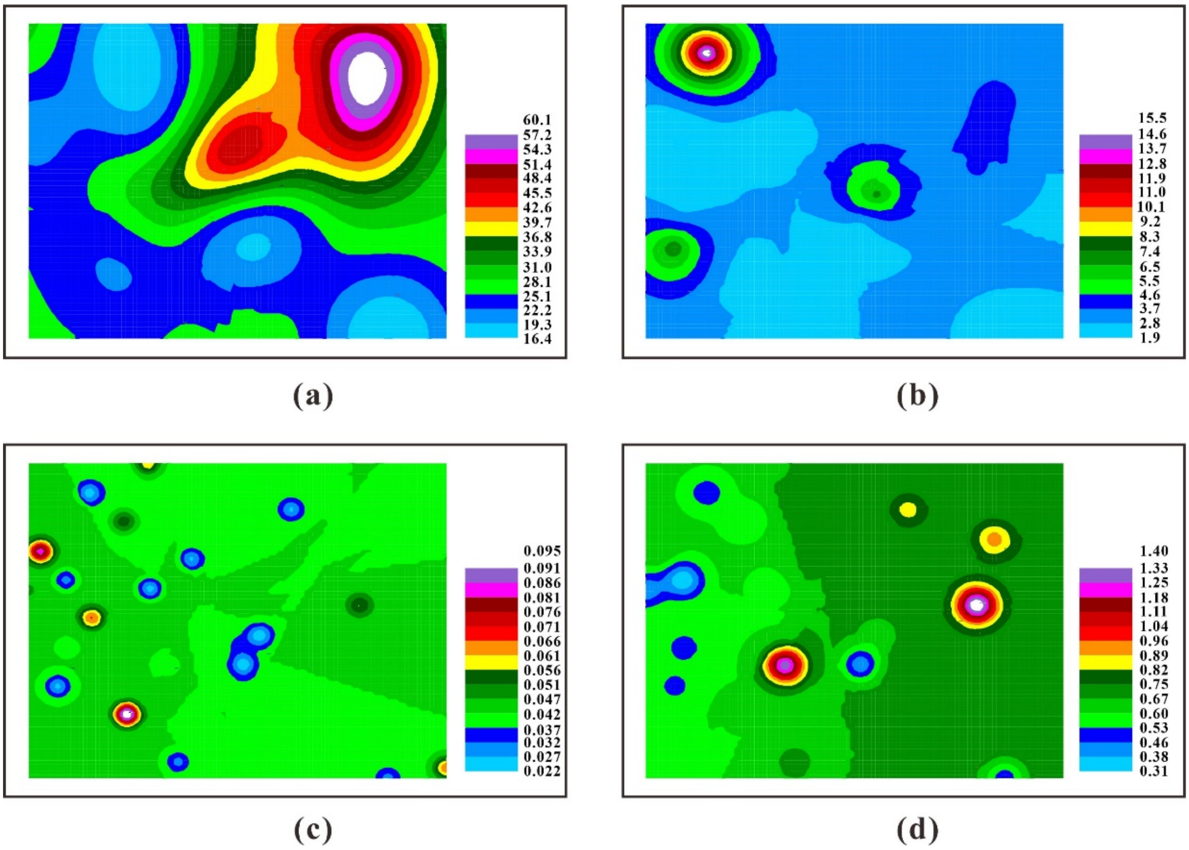

Figure 4. Interpolated maps of SOCD (**a**), TND (**b**), APD (**c**), and AKD (**d**) at 0–60 cm.

