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Patterns and Driving Mechanisms of Soil Organic Carbon, Nitrogen, and Phosphorus, and Their Stoichiometry in Limestone Mines of Anhui Province, China

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Abstract: Active vegetation restoration plays an important role in the improvement in soil organic matter (SOM), including the carbon (C), nitrogen (N) and phosphorus (P) sequestration of degraded mining ecosystems. However, there is still a lack of understanding of the key drivers of SOM pool size and dynamics in active vegetation restoration. For this study, soil was collected from five different sites (Xiaoxian, Dingyuan, Chaohu, Tongling and Dongzhi), four habitats (platforms, slopes, steps and native areas) and two soil layers (0–20 cm and 20–40 cm) in limestone mines of Anhui province to quantify the spatial distribution of SOM contents and their stoichiometric characteristics and influential factors. It was found that the top soil in Chaohu had the highest significant C, N and P contents in the ranges of 14.95–17.97, 1.74–2.21 and 0.80–1.24 g/kg, respectively. Comparing the stoichiometric ratios of the different sites revealed significant differences in C:N and N:P ratios, but C:P ratios were relatively consistent. In particular, the C:N and C:P ratios in deep soil were higher than those in top soil, whereas the N:P ratio in deep soil was lower than that in top soil, suggesting that soil N is a major limiting factor in the top soil. The SOM content did not differ significantly between the three reclaimed habitats, but was significantly higher than that in the native habitat, suggesting that mine restoration has significantly enhanced SOM accumulation. Further analysis showed that nutrient availability and enzyme activity are important factors affecting soil C, N and P content in top soil, while the relationship gradually weakens in deep soil. This was attributed to active anthropogenic management and conservation measures during the early stages of reclamation. This study shows that the ecological recovery of the mining area can be enhanced by implementing differentiated vegetation planting strategies and anthropogenic management on different habitats in the mining area.

Keywords: soil organic matter; stoichiometric characteristics; vegetation restoration; limestone mine areas; mine habitats

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1. Introduction

Open-pit mining profoundly impacts the surface environment, potentially causing soil erosion, while significantly reducing the stability of local ecosystems [1,2]. Vegetation restoration is one of the primary strategies for mine reclamation, effectively enhancing soil organic matter (SOM), including carbon (C), nitrogen (N) and phosphorus (P) content [3], thereby affecting water retention and nutrient supply [4]. SOM reflects the potential for nutrient supply and storage and is influenced by a number of factors, including climatic conditions [5], soil properties [6,7] depth [8], anthropogenic disturbance [9] and vegetation type [10]. Concurrently, landform modification is performed in the mining area to accelerate the recovery process and to achieve a structure and function similar to that of the surrounding natural ecosystem [11,12]. However, intensive reclamation activities can alter the topography and soil structure, and thereby significantly affect the turnover of SOM in the microenvironment [13]. Most studies only focus on the effect of vegetation type or restoration time on SOM after mine reclamation, but there is still considerable uncertainty about how climate and habitat conditions in mining areas affect the cycling of SOM in different soil layers.

Traditional mines use a platform–slope–step structure to minimize damage to the original structure of the mountain and maintain consistency with the surrounding natural environment. This result in different standing conditions and soil erodibility differences across habitats. Therefore, configuring different plant species is necessary to promote soil and water conservation and ecological restoration [14]. In platform areas, the soil is prone to sloughing and thus has a high bulk density, which may restrict the rooting and growth of vegetation. Therefore, these areas are planted with a combination of tree–shrub–grass to increase soil permeability. Given that slopes are not mechanically compacted, soil has a low bulk density and the particles are large and poorly cemented [15]. For such conditions, climbing plants with developed root systems that can form net-like roots or low shrubs and grasses are selected to stabilize the slope surface and enhance the soil and water holding capacity [16,17]. Topography and vegetation type are key factors in the cycling of SOM, as these directly influence litter input and decomposition [18]. With the passage of restoration time, how differences in the soil microenvironment in different reclaimed habitats affect the accumulation of SOM has not yet been further explored.

Meanwhile, soil stoichiometric ratios, which are closely linked to SOM balances and vegetation productivity, provide further insights into the effectiveness of SOM cycling [19–21]. For example, the soil C:N ratio directly affects the SOM mineralization rate and microbial activity and is an effective indicator for predicting the SOM decomposition rate [22]. By contrast, the C:P ratio indicates the mineralization capacity of soil P, and the N:P ratio reveals potential nutrient limitations for plants [23]. During the initial stages of mine reclamation, conventional anthropogenic management measures may alter the ecological stoichiometry of the soil due to the increased N and P levels and lead to an imbalance in the C:N:P ratio, which in turn stimulates SOM mineralization [24]. Recent studies on reclaimed mines have focused on the effects of vegetation type and reclaimed time on the physicochemical properties of top soil [25–28]. However, the contents and stoichiometric ratios of C, N, and P in different soil layers remain unclear, contributing to uncertainties regarding the sustainability of mine ecosystems following vegetation restoration. Therefore, a detailed analysis of the dynamics and stoichiometric ratios of nutrients in different soil layers is important to understand the reclamation of mining ecosystems and ensure their long-term sustainability [3,27].

Degraded mining areas in China exhibit ecological fragility, characterized by significant vegetation loss and severe soil erosion. In recent years, integrated management practices, such as mine restoration projects, have significantly contributed to controlling land degradation and enhancing vegetation cover [29]. To date, research on the restoration of mining areas has primarily emphasized soil C stock and its influencing factors. However, there is a lack of studies explicitly addressing the SOM and stoichiometric variations across different habitats, as well as the factors influencing these variations. This study investigated the effects of topographic and climatic factors on the contents and stoichiometric ratios of soil C, N, and P. Samples were collected from various habitats across five limestone mines, including platform, slopes, and steps, and compared with those from adjacent natural habitats. The specific objectives of this research were as follows: (1) to determine how SOM and their stoichiometric ratios in the soil profile respond to managed and natural vegetation restoration in different sites, and (2) to determine what factors lead to differences in SOM between sites and habitats.

