RESEARCH

Responses of soil stoichiometry and soil enzyme activities in the different distance around opencast coal mine of the Hulun Buir Grassland of China

Yinli Bi[1,2] · Nan Guo[1] · Yanxu Zhang[1] · Xianglei Li[1] · Ziheng Song[1]

Abstract

The objectives of this study were to explore the changes in soil stoichiometry and enzyme activities at different distances from an opencast coal mine in the Hulun Buir Grassland of China. Four transects were established on north and east sides of the opencast coal mining area, and samples were collected at 50 m, 550 m, and 1550 m from the pit on each transect. Control samples were collected from a grassland station 8 km from the opencast coal mining area that was not disturbed by mining. Four replicate soil samples were collected at each point on the four transects. Soil physicochemical properties and enzyme activities were determined, and correlations between soil properties and stoichiometric ratios and enzyme activities were explored using redundancy analysis. The increase in distance from mining did not significantly affect soil properties, although soil urease activity was significantly lower than that of the control area. Soil properties 1550 m from the mine pit were similar to those at the grassland control. In addition, soil total nitrogen had the greatest effect on soil stoichiometry, and soil total potassium had the greatest effect on soil enzyme activities. Coal dust from opencast mining might be the main factor affecting soil stoichiometry and enzyme activities. The results of this study provide direction for the next step in studying the influence of mining areas on soil properties and processes.

Keywords Opencast coal mine · Soil stoichiometry · Soil enzyme activities · Distance · Grassland

1 Introduction

Coal is the main source of energy in China, and thus, it is important in economic and social development in China (Yang et al. 2018; Suo et al. 2021). With rapid economic development, coal resources have been overexploited, which affects the ecological environment and causes degradation of vegetation and soil (Younger et al. 2004). Mining dust can affect plant growth, and plant health around mines is related to the dust generated by mining and the distance to

Co-first authors: Yinli Bi and Nan Guo.

✉ Yinli Bi
    ylbi88@126.com

1   State Key Laboratory for Fine Exploration and Intelligent
     Development of Coal Resources, China University of Mining
     and Technology (Beijing), Beijing 100083, China

2   Institute of Ecological Environment Restoration in Mine
     Areas of West China, Xi'an University of Science
     and Technology, Xi'an 710054, China

a mine (Kayet et al. 2019a, 2019b). However, with the rapid economic development, the focus has been on ecological restoration, whereas soil quality is often neglected. In addition to climate change and human activities (Yang et al. 2019b), changes in soil characteristics can also significantly affect plant growth.

Soil quality is the main factor limiting growth of grassland vegetation (Wang et al. 2018; Dong et al. 2019). Soil carbon (C), nitrogen (N), phosphorus (P), and potassium (K) are the main elements that determine soil fertility (McDonald 1992; Pettigrew 2008; Khan et al. 2018; Hinojosa et al. 2021; Wang et al. 2021b), and C, N, P, and other element cycles in an ecosystem are coupled with one another. In addition, changes in element ratios determine the main characteristics of organisms and ecosystems (Hessen et al. 2013), regulate most biochemical processes, and affect the energy balance of biosystems (Sardans et al. 2012; Cui et al. 2018; Yang et al. 2019a). Coal mining introduces inorganic C dust and waste gas into ecosystems, and in grassland ecosystems, the inputs disturb original patterns, including regional water and thermal conditions, and lead to subsequent changes in

soil nutrients (Zhang et al. 2018). Soil ecological stoichiometric ratios are used as primary indices to reflect changes in soil element contents. Therefore, because of the importance of coal in China, it is essential to study nutrient cycles and mechanisms to maintain nutrient balances in ecosystems affected by proximity to coal mines.