3.3. Influencing Factors of SOCD, TND, APD, and AKD in Reclaimed Land

3.3.1. Afforestation

Numerous studies have explored the effects of afforestation on soil nutrient stocks in natural ecosystems [14,18,20,54,55]. It has remained controversial about the specific influence of afforestation on the evolution of soil nutrient stocks and different studies might draw different conclusions due to the comprehensive influence of climate, topography, and geological background [20]. Zhao et al. [56] explored the spatial distribution characteristics of SOC across the Wangmaogou Watershed on the Loess Plateau and they found that the SOC content at 0–20 cm was significantly influenced by land-use types. However, few studies have been carried out to examine how afforestation regulates the sequestration of both soil nutrients and available nutrients in the reclaimed land of opencast coalmines. As mentioned above, the forest land was mainly dominated by *Robinia pseudoacacia*, *Pinus tabuliformis,* and *Ulmus pumila,* while non-forest land was mainly covered by *Caragana korshins* and *Artemisia Capillaris Thunb*. In this study, soil samples were categorized into two groups based on the land use types (forest land vs. non-forest land) and the difference of the nutrient stocks between the two groups was compared by the Mann-Whitney U test (Figure 5). The results demonstrated that there was no significant difference between these soil nutrient stocks in forest land and non-forest land, indicating that the influence of afforestation on soil nutrient stocks was positive but not significant. The phenomenon could be attributed to that soil nutrient stocks were affected by numerous factors and the influence of single factors was difficult to be directly examined. Moreover, the influence of afforestation was also determined by reclamation time because the improvement of soil physicochemical properties and the accumulation of SOM was gradually achieved.