2. Materials and Methods

2.1. Description of the Studied Area

This study was conducted at limestone mines in five counties from the north to south of Anhui Province, namely Xiaoxian (XX), Dingyuan (DY), Chaohu (CH), Tongling (TL), and Dongzhi (DZ). The elevations of the studied areas ranged from 32 to 527 m, and the slope gradient was from 6 to 65%. Anhui province is a transition zone between a warm temperate zone and a subtropical zone, with an average annual temperature varying from 14.4 to 16.9 °C and an annual precipitation varying from 854.60 to 1601 mm. The five study sites were chosen on the basis of soil type and mining and reclamation method and time. An interview with the Public Geological Survey Management Center in Anhui Province, was arranged to obtain information on the methods of mining (soil scraping and storage) and reclamation (age, depth, method, leveling, top soil application, and vegetation). Mine sites that were surface mined between 2006 and 2011 and reclaimed <4 years ago were selected, and are hereinafter termed "reclaimed area". Limestone mining was carried out in the form of open-pit mining, resulting in pits all over the place, discontinuous top soil, and increased soil erosion, all of which highlight the waste of large land resources. Reclamation comprised backfilling using the spoil material, grading to the original contour, applying 60 cm of top soil, and planting a tree–shrub–grass mixture, with dominant trees including *Broussonetia papyrifera*, *Robinia pseudoacacia*, *Pterocarya stenoptera*, and *Cupressus funebris*; shrubs including *Amorpha fruticosa*, *Photinia*, and *Lespedeza bicolor*; and grass including *Setaria viridis*, *Humulus scandens*, and *Cynodon dactylon*. According to the Chinese Soil Taxonomic Classification, the recovered soils at the mine site were dominated by yellow–brown soil interspersed with gravel. Specific information on the study sites is shown in Table 1.

Table 1. Basic characteristics of the sample plots in different sites of Anhui Province, China.

Site	Longitude	Latitude	MAT	MAP	Recovery Time	Dominant Species	Simpson Index	Margalef Index	Shannon-Wiener Index	Pielou Index
XX	117°33′08.77″	34°08′34.18″	14.4 °C	854.60 mm	3.6	*Cupressus funebris*, *Lespedeza bicolor*	0.61 ± 0.11 a	0.85 ± 0.28 ab	1.17 ± 0.28 a	0.8 ± 0.1 ab
DY	117°33′58.63″	32°37′23.27″	15 °C	960 mm	1.2	*Platycladus orientalis*	0.56 ± 0.12 a	0.69 ± 0.19 b	0.96 ± 0.28 a	0.85 ± 0.1 a
CH	117°45′17.32″	31°29′44.48″	16.8 °C	1151.7 mm	1	*Robinia pseudoacacia*, *Amorpha fruticosa*	0.52 ± 0.12 a	0.9 ± 0.31 ab	0.97 ± 0.19 a	0.74 ± 0.15 b
TL	117°48′58.21″	30°52′9.87″	16.2 °C	1388.6 mm	4	*Pterocarya stenoptera*, *Cnidium monnieri*	0.59 ± 0.18 a	1.04 ± 0.49 a	1.13 ± 0.38 a	0.8 ± 0.14 ab
DZ	116°57′55.65″	30°7′9.29″	16.9 °C	1601 mm	2.5	*Pinus massoniana*	0.61 ± 0.16 a	0.96 ± 0.29 a	1.18 ± 0.37 a	0.84 ± 0.1 ab

Note. XX, Niutoushan Marl Mining Area, Baitu Town, Xiaoxian County, Suzhou City; DY, Quarrying Plant of Antai Cement Co., Ltd. in Dingyuan County, Chuzhou City; CH, Limestone Mining Area for Cement at Litoujian, Chaohu City; TL, Jinhua Quarrying Plant in Tongling City; DZ, Mianshan Mining Hill in Yaodu Town, Dongzhi County, Chizhou City; MAT, mean annual temperature; MAP, mean annual precipitation; data are mean ± SE. Different letters indicate significant differences between locations ($p < 0.05$).

In mining, reasonable slopes and steps must be designed to prevent landslides. In addition, a certain amount of space must be left under the steps to facilitate the operation of mining equipment and the loading of ore. Hence, the three types of habitats in most open-pit mines are platforms, slopes, and steps. In July 2023, soil samples of platforms, slopes, and steps were collected along the same direction. Paired, natural, and undisturbed sites adjacent to newly reclaimed area were also selected for reference and are hereinafter called "native area". Three sampling locations were identified for each site, and each sampling location consisted of a paired reference site.

2.2. Soil Sampling

Three 10 m × 10 m sample plots were randomly selected at the same elevation in each habitat, with each plot separated by more than 50 m. After the surface vegetation and mulch in the sample plots were removed, the five-point sampling method was adopted to collect 0–20 cm top soil layer samples and 20–40 cm deep soil samples using an earth auger. These samples were mixed thoroughly. Three soil samples were collected from each soil layer, with a total of 120 soil samples collected from the five mining areas (five sites × four habits × two soil layers × three replicates). The soil samples were placed in self-sealing bags, stored at a low temperature, and immediately brought back to the laboratory. Plant roots, stones, and other debris were removed in the laboratory, ground through a 2 mm mesh sieve, and prepared for use. One part of the soil was air-dried for the determination of soil physicochemical properties, and the other was stored in a refrigerator at 4 °C for the determination of soil enzyme activities.