Soil enzymes, derived from root exudates, litter, and microbial activity (Pausch and Kuzyakov 2018), are active in various biochemical processes and nutrient cycles (Li et al. 2014) and thus have vital roles in recycling of soil nutrients and maintaining soil fertility. Changes in soil enzyme activities provide early warnings of soil biological changes (Bandick and Dick 1999), and therefore, enzymes are good indicators of soil quality (Bastida et al. 2006). In addition, enzymes are highly sensitive to environmental and anthropogenic stimuli (Rutigliano et al. 2009). Consequently, soil enzyme activities have been extensively investigated in objective evaluations of soil fertility and biological activity (Roldán et al. 2005). Moreover, soil enzyme activity increases with vegetation restoration (Xiao et al. 2020) and is a primary factor affecting soil C and N transformations. Therefore, soil chemical properties are likely closely related to soil enzyme activities (Cui et al. 2019). However, previous studies have not associated soil enzyme activities with soil properties (Lauber et al. 2008; de Vries et al. 2012).

In this study, the hypothesis was that changes would occur in soil stoichiometry and enzyme activities at different distances from an opencast coal mine. In addition, the factors affecting changes in soil properties around the opencast mining area were explored. Samples were collected at different distances from the coal mining area, and soil properties in those samples were compared with those from two undisturbed controls at inner and outer of grassland stations that were fenced and far from the coal mining area. Ecological econometric ratios were used to analyze the changes in soil physicochemical properties and enzymes at different distances from the mining area.

2 Materials and methods

2.1 Study area

The study area (Fig. 1) was a typical grassland in the Hulun Buir high plain that included grasslands to the north and east of an opencast mine (48° 48′–50° 12′ N, 118° 22′–121° 02′ E) in the Inner Mongolia Autonomous Region, Northeast China. Winters are cold and long, with an average of 110 frost-free days, and summers are cool and short, with concentrated and relatively low amounts of rainfall. Temperatures change dramatically in spring and autumn. In 2018,
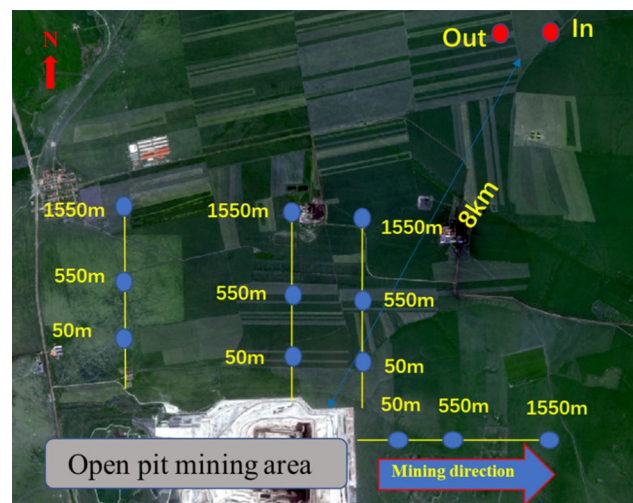
Fig. 1 Schematic of the study area and sampling sites

mean annual precipitation was 29.1 mm, and mean annual temperature was − 0.1 °C. In a typical ecologically fragile area, the grassland in the area was degenerating. The grassland soils were a light calcareous and dark chestnut calcareous soils, according to the Chinese soil classification system. Soils had a thin humus layer and were poor in nutrients. Study area vegetation included the dominant species *Carex duriuscula* C. A. Mey., *Stipa baikal*, and *Leymus chinensis* (Table 1).

2.2 Study site selection

Four replicate grassland transects were set up (Fig. 1) to determine the effects of different distances from an opencast coal mine on soil stoichiometry and enzyme activity. Three transects extended from the northern edge of the mining area and one extended from the eastern edge. The transects were distance gradients, with soil samples collected 50 m, 550 m, and 1550 m from the mine. Two undisturbed controls were established. One area (Inner) is inside the enclosed national grassland station in Prairie Chenbarhu Banner where grass naturally grows with Stipa being the main species, and the other area (Outer) is outside the grassland station in the natural grazing area. The station was 8 km from the mining area boundary and was not affected by the mining. Thus, 14 sites were established to represent four zones of different distance from the opencast coal mine.