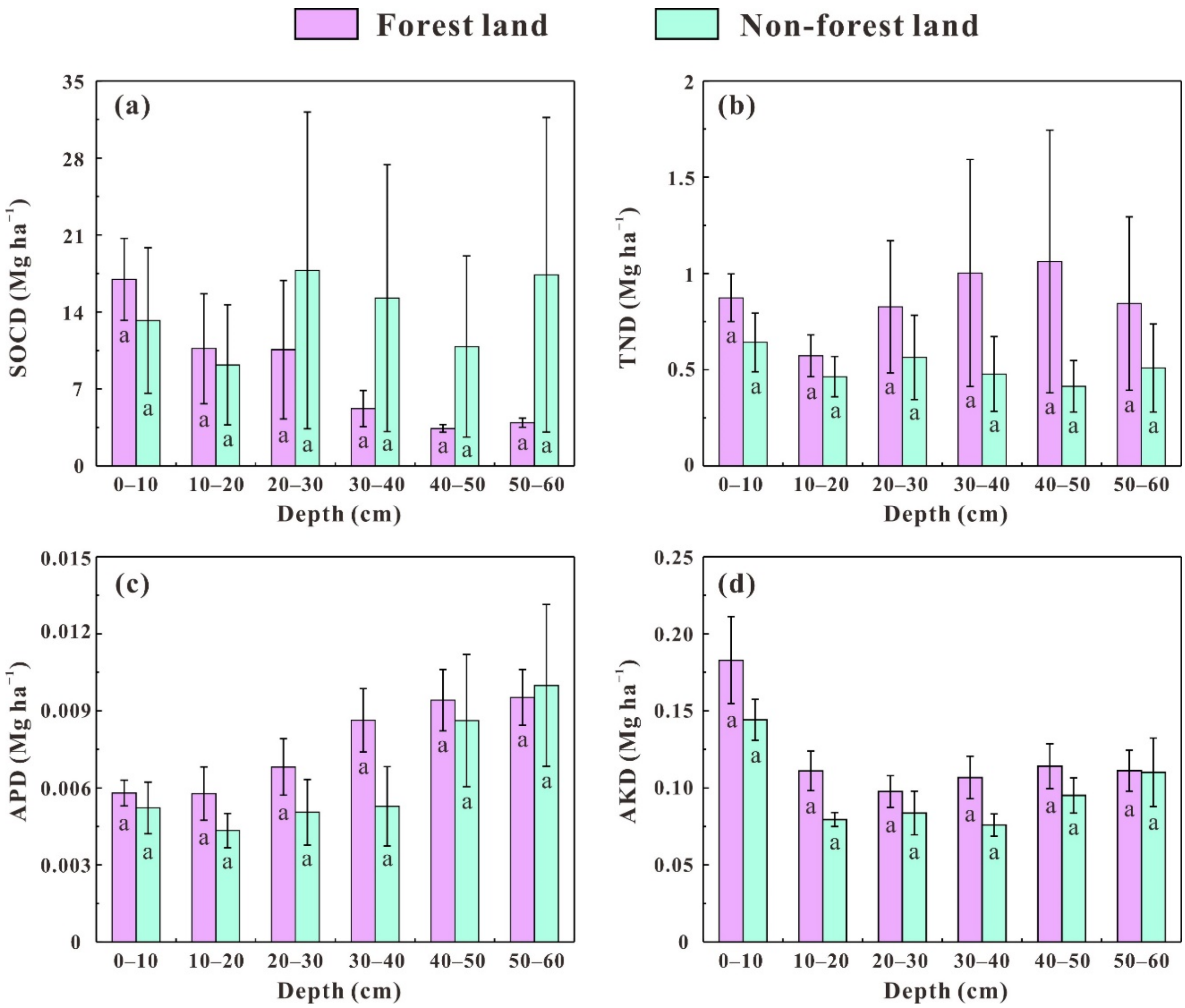

Figure 5. The average SOCD (**a**), TND (**b**), APD (**c**), and AKD (**d**) values in forest land and non-forest land. The same letters indicate that there is no significant difference between the two data groups. The error bars represent the standard errors of different groups.

Understanding the mechanisms by which afforestation regulated nutrient stocks in reclaimed soils was of great significance for the optimization of land reclamation measures in opencast coalmine. Previous studies reported that afforestation can increase aboveground biomass and provide abundant raw materials for microorganisms; on the other hand, afforestation can improve soil properties and benefit the accumulation of soil nutrients [57–59]. For instance, our previous study found that surface runoff or soil erosion intensity in forest land was much lower than that in non-forest land [21], indicating that the forest land owned a stronger ability to retain soil nutrients when compared with non-forest land during soil erosion process. Moreover, afforestation can reduce soil bulk density and improve the infiltration of dissolved soil nutrients (e.g., AP and AK) along soil profiles [21], which can also benefit the retention of soil nutrients in reclaimed soils. More studies are required to explore the detailed mechanisms by which afforestation affects the balance of soil nutrient stocks. Overall, afforestation can be identified as an effective pathway to increase the stocks of SOC, TN, AP, and AK in the South Dump.

3.3.2. Soil Texture and pH

Soil texture is an essential property determining the mechanical composition of soil particles, which can significantly affect the cycling and storage of soil nutrients [20,32,60]. Generally, finer soil particles owned a stronger ability to absorb soil nutrients and can prevent them from being leached along soil profiles [60–62]. However, the effects of soil texture on SOCD, TND, APD, and AKD were very limited in this study. As shown in Figure 3, the main soil types (91.67%) were silt loam, loam, and sandy loam, which were characterized by similar clay contents. The similar clay contents might make it difficult to distinguish the effects of different soil texture on soil nutrient stocks, which supported the idea that the influence of soil texture varied regionally based on local soil conditions [63].

On the other hand, soil pH has been considered as the dominant factor regulating the bioavailability and turnover of soil nutrients [32,64], which highlights the significance of examining the interactions between soil pH and soil nutrients in reclaimed soils. To minimize the potential interference of surface vegetation and backfilled coal gangue, soil samples at 40–60 cm were adopted for regression analyses to explore the pure influence of soil pH on soil nutrient accumulation in reclaimed soils. Since soil nutrient stocks were significantly affected by soil bulk density that was not correlated with soil pH, soil nutrient contents instead of stocks were employed as dependent variables in the following analyses. Overall, the results indicated that SOC and TN contents were negatively associated with soil pH, while AP and AK contents were positively associated with soil pH. Meanwhile, the relationships between SOC, TN, and soil pH can be appropriately described by unary quadratic equations, while the relationships between AP, AK, and soil pH can be roughly described by sigmoid fitting equations (Figure 6). The ratio of total carbon to total nitrogen (TC/TN) was an essential parameter for the evaluation of SOM quality [32,65,66], which controlled the mineralization/immobilization processes of SOM. Since the soil inorganic carbon contents were quite low and can be negligible, SOC/TN was adopted to denote the decomposition rates of SOM in this study. Generally, a lower C/N ratio can denote the quicker depletion of SOC and TN in the process of decomposition by microorganisms [67]. As shown in Figure 6, the C/N ratio can be estimated by soil pH based on a logarithmic equation (Figure 6).