2.3. Soil Physicochemical Properties and Enzyme Activities

Soil pH and electrical conductivity (EC) were measured using a pH meter (PHS-3E, Leici, Weihai, China) and a conductivity meter (DDS-11A, Leici, Weihai, China), respectively, in a 1:5 (soil:water) suspension shaken at 25 °C for 15 min. Total carbon (TC) was determined by the potassium dichromate gravimetric method. Soil total nitrogen (TN), total phosphorus (TP), and total potassium (TK) were measured by the Kjeldahl N determination method, sodium hydroxide melt-molybdenum-antimony anticolorimetric method, and sodium hydroxide melt-flame photometry, respectively. Available P (AP) was determined by the 0.5 M $NaHCO_3$ determined by using molybdenum blue method. Available potassium (AK) was determined by ammonium acetate leaching and then tested by using flame photometer (FP640, INASA, Beijing, China). Ammonium nitrogen (NH_4^+) and nitrate nitrogen (NO_3^-) were measured by a spectrophotometer (UV-2550, Shimadzu, Kyoto, Japan) after extracted with 2 M KCl. Soil enzyme activities were determined using the kit method as follows: soil urease (S-UE, EC3.5.1.5) was measured by indophenol blue colorimetry to determine the amount of NH_3-N produced by urease during urea hydrolysis to indicate urease activity. Soil catalase (S-CAT, EC1.11.1.6) was indicated by the characteristic absorption peak of H_2O_2 at 240 nm, and the change in the absorbance of the solution at this wavelength after reacting with soil was measured. Soil sucrase (S-SC, EC3.2.1.26) activity was measured using the 3,5-dinitrosalicylic acid colorimetric method and expressed as the number of glucoses produced per hour per gram of soil sample incubated for 4 h at 37 °C. Soil acid phosphatase (S-ACP, EC3.1.3.2) activity was determined using a colorimetric method with disodium benzene phosphate by incubating for 1 h at 37 °C and expressed in terms of the amount of phenol produced per gram of soil sample per hour.

2.4. Data Analysis

The vegetation diversity index was calculated as follows [30]:

Simpson's diversity index:
$$B = 1 - \sum_{i=1}^{s} P_i^2 \quad (1)$$

Margalef index:
$$D = \frac{S-1}{\ln N} \quad (2)$$

Shannon Weiner index:
$$H = -\sum_{i=1}^{s} (P_i \ln P_i) \quad (3)$$

Pielou's index:
$$E = \frac{H}{\ln S} \quad (4)$$

where P_i is the proportion of individuals of each species to the number of individuals in the community, S is the number of species in the sample, and N is the total number of individuals observed.

We used linear mixed models (LMMs) to analyze the effect of the site, layer and their interaction, as well as the effects of habitat, layer and their interaction on SOM content (Figures 1 and 2,TC, TN, TP, TC:TN, TC:TP and TN:TP), enzymatic activities (enzyme-C, enzyme-N, enzyme-P and CAT, Figures 3 and 4) and soil properties (NO_3^-, NH_4^+, TK, AK, AP pH and EC, Figures S1–S3). We set the site, the layer and the interaction between both as fixed effects and the plot nested in the habitat as a random factor in. We set the habitat, the layer, and the interaction between both as fixed effects, and the plot nested in the site as a random factor. One-way analysis of variance and Tukey's post hoc test (with a confidence of 95%) were used to analyze the differences in different habitat/sites and layers with SPSS 29.0 software. Pearson correlations analysis was conducted to correlate climates, soil properties, and soil enzyme activities with SOM content and their stoichiometric ratio. The relative importance analysis was performed by the R package of "relaimpo" to identify the relative contributions of climates (MAT, MAP, longitude and latitude), soil properties (pH, EC, NO_3^-, NH_4^+, TK, AK, and AP), and soil enzyme activities (enzyme-C, enzyme-N, enzyme-P and CAT) on SOM content and their stoichiometric ratio in two soil layers. First, the generalized linear model was used to fit the SOM content and their stoichiometric ratio and 16 independent variables. Then, we selected the metric of "lmg" to quantify the contribution of the independent variables to dependent variables in the relative importance analysis.