2.3 Soil sampling and processing

At each site, four 1 m × 1 m plots were set up, spaced at least 10 m from one another. In each plot, soil samples at a 0–10 cm depth were collected using the S-shaped method,

Table 1 Geographic information on the sampling sites

Distance (m)	Transects	Latitude (N)	Longitude (E)	Altitude (m)	Dominant species
50	1	49° 24′ 50″	119° 42′ 34″	626.3	*Carex duriuscula* C.A. Mey.; *Cleistogenes squarrosa* (Trin.) Keng*; Calamagrostis epigeios* (L.) Roth
	2	49° 24′ 30″	119° 45′ 17″	642.3	*Carex duriuscula* C.A. Mey.; *Stipa baicalensis* Roshev.; *Cleistogenes squarrosa* (Trin.) Keng
	3	49° 24′ 24″	119° 45′ 44″	644	*Carex duriuscula* C.A. Mey.; *Stipa baicalensis* Roshev.; *Leymus chinensis* (Trin.) Tzvel
	4	49° 24′ 00″	119° 46′ 20.″	671.3	*Carex pediformis; Stipa baicalensis* Roshev.; *Carex duriuscula* C.A. Mey.;
550	1	49° 24′ 50″	119° 42′ 31″	639	*Galium verum* L.; *Carex duriuscula* C.A. Mey.; *Potentilla acaulis* L
	2	49° 24′ 46″	119° 45′ 17″	642	*Carex duriuscula* C.A. Mey.; *Leymus chinensis* (Trin.) Tzvel.; *Cleistogenes squarrosa* (Trin.) Keng
	3	49° 24′ 40″	119° 45′ 44″	652.6	*Carex duriuscula* C.A. Mey.; *Stipa baicalensis* Roshev.; *Artemisia frigida* Willd
	4	49° 24′ 02″	119° 46′ 45″	660.9	*Carex duriuscula* C.A. Mey.; *Carex pediformis; Stipa baicalensis* Roshev.;
1550	1	49° 25′ 38″	119° 42′ 32″	626.7	*Carex duriuscula* C.A. Mey.; *Potentilla acaulis* L
	2	49° 25′ 18″	119° 45′ 17″	669	*Carex duriuscula* C.A. Mey.; *Leymus chinensis* (Trin.) Tzvel.; *Stipa baicalensis* Roshev
	3	49° 25′ 12″	119° 45′ 47″	684.4	*Carex duriuscula* C.A. Mey.; *Stipa baicalensis* Roshev.; *Leymus chinensis* (Trin.) Tzvel
	4	49° 24′ 02″	119° 47′ 34″	668.2	*Cleistogenes squarrosa* (Trin.) Keng; *Carex duriuscula* C.A. Mey.; *Stipa baicalensis* Roshev
≥ 8000	1	49° 28′ 03″	119° 49′ 30″	637.3	*Leymus chinensis* (Trin.) Tzvel.; *Stipa baicalensis* Roshev.; *Carex duriuscula* C.A. Mey.
	2	49° 28′ 07″	119° 48′ 33″	653.4	*Carex duriuscula* C.A. Mey.; *Leymus chinensis* (Trin.) Tzvel.; *Cleistogenes squarrosa* (Trin.) Keng

and samples from the same plot were pooled as one composite sample. In the laboratory, all roots, stones, and visible fauna were removed from the composite samples. Samples were then separated into three portions. One portion was air-dried and sieved to 2 mm and used to analyze soil physicochemical properties, including pH, electrical conductivity (EC), particle size, available P (AP), and available K (AK). One portion was air-dried and sieved to 0.147 mm and used to analyze soil chemical properties, including soil organic C (SOC), total N (TN), total P (TP), and total K (TK). The remaining portion of fresh soil samples was stored at 4 °C and used to determine soil enzyme activities, including sucrase, urease, and acid phosphatase activities.

2.4 Soil enzyme activities

Soil sucrase (S-SC) and urease (S-UE) activities were determined as previously reported (Xiao et al. 2018). In brief, soil sucrase activity was determined by 3,5-dinitro salicylic acid colorimetry using sucrose as the substrate and expressed in milligrams of glucose produced by 1 g of dry soil in

24 h. Soil urease activity was determined by a sodium phenol–sodium hypochlorite colorimetric method and expressed in milligrams of NH_3–N produced by 1 g of dry soil in 24 h. Soil acid phosphatase (S-ACP) activity was determined as reported by Tarafdar and Marschner (1994) and expressed by the amount of acid phosphatase converted to *p*-nitrophenyl disodium phosphate (PNPP) in 1 h per gram of soil sample.