The relationships between SOC, TN, and soil pH are very complex, and it was difficult to identify the dominant influencing factor among them. On the one hand, the breakdown of SOM would lower soil pH by excreting organic acids accompanied by the increase of SOC and TN contents, which can account for the negative relationships between SOC, TN, and soil pH. On the other hand, soil pH was an essential parameter regulating the activity and community structure of microorganisms that were reported to be the main reason for the decomposition of SOM in terrestrial ecosystems [32,67–69]. In this study, soil pH was negatively associated with C/N ratio, denoting that relatively higher soil pH (5.7–8.4) would accelerate the utilization of SOC and TN by microorganisms and reduce SOC and

TN contents [32,67,70]. Therefore, the negative association between soil pH and C/N ratio can support the conclusion that soil pH influenced SOC and TN contents by regulating microorganisms' decomposition process. By contrast, available soil nutrients (AP and AK) were positively correlated with soil pH, indicating that a relatively higher pH benefited the accumulation of AP and AK in reclaimed soils. Since these soil samples were collected at 40–60 cm, where few plant roots can reach and utilize soil nutrients, the influence of plant roots on AP and AK would not be considered as the dominant factor for their negative relationships with soil pH. Previous studies also found that the adsorption of AP and AK by clay is strongly regulated by soil pH, and that alkaline soils own a stronger ability to absorb and accumulate available soil nutrients [71–73]. The results of this study supported the assumption that soil pH can regulate the adsorption/desorption processes of AP and AK in soil environment.