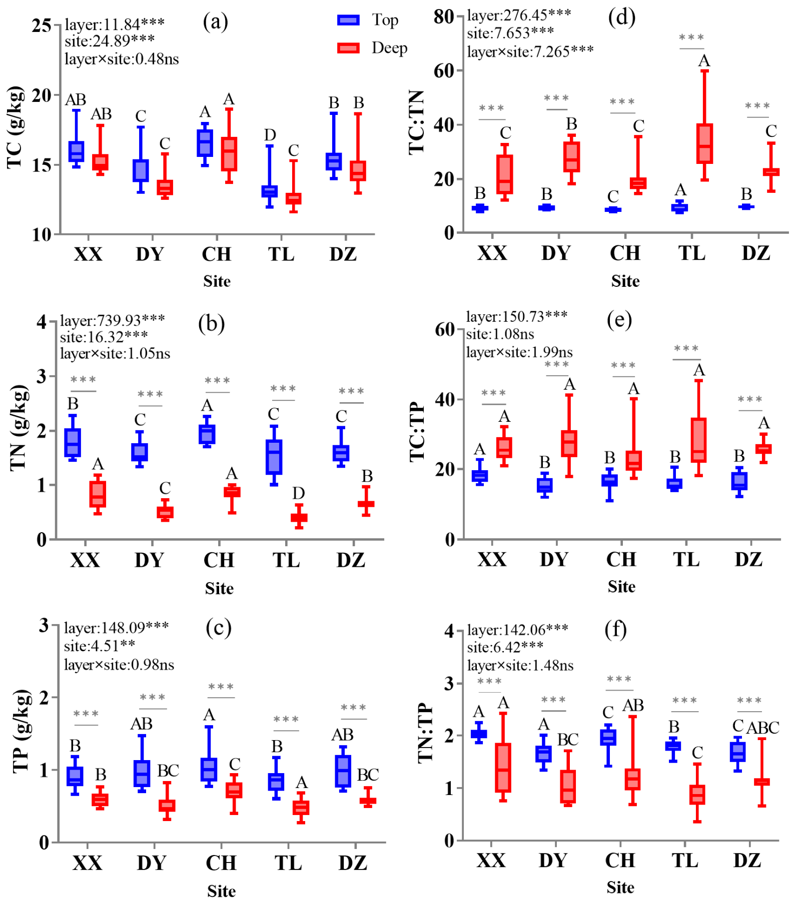

Figure 1. Soil total carbon (**a**), nitrogen (**b**), phosphorus (**c**) and their stoichiometric ratio (**d**–**f**) from different sites and layers. Different capital letters over the bars indicate statistical significance among different sites in the same layer at $p < 0.05$. The lines with * are significantly different between the top and deep layer at the same site. **, $p < 0.01$; ***, $p < 0.001$, ns, no significant difference. XX, Xiaoxian; DY, Dingyuan; CH, Chaohu; TL, Tongling; DZ, Dongzhi. TC, total carbon; TN, total nitrogen; TP, total phosphorus.

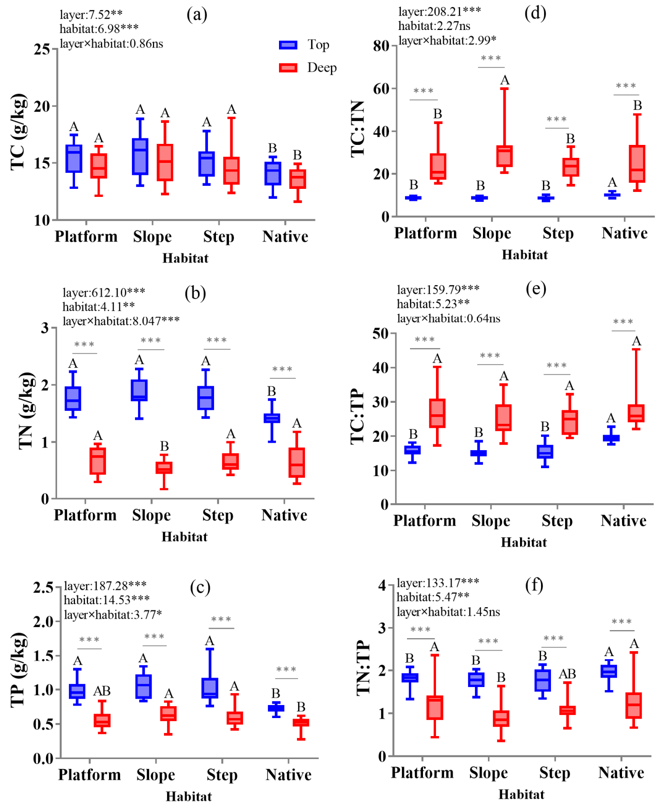

Figure 2. Soil carbon (**a**), nitrogen (**b**), phosphorus (**c**) and their stoichiometric ratio (**d**–**f**) from different habitats and layers. Different capital letters over the bars indicate statistical significance among different habitats in the same layer at $p < 0.05$. The lines with * are significantly different between the top and deep layer in the same habitats. *, $p < 0.05$; **, $p < 0.01$; ***, $p < 0.001$, ns, no significant difference. See abbreviations in Figure 1.

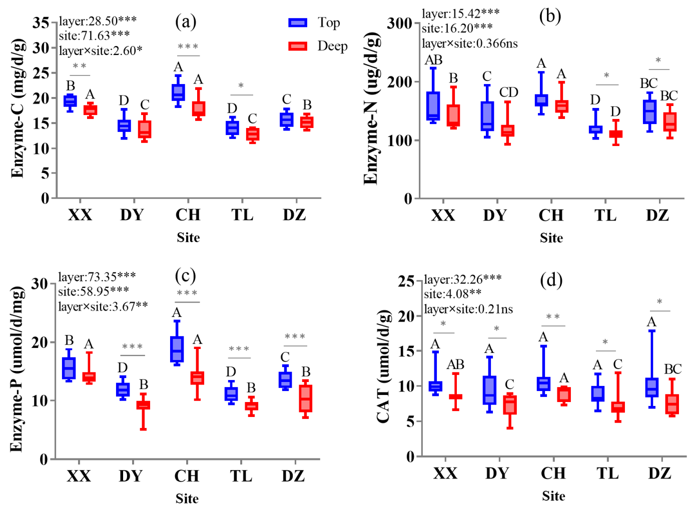

Figure 3. The soil enzyme-C (**a**), enzyme-N (**b**), enzyme-P (**c**) and catalase (**d**) activities from different sites and layers. Different capital letters over the bars indicate statistical significance among different sites in the same layer at $p < 0.05$. The lines with * are significantly different between the top and deep layer under the same site. *, $p < 0.05$; **, $p < 0.01$; ***, $p < 0.001$, ns, no significant difference. See abbreviations in Figure 1.