2.5 Soil physicochemical properties

Soil variable water content (VWC) was measured using a TDR350 soil moisture meter (Spectrum, USA). Soil pH was measured in soil suspensions with soil to water (weight to volume) ratios of 1:2.5 using an electronic pH meter fitted with a glass electrode (Mettler Toledo FE30, Shanghai, China). Soil EC was determined using a leaching–conductivity method with soil to water (weight to volume) ratios of 1:5 with a conductivity meter fitted with a glass electrode (Mettler Toledo FE30/EL30). Soil particle size was determined using a laser particle size analyzer (Malvern Mastersizer 3000, UK). Soil organic C was measured by a potassium dichromate external heating method (Kalembasa

and Jenkinson 1973). Total N was determined using a Kjeldahl digestion method (Bai et al. 2019). Total P content was determined with inductively coupled plasma-atomic emission spectroscopy (ICP-AES) after digestion with $HCl–HNO_3–HF–HClO_4$ (Bing et al. 2016). Soil available P and AK) were determined with ICP-AES after extraction with ammonium carbonate.

2.6 Statistical analyses

One-way ANOVA was used to test differences among distances, with $P < 0.05$ as the significance threshold with Duncan test. Statistical analyses were conducted with SPSS (version 19.0; SPSS Inc., Chicago, IL, USA). Redundancy analysis (RDA) was used to examine which soil factors affected stoichiometry and enzyme activities at different distances. The RDA was implemented in Canoco 5.0 software (Microcomputer Power, Inc., Ithaca, NY, USA).

3 Results

3.1 Soil properties

Soil properties in the study area are presented in Table 2. With an increase in distance to the mine pit, soil clay and silt contents increased, soil sand content decreased, and soil VWC remained relatively stable. Soils were acidic, with pH ranging from 6.27 to 6.57. With an increase in distance to the mine pit, soil pH and EC gradually decreased, with values at 1550 m and 8000 m from the pit significantly lower than those at 50 m ($P < 0.05$). Contents of both SOC and

TN tended to increase with distance from the pit, but there were no significant differences among samples at different distances. The highest contents of both SOC and TN were in the control area 8 km from the mine pit. Contents of TP and TK tended to increase with distance to the mine pit. However, there were no significant differences among different distances to the mine pit. Soil TK content also increased with an increase in distance to the mine pit, but differences among sites were not significant. Soil physicochemical properties at 1550 m from the mine pit were most similar to those in the grassland station control area, indicating the coal mine had little effect on soil properties at 1550 m.

3.2 Stoichiometry of soil organic carbon, total nitrogen, total phosphorus, and total potassium

The SOC:TN, SOC:TK, and TN:TK soil mass ratios were not significantly different among different distances from the pit (Fig. 2). Responses of SOC:TP and TN:TP mass ratios to distance from the mine pit were similar. Within 1550 m of the mining area, SOC:TP mass ratios ranged from 61.63 to 65.91 and TN:TP mass ratios ranged from 5.19 to 5.38. Those ratios were lower than the SOC:TP (71.85) and TN:TP (5.84) ratios in the control area. The ratios at 550 m and 1550 m were significantly lower than those in the control area. Mass ratios of TP:TK tended to increase with distance from the pit. However, the lowest TP:TK mass ratios were in the control area.

Table 2 Soil physicochemical properties at different distances from an opencast coal mine