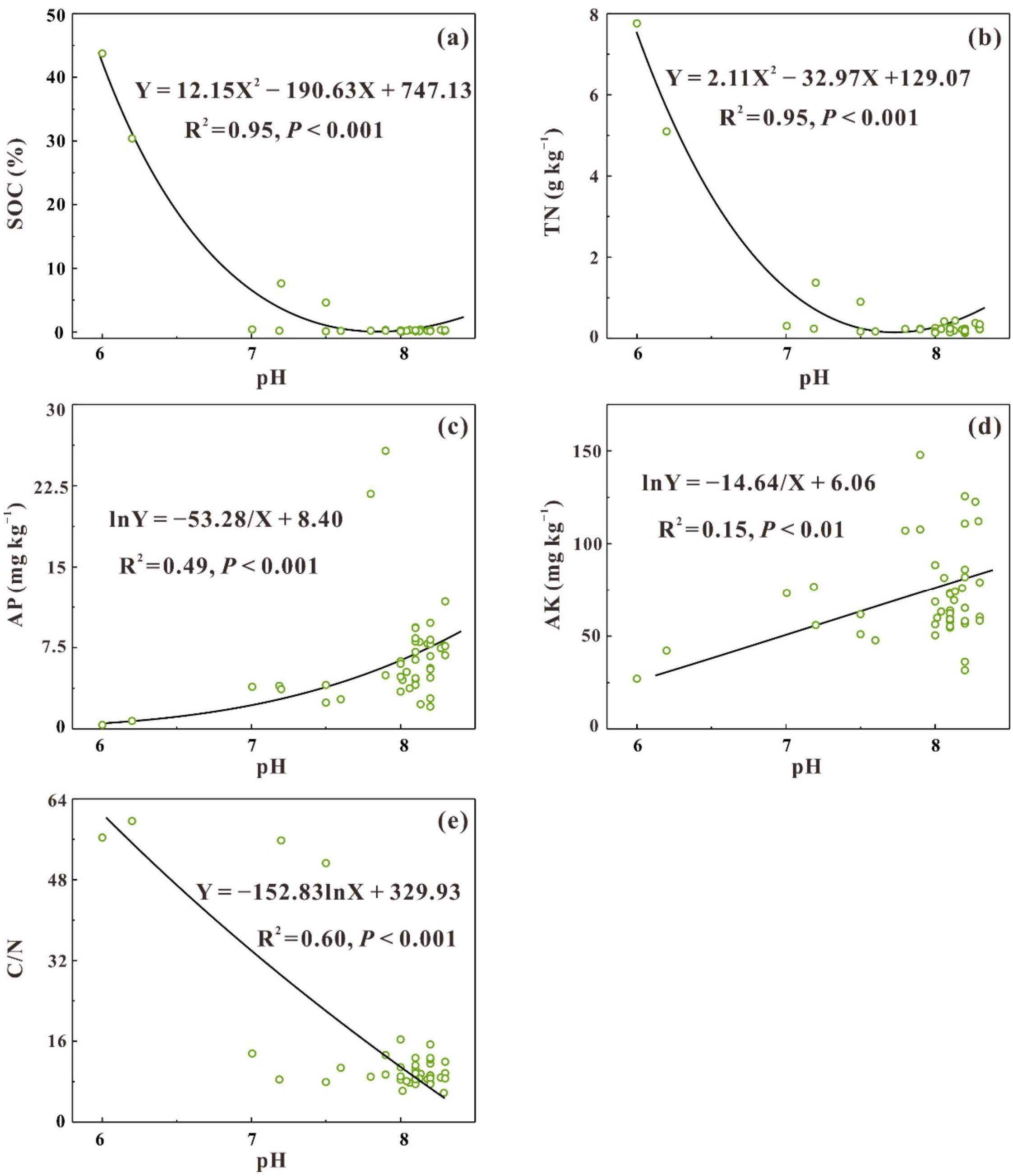

Figure 6. Results of regression analyses between soil pH and SOC (**a**), TN (**b**), AP (**c**), AK (**d**), and C/N (**e**). All coefficients and constants in regression equations are significant at 0.01 or 0.001 level.

3.4. Suggestion for Nutrient Management in Reclaimed Soils of Opencast Coalmine

Soil fertility maintenance was essential for the recovery of the natural resilience of local soil ecosystems in the process of land reclamation [1,74]. The findings of this study can provide some inspiration for the soil nutrient management in similar ecosystems. The spatial distribution patterns of SOCD were much more complex than those of TND, APD, and AKD (Figure 4), indicating that the SOC stocks in the reclaimed land were more sensitive to environmental factors (e.g., surface vegetation and soil properties). Regular monitoring of soil nutrient stocks was required, and land reclamation measures should differ regionally based on soil conditions. Afforestation or revegetation was an effective pathway to improve soil nutrient stocks and the optimal vegetation configuration should be determined based on local soil conditions. The *Robinia pseudoacacia*, *Pinus tabuliformis,* and *Ulmus pumila* species were the suitable vegetation species in the South Dump, which can provide some reference for the vegetation configuration in the opencast coalmine of similar ecosystems. Moreover, soil pH was a vital regulating factor for the accumulation of SOC, TN, AP, and AK. Numerous studies have reported that the availability of soil nutrients to plant roots would reach maximum when soil pH ranged from 5.5–7 [72,73]. Meanwhile, this study showed that alkaline soils owned a stronger ability to absorb or accumulate AP and AK in deep soil horizons, but the utilization of SOC and TN would be accelerated in an alkaline soil environment. Measures should be taken to adjust the pH values of reclaimed soils, but specific decisions should be made depending on the stages of land reclamation, and different measures should be taken in surface soil and deep soil.

4. Conclusions

This study investigated the spatial distributions of SOCD, TND, APD, and AKD at 0–60 cm across the South Dump and explored the influence of afforestation and soil physicochemical properties on the variations of these soil nutrients. The stocks of these soil nutrients did not show clear vertical distribution patterns, although the SOCD in deep soil was much higher than that in topsoil due to the existence of backfilled coal gangue. Horizontally, the results of $C_0/(C + C_0)$ ratios demonstrated that soil nutrient stocks at 0–60 cm were characterized by moderate (TND) to strong (SOCD, APD, and AKD) spatial dependence, indicating that their spatial distributions were mainly regulated by intrinsic factors, although extrinsic factors also slightly influenced the spatial distribution of TND. Moreover, the spatial distribution of SOCD was characterized by a striped distribution pattern while those of TND, APD, and AKD were characterized by "point distribution patterns". On the other hand, the effect of afforestation on soil nutrient stocks appeared to be positive but not significant in our study, most likely due to the growth of some species in the non-forest land. Moreover, soil pH was the dominant controlling factor for the dynamic balance of SOC, TN, AP, and AK in reclaimed soils and their relationships can be roughly described by regression equations, while the influence of soil texture on these soil nutrients was quite limited in the study area. These results indicated that more measures should be taken to appropriately adjust reclaimed soil pH according to land reclamation stages and soil nutrient conditions.

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