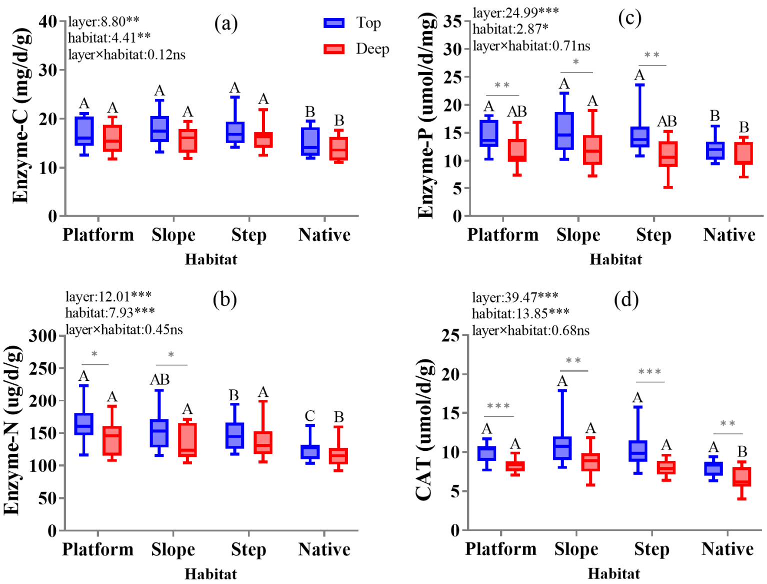

Figure 4. The soil enzyme-C (**a**), enzyme-N (**b**), enzyme-P (**c**) and catalase (**d**) activities from different habitats and layers. Different capital letters over the bars indicate statistical significance among different habitats in the same layer at $p < 0.05$. The lines with * are significantly different between the top and deep layer in the same habitats. *, $p < 0.05$; **, $p < 0.01$; ***, $p < 0.001$, ns, no significant difference.

3. Results

3.1. Contents and Stoichiometric Ratios of C, N, and P in Reclaimed Mining Areas

The variation trends of C, N and P in the five mining areas are generally consistent, all of which are CH > XX ~ DZ > DY > TL, showing that CH is the highest and TL is the lowest. The contents of TC, TN and TP in the deep soil and top soil of different mining areas were significantly different. The average TC, TN, and TP contents of the top soil (0–20 cm) in the study area were in the ranges of 11.97–18.90, 1.01–2.27, and 0.61–1.59 g/kg, respectively, which were significantly higher than those in the deep soil (20–40 cm, Figure 1a–c). Overall, the C:N ratio was in the range of 7.36–59.99 g/kg and was significantly lower in the top soil (9.07 ± 0.98 g/kg, values are presented as means ± standard error here in after) than in the deep soil (25.36 ± 8.97 g/kg, Figure 1d). TL was, significantly, the highest. The C:P ratio ranged from 11.06 to 45.36 and was significantly lower in the top soil (16.47 ± 2.54 g/kg) than in the deep soil (26.31 ± 5.73 g/kg). The N:P ratio showed the opposite trend, ranging from 1.33 to 2.25; it was significantly higher in the top soil (1.82 ± 0.23 g/kg) than in the deep soil (1.15 ± 0.42 g/kg) and higher in CH and XX than in the other sampling sites (Figure 1d–f).

From the perspective of habitat, although there is no significant difference in C, N, and P among the top soils of the platform, slope, and step, the overall level is significantly higher than that of the native habitat. The soil N content of the slope in the deep soil layer is significantly lower than that of other habitats (Figure 2a–c). The C:N, C:P, and N:P ratios of the top soil in the native areas (10.12 ± 0.93, 19.63 ± 1.35, 1.95 ± 0.19) are the highest according to the values with significance, while the C:N (30.68 ± 9.67) ratio of the slope in deep soil is the highest, significantly, but the N:P (0.89 ± 0.28) ratio is the lowest. There is no significant difference in the C:P ratio (Figure 2d–f).

3.2. Spatial Distribution of Soil Physical and Chemical Properties and Enzyme Activities

The TK content of the mine ecosystem after vegetation restoration was 5.25 ± 1.59 g/kg. In particular, the TK content of the deep soil (3.98 ± 0.83 g/kg) was significantly lower than that of the top soil (6.53 ± 1.07 g/kg, $p < 0.01$). The AK and AP contents of the top soil were 129.90 ± 42.06 and 36.4 ± 9.5 mg/kg, respectively, which were higher than those of the deep soil (88.74 ± 28.61 and 32.18 ± 8.04 mg/kg, respectively). Similarly, the NH_4-N (12.79± 2.62 mg/kg) and NO_3^- (41.78± 12.75 mg/kg) contents of the top soil were significantly higher than those of the deep soil (NH_4^+: 9.16± 2.15 mg/kg; NO_3^-: 28.70 ± 10.21 mg/kg, Figure S1).

The enzyme-C, enzyme-N, enzyme-P, and CAT activities of the top soil were 16.89 ± 3.12 mg/d/g, 147.95 ± 28.26 μg/d/g, 14.18 ± 3.27 μmol/d/mg, and 9.85 ± 2.18 μmol/d/g, respectively, which were significantly higher than those in the deep soil (15.39 ± 2.52 mg/d/g, 132.26 ± 24.63 μg/d/g, 11.38 ± 2.93 μmol/d/mg, and 7.94 ± 1.55 μmol/d/g, respectively). Except for CAT, the soil enzyme activities significantly differed among the regions, with the highest in CH and the lowest in DY and TL (Figure 3). In different habitats, the enzyme-C and enzyme-P activities of the platform, slope and step were significantly higher than those of the original habitat. The variability of enzyme-N in the top soil was larger, and the step and the original habitat were significantly lower than the platform and slope. There was no significant difference in CAT activity in the top soil of the four habitats (Figure 4).