Properties	50 m	550 m	1550 m	8000 m
Soil clay (< 0.002 mm)	$21.41 \pm 0.11b$[a]	$21.77 \pm 0.15ab$	$21.62 \pm 0.07ab$	$21.91 \pm 0.12a$
Soil silt (0.002–0.02 mm)	$30.73 \pm 1.05a$	$30.56 \pm 0.91a$	$31.1 \pm 0.37a$	$32.99 \pm 0.73a$
Soil sand (0.02–2 mm)	$47.86 \pm 1.13a$	$47.68 \pm 1.04a$	$47.28 \pm 0.37a$	$45.1 \pm 0.84b$
VWC (%)[b]	$19.23 \pm 0.7ab$	$22.03 \pm 0.98a$	$21.7 \pm 0.81a$	$18.34 \pm 1.53b$
pH	$6.57 \pm 0.07a$	$6.43 \pm 0.06ab$	$6.31 \pm 0.04b$	$6.27 \pm 0.06b$
EC (µs/cm)	$380.94 \pm 28.17a$	$290.49 \pm 19.08b$	$276.09 \pm 16.79b$	$254.34 \pm 14.77b$
SOC (g/kg)	$36.34 \pm 2.59a$	$33.03 \pm 2.93a$	$36.64 \pm 2.7a$	$40.19 \pm 1.74a$
TN (g/kg)	$3.00 \pm 0.25a$	$2.74 \pm 0.28a$	$3.15 \pm 0.25a$	$3.27 \pm 0.15a$
TP (g/kg)	$0.54 \pm 0.03a$	$0.51 \pm 0.04a$	$0.58 \pm 0.02a$	$0.56 \pm 0.01a$
TK (g/kg)	$6.05 \pm 0.32a$	$5.89 \pm 0.32a$	$6.26 \pm 0.17a$	$6.7 \pm 0.09a$
AP (mg/kg)	$8.78 \pm 0.55b$	$8.44 \pm 0.81b$	$9.98 \pm 0.64ab$	$12.04 \pm 1.15a$
AK (mg/kg)	$206.16 \pm 10.04a$	$162.23 \pm 11.75b$	$196 \pm 12.38ab$	$215.58 \pm 9.84a$

EC electrical conductivity, *SOC* soil organic matter carbon, *TN* total nitrogen, *TP* total phosphorus, *TK* total potassium, *AP* available phosphorus, *AK* available potassium

[a]The values are presented mean $\pm$ SE, n = 12. Different letters within a row indicate significant differences among sites at $P < 0.05$

[b]VWC, variable water content of soil

3.3 Enzyme activities

Significant differences were observed in enzyme activities among distances from the mine pit (Fig. 3). Soil sucrase activity fluctuated within 1550 m from the pit, but activity was significantly higher in the control area than at 550 m from the pit. There was little variation in S-UE activity within 1550 m, but activity at all distances was significantly lower than that in the control area. Soil acid phosphatase activity was not significantly different along the distance gradient.

3.4 Relations between soil factors and soil chemometrics and enzyme activities

In RDA sorting diagrams (Figs. 4 and 5), blue arrows represent response variables and red arrows represent interpretation variables. In the RDA in Fig. 4, soil stoichiometric ratios were used as response variables, and soil physicochemical properties were used as interpretation variables. The total interpretation by the variables reached 97.3%, with the first axis of the RDA explaining 64.35% of the variability and the second axis explaining 22.41% of the variability. Total N, SOC, TK, and TP explained 55.7%, 20.5%, 12.3%, and 8.5% of the variation respectively (Fig. 4). In general, the longer an arrow in an RDA sorting diagram is, which indicates the greater the explanatory power. The smaller the cosine value of the angle, which indicates the two variables are closely related. Therefore, an interpretation variable can explain the change in a response variable. Soil organic carbon and nitrogen mass were significantly negatively correlated with SOC:TN but were positively correlated with other soil chemometric ratios (Fig. 4). The constraint accumulation analysis considering soil comprehensive factor conditions showed that soil chemometric characteristics were mainly affected by SOC, TP, TN, TK, and soil grains, each with a significant contribution ($P < 0.05$).

Soil enzyme activities were response variables, and soil physicochemical properties were interpretation variables in a second RDA. Total interpretation by the soil property variables was 56.4%. In the RDA, the first axis explained 47.18% of the variability in soil enzyme activities and the second axis explained 5.33% of the variability. Total K, AK, and AP explained 38%, 7.1%, and 4.2% of the variation, respectively (Fig. 5). Total K, AP, and AK were significantly positively correlated with soil enzyme activity (Fig. 5). The cumulative amount of conditional restriction analysis of the integrated soil factors with consideration of the interaction between factors showed that soil enzyme activity was mainly affected by TK AK, and AP, each with a significant contribution ($P < 0.05$).