3.3. SOM Content in Relation to Soil Physicochemical Properties, Enzyme Activities, and Climatic Factors

Person correlation analysis indicated that soil C, N, and P contents were significantly positively correlated with soil available nutrient contents and soil enzyme activities ($p < 0.05$). On the contrary, their stoichiometric ratios were negatively correlated with the above indicators (Figure 5). Relative importance analysis revealed that soil physicochemical properties had the greatest influence on TC, mainly AP (top soil: 13.04%; deep soil: 15.15%) and enzyme-C (top soil: 12.15%; deep soil: 13.69%). For the C:N ratio, soil physicochemical properties also had the greatest influence, mainly AP (top soil: 13.04%; deep soil: 15.15%) and enzyme-C (top soil: 12.15%; deep soil: 13.69%). For TN and TP, the top soil was mainly affected by soil physical and chemical properties and the deep soil was mainly affected by soil enzyme activities. For TN, TP, C:N, and C:P, the top soil was mainly affected by soil physical and chemical properties and the deep soil was mainly affected by soil enzyme activities (Figures 6 and 7).

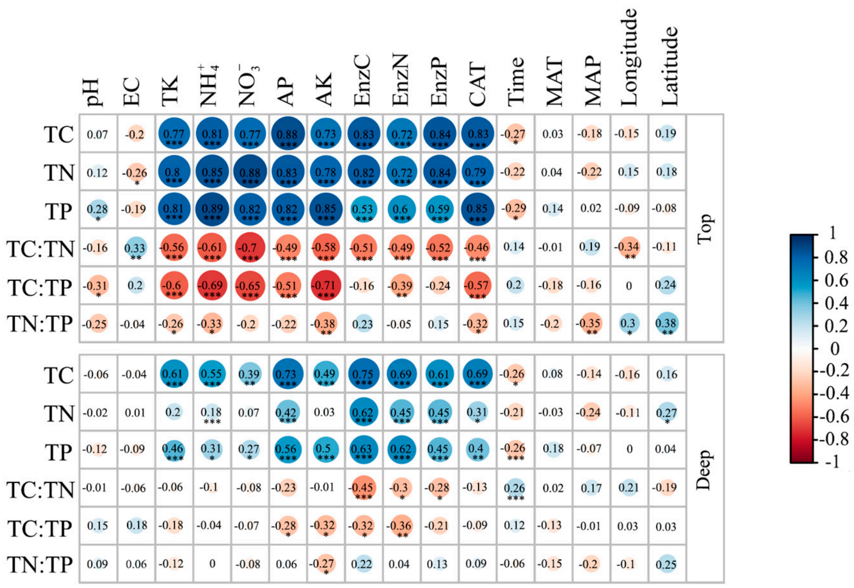

Figure 5. Pearson correlation coefficients of soil carbon, nitrogen, phosphorus and their stoichiometric ratio on climates, soil properties and soil enzyme activity across different layers (* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$; numbers are F-values). EC, electrical conductivity; TK, total potassium; AK, available potassium; NO_3^-, nitrate nitrogen; NH_4^+, ammonium nitrogen; AP, available phosphorus. EnzC, sucrase; EnzN, urease; EnzP, acid phosphatase; CAT, catalase. See abbreviations in Figure 1.

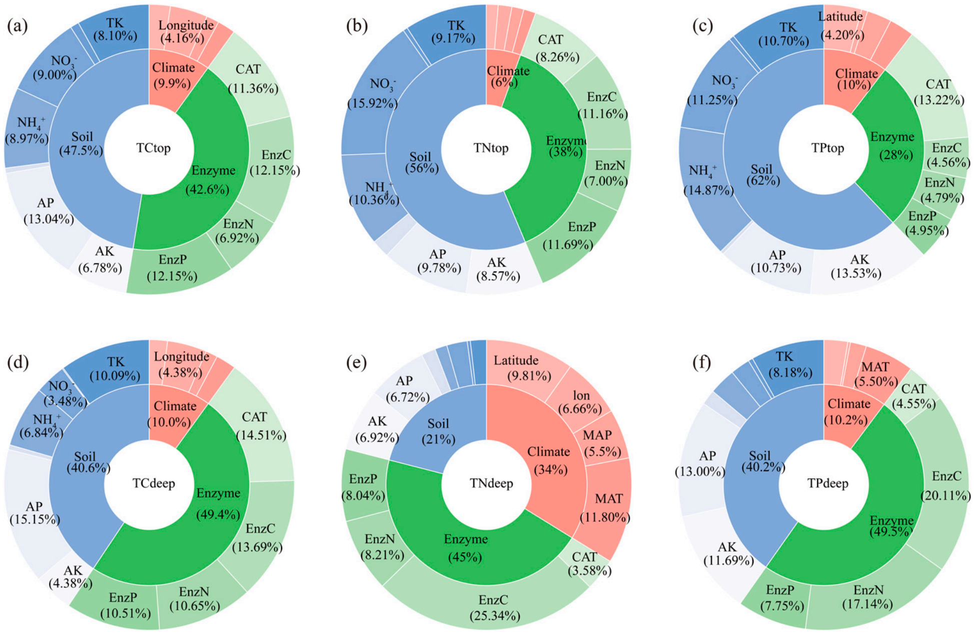

Figure 6. Relative importance analysis showing independent and combined effects of climate, soil properties and enzyme activities on soil carbon, nitrogen and phosphorus content in top (**a**–**c**) and deep soil (**d**–**f**). The effects of climates including MAT, MAP, longitude and latitude were marked in red. The soil properties including pH, EC, NO_3^-, NH_4^+, TK, AK, and AP were marked in blue, and soil enzyme activities including enzyme-C, enzyme-N, enzyme-P and CAT were marked in greed. See abbreviations in Figures 1 and 5.

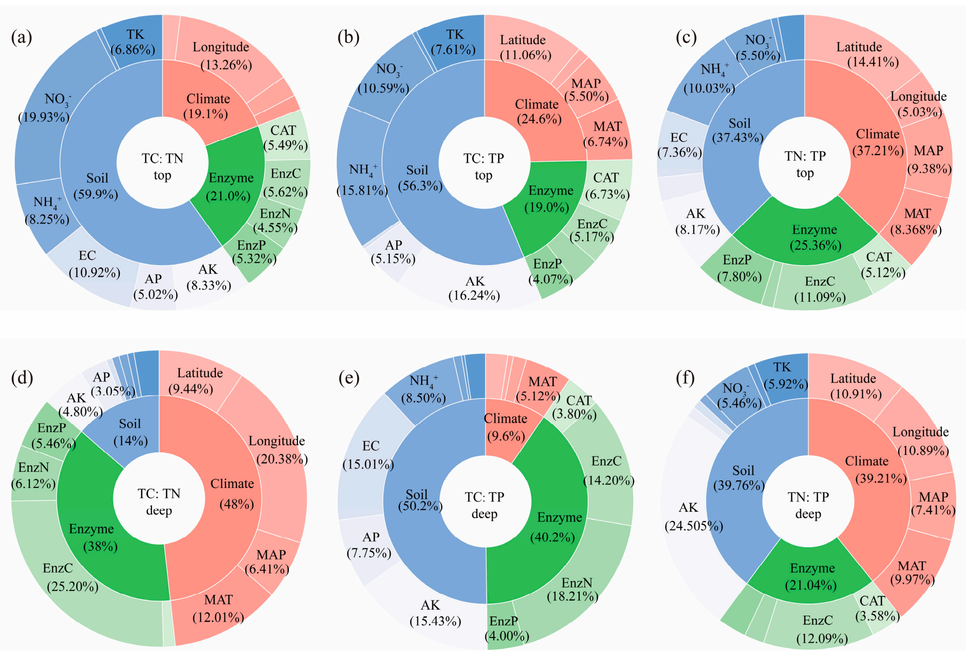

Figure 7. Relative importance analysis showing independent and combined effects of climate, soil properties, and enzyme activities on stoichiometric ratio in top (**a**–**c**) and deep soil (**d**–**f**). The soil properties including pH, EC, NO_3^-, NH_4^+, TK, AK, and AP were marked in blue, and soil enzyme activities including enzyme-C, enzyme-N, enzyme-P and CAT were marked in greed. See abbreviations in Figures 1 and 5.

4. Discussion

Soil C, N, and P are fundamental elements of ecosystems, and their contents and ratios play a critical role in the recovery and reconstruction of soil ecosystem functions in mining areas [24,31,32]. This study examined several mining areas with diverse habitat characteristics to elucidate the effects of climate, soil physicochemical properties, and soil enzyme activities on the turnover of SOM. Our findings indicated that soil C, N, and P contents exhibited consistent trends across the five study sites (Figure 1a–c). In addition, the duration of mine site restoration was negatively correlated with SOM contents (Table 1 and Figure 5). Analysis of SOM content at different soil depths revealed that vegetation restoration in the mining area led to a pronounced surface accumulation of C, N, and P, with the contents being significantly higher in the top soil than in the deep soil. This observation aligns with findings from other mining areas regarding the effects of vegetation restoration on SOM [33–35]. A study on coal mine restoration indicated that the accumulation of SOM in the top soil was significantly greater than that in the deep soil [36]. This phenomenon may be attributed to the increase in aboveground biomass and fine root inputs during vegetation restoration, improving the structure and aeration of the top soil and facilitating SOM accumulation [36]. By contrast, the deep soil exhibited sparse rooting, which necessitates leaching from aboveground materials for further nutrient accumulation. As a consequence, the SOM content in the deep soil was significantly lower than that in the top soil. Correlation analysis revealed the positive relationship of surface SOM with soil physical and chemical properties and enzyme activities. Relative importance analysis indicated that soil physicochemical properties including NH_4^+, NO_3^-, AK, and TK were the main factors affecting SOM (Figure 6). On the contrary, the deep soil was mainly affected by soil enzyme activities including sucrase, urease, phosphatase, and catalase. In general, high levels of available nutrients in the soil directly promote plant growth and microbial activity, thereby enhancing SOM accumulation [37]. Furthermore, vegetation restoration improves soil pore structure and water aeration, significantly increasing the activity of soil enzymes related to the element cycle [38].