4 Discussion

With increasing distance from the mine pit, overall soil quality, characterized by soil physicochemical properties, tended to improve. Soil particle size was measured by a laser particle size analyzer, which considers soil particles as spherical and calculates particle size according to diameter. Soil clay content increased, and soil sand content decreased with increasing distance from the pit. Soil pH also decreased with increasing distance. Plant root secretions can improve soil physical structure and with other root inputs, can increase soil quality and nutrient content (Liu et al. 2021), and wind and associated dust can increase soil sand content (Kayet et al. 2019a). In this study, with dust decreasing with increasing distance from the mine area, overall vegetation coverage and density and whole root systems increased. As a result, soil conditions also improved. Therefore, with increasing distance from the pit, increases in vegetation coverage, root systems, litter biomass, and soil microbial activity all contributed to improved soil quality.

Soil organic C levels mainly depend on return of plant litter and transformation of the inorganic C pool (Houlton et al. 2018). Soil N levels also mainly depend on return of plant litter, but atmospheric deposition and biological N fixation also contribute to the soil N pool (Houlton et al. 2018). By contrast, soil P and K levels mainly depend on rock weathering (Walker and Syers 1976; Chadwick et al. 1999). Near the opencast mining area, as the influence of mining decreased, the overall soil nutrient content increased. The increase might be because vegetation types and coverage increased and thus soil nutrients from the return of plant litter also increased. Soil stoichiometric ratios are the main indices of soil element contents and are important in studies on ecosystem nutrient cycling and balance mechanisms. Cycles of C, N, P, and other elements are coupled, and thus, contents of those nutrients are commonly used to indicate soil fertility status. Rates of change among indices determine the main features of biological and ecological systems (Hessen et al. 2013). In this study, soil C, N, P, and K contents increased with increasing distance from the pit. However, soil C:N, C:K, and N:K ratios did not differ significantly with increasing distance from the pit. Soil nutrient status is strongly related to distance from a mining pit because soil nutrients are influenced by litter input and microbial decomposition at local sites (Troelstra et al. 1990; Chadwick et al. 1999; Van Sundert et al. 2020). In addition, soil contents of C, N, P, and K are primarily regulated by organic matter accumulation and decomposition (Li et al. 2018; Bai et al. 2019; Kooch et al. 2019).
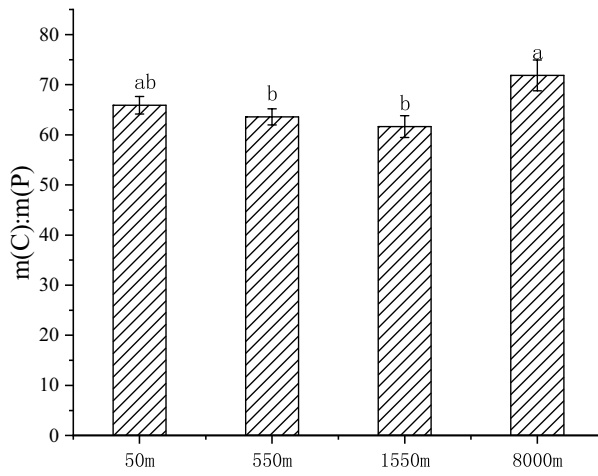
Soil eco-chemometrics are important in revealing mechanisms of element circulation and balance (Lal 2004).
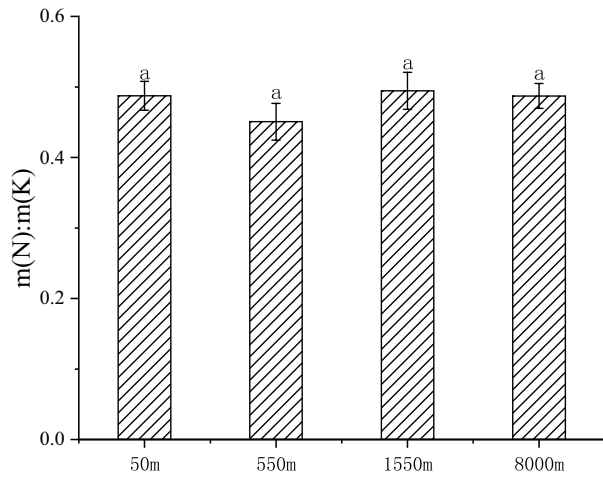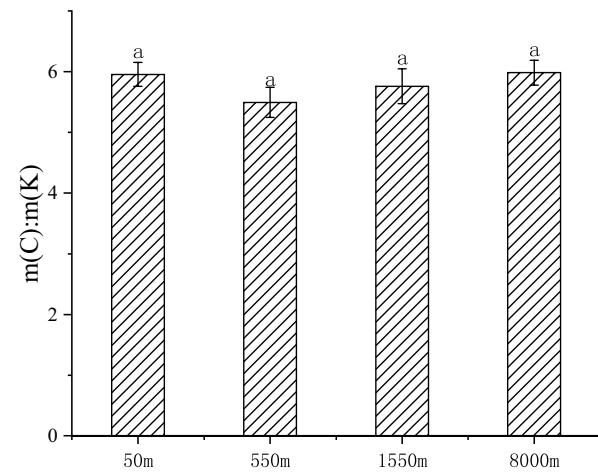
(a)