This study found a negative correlation between the number of years of restoration and SOM content, contradicting the majority of previous studies that suggested that an increase in restoration duration enhances soil fertility [39,40]. The highest C, N, and P contents were observed in the mine site (CH) that had been restored for only 1 year. On the one hand, this phenomenon may be attributed to the significant short-term enhancement of soil quality resulting from the large input of organic fertilizers and other inputs in the initial restoration, leading to a high background value of soil at the initial stage of reclamation (Figure 1). On the other hand, Zipper et al. (2011) also found that nutrient limitation due to the gradually reduced anthropogenic management in the later stages of vegetation growth may have caused further a reduction in AP, NH_4^+, and NO_3^- contents [41]. In addition, variations in soil nutrient levels across different sites may be influenced by the types of vegetation present. Among the five mines that underwent vegetation restoration, the CH site utilized a mixture of trees, shrubs, and grasses, including *R. pseudoacacia*, *C. sinensis*, *A. fruticosa*, *V. sativa*, and *C. dactylon*. This diversity may contribute to high soil nutrient levels due to the high-quality litter input from *R. pseudoacacia* and *A. fruticose* [42,43]. Furthermore, increased plant diversity promotes soil C accumulation and enhances soil fertility by elevating inter-root C inputs and stimulating microbial activity [10,44]. It has been demonstrated that the C, N, and P contents of *R. pseudoacacia* leaves were high in the early part of the growing season, suggesting that this high-quality litter significantly contributed to soil nutrient enhancement during the short ecological restoration period [45]. By contrast, the primary tree species planted in the DZ site was *Pinus massoniana*, a coniferous species that has a relatively high C:N ratio and decomposes slowly, resulting in its lower nutrient return compared with that of *A. fruticose* [46]. In the present study, the C:N and C:P ratios in the deep soil of the five mining areas were greater than those in the top soil. In the restoration area, characterized by a low N:P ratio, the growth of plants was predominantly constrained by N availability [47]. This finding suggests that the effectiveness of N in the artificially reclaimed soils of the mining areas was relatively low, resulting in varying degrees of N limitation across all five sites. The different levels of N limitation were largely alleviated by the N-fixing plants such as *R. pseudoacacia* and *A. fruticosa* planted at the CH site [48,49]. Meanwhile, the mine site (TL) that had been restored for 4 years exhibited high C:N and C:P ratios, particularly in the deep soil (Figure 2). This result shows that vegetation growth was increasingly constrained by nutrient availability as the restoration progressed [50].

Analyses of SOM in three habitats—platform, slope, step and native area—revealed a general trend of gradually decreasing C and N contents, although no significant differences were observed among the reclaimed habitats. The P and C content in the slope was slightly higher than that in the platform and step. In addition, the C, N, and P contents of these habitats were significantly greater than those of the native habitats (Figure 2). With regard to soil types in reclaimed areas, the relatively weak decomposition and mineralization of SOM in yellow and yellow–brown soils contributed to an increase in SOC and TN contents [51]. It has been suggested that Ca is a primary factor influencing the stability of SOM. In soils with high concentrations of Ca^{2+}, the formation of mineral complexes involving SOM and Ca^{2+} is considered the main mechanism for SOM stabilization. The increased SOM content in reclaimed mine soils may be attributed to the high clay content and Ca^{2+} levels present [52]. Key nutrient indicators such as NH_4^+, NO_3^-, AP, TK, and AK were significantly higher in the reclaimed areas than in the native area. The abundance of these nutrients could drive changes in the complexity of plant community structure and influence understory microclimatic conditions, thereby contributing to species diversity [38]. By contrast, the scarcity of soil nutrients in the native habitats may be attributed to the impoverished nature of their parent mineral composition. Soil N and P contents are low in younger and older soils possibly because the nutrient output from the soil (runoff and uptake) exceeds the nutrient input (litter decomposition). In addition, the nutrients released by soil weathering cannot compensate for the biological uptake of nutrients [53]. The significant increase in N, P, and Ca net loss indicates that soil nutrient depletion increased with forest age. Although vegetation restoration can significantly enhance the effectiveness of soil nutrients, attention should be paid to the nutrient limitations that may result from long-term restoration.

For ecological restoration in mining areas, different vegetation restoration strategies are employed based on various geomorphological features [54]. In regions characterized by wide steps and platforms and relatively gentle terrain, a mixed-species approach incorporating trees, shrubs, and grasses is often implemented to maximize the restoration of vegetation cover and ecological functions. In sloped areas, the establishment of trees and shrubs is challenging due to the steep gradients. Therefore, engineering measures such as the installation of hanging nets, the spraying of grass seeds, or the use of planting bags are predominantly utilized for restoration [14]. Although these measures contribute to vegetation recovery to some extent, the types of vegetation and their specific plant characteristics influence the effects of restoration on post-mining soil properties. Soil enzyme production is a crucial process that regulates soil ecosystem functions, including C and nutrient cycling [55]. The levels of soil enzymes were significantly higher in all three landscapes compared with those in the native habitats (Figure 4). The observed increase in enzyme activity following the vegetation restoration of post-mining lands may result from the accumulation of new substrates, the decomposition of plant debris, and the exudation of roots [56].

5. Conclusions

The restoration of vegetation in the mining area has significantly increased the storage of SOM, particularly in the surface layer, with relatively little effect on the deeper soil. Meanwhile, the stoichiometric characteristics indicates soil N is a major limiting factor in the top soil. The SOM content in different sites showed substantial spatial variability, while climatic factors had little effect on the variation in SOM. The correlation analysis and relative importance analysis showed that SOM content was mainly related to soil available nutrients and enzyme activities. This may be because the active artificial management in the early recovery period of the mining area promoted the accumulation of available nutrients and enzyme activity, which were very important for maintaining soil fertility and health, and further promoted the accumulation of SOM.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/f15111969/s1: Figure S1: The soil properties from different sites and layers. Different capital letters over the bars indicate statistically significant among different sites in the same layer at $p < 0.05$. The line with * are significant difference between top and deep layer under the same site. *, $p < 0.05$; **, $p < 0.01$; ***, $p < 0.001$. XX, Xiaoxian; DY, Dingyuan; CH, Chaohu; TL, Tongling; DZ, Dongzhi; TK, total potassium; AK, available potassium; NO_3^-, nitrate nitrogen; NH_4^+, ammonium nitrogen; AP, available phosphorus.; Figure S2: The soil properties from different habitats and layers. Different capital letters over the bars indicate statistically significant among different habitats in the same layer at $p < 0.05$. The line with * are significant difference between top and deep layer under the same habitats. See Figure S1 for the abbreviations; Figure S3: The soil pH and EC from different sites, habitats and layers. Values followed by a different capital letter are significant different among different sites or habitat in the same layer at $p < 0.05$. There was no significant difference in soil layer. See Figure S1 for the abbreviations.

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