(b)

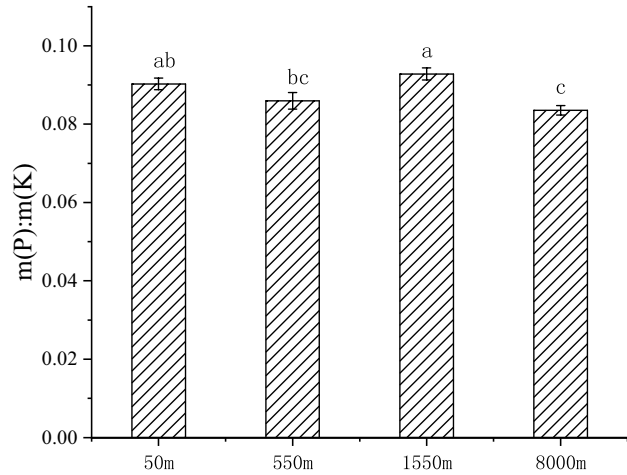(c)

(d)

(e)
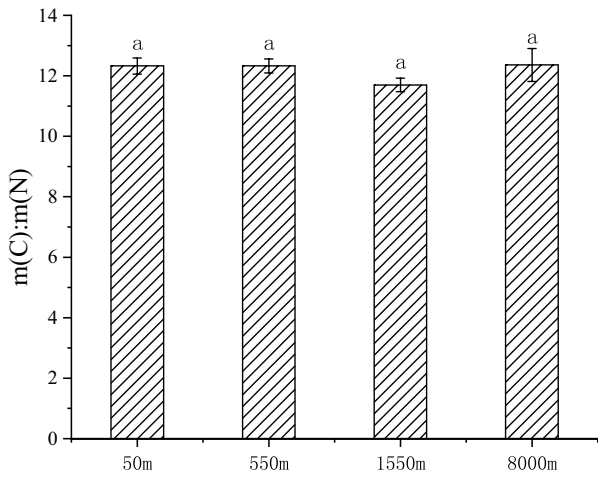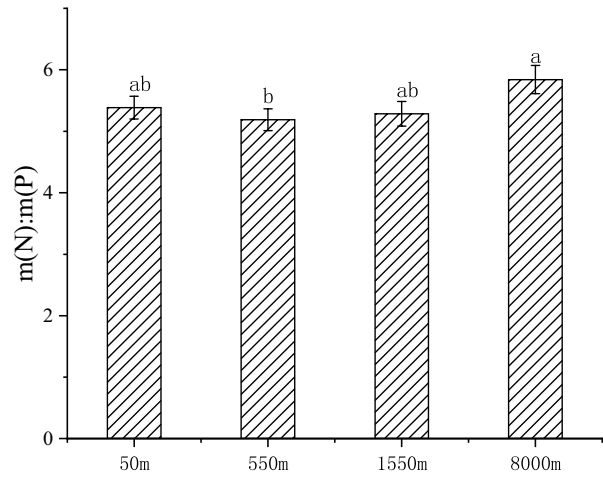
(f)

◄**Fig. 2** Soil stoichiometric ratios at different distances from an opencast coal mine. The values are presented mean±SE, *n*=12. The x-axis represents the distance from the mining area. In Figures **a–f** C:N, soil organic carbon (C):soil total nitrogen (N); C:P, soil organic C:soil total phosphorus (P); C:K, soil organic C:soil total potassium (K); N:P, soil total N:soil total P; N:K, soil total N:soil total K; P:K, soil total P:Ssoil total K. Different letters indicate significant differences among sites at *P* < 0.05

Regional hydrothermal conditions, vegetation communities, and human activities all greatly influence soil nutrient contents and lead to increased spatial variability in soil stoichiometry (Wang et al. 2021a). Soil stoichiometry reflects the decomposition and accumulation of organic matter to a certain extent, and N and P enrichment and availability can be used as indicators of soil fertility in a certain range (Méndez and Karlsson 2005). The global soil C:N ratio ranges from 9.9 to 29.8, and according to soil C and N reserves, the average global soil C:N ratio is 13.33 and the average global grassland soil C:N ratio is 11.8 (Cleveland and Liptzin 2007). The average soil C:N ratio in China is 11.9 (Tian et al. 2010). The high C:N ratio in this study indicated slow mineralization of organic matter, and slow decomposition of organic matter is conducive to maintaining soil fertility (Li et al. 2021). As a diagnostic index of soil N saturation, the N:P ratio is used to determine the threshold of nutrient limitation (McLauchlan et al. 2006). The N:P ratio of surface soil in the mining area was lower than the average soil N:P ratio in China by a factor of 5.2 (Tian et al. 2010), which might be due to dust pollution resulting from mining and further increases in surface soil P content.

The soil C pool consists of SOC and inorganic C pools. The CO_2 released by decomposition of the SOC pool dissolves in soil water and is converted into inorganic C (Sasmito et al. 2020). Soil inorganic C mainly occurs in arid soils, and the inorganic C content in arid soil can reach levels five times higher than those of organic C (Bhattacharya et al. 2016). As a component of the C cycle, soil inorganic C content is also affected by climate change and human activities (Bhattacharya et al. 2016). In this study, the stoichiometric ratios of SOC with other soil elements were relatively high around the opencast mining area, possibly because coal forms as the product of plant death and accumulation and is rich in inorganic C. Long-term exposure changes the composition and physical and chemical properties of coal because of weathering or oxidation (Zhang et al. 2019). Many coal ash particles in coal mining areas spread to various other areas because of atmospheric movement. Particles then settle into soil and enter the terrestrial C cycle. Thus, ash particles can affect soil quality around mining areas, which leads

to changes in spatial and temporal developmental patterns of regional vegetation coverage and ultimately soil stoichiometry (Zhang et al. 2019). Different distance gradients in opencastt mining areas can have an interaction because of different environmental factors. In this study, SOC content significantly affected the characteristics of soil ecological stoichiometry. Soil organic C affects plant growth and development and is the major driving factor of ecological stoichiometry (Helton et al. 2015). This conclusion was confirmed in this study. This preliminary study only examined changes in soil nutrient and stoichiometric characteristics at different distances from a mining area. To comprehensively evaluate soil nutrient status in grassland ecosystems around opencast mining areas, it is necessary to conduct in-depth explorations that combine analyses of vegetation, N deposition, and litter nutrient dynamics. It is also necessary to link biogeochemical cycles of different vegetation communities with additional environmental factors in order to reveal the eco-stoichiometric characteristics of vegetation–litter–soil, as well as mutual relations and spatial variations.

Soil enzyme activity is an important index to comprehensively evaluate changes in soil quality and soil microbial communities (Nadimi-Goki et al. 2018; Boughattas et al. 2019). Soil sucrase is directly involved in the metabolic processing of soil organic matter. Generally, the higher the content of soil organic matter is, the higher the sucrase activity. Thus, sucrase activity can be used to evaluate soil maturity and fertility (Akhtar et al. 2018; Qiu et al. 2018). Soil enzyme activity is affected by many factors, including levels of soil nutrients, intensity of soil respiration and degree of human disturbance (Datta et al. 2021). Organic matter content, water content, N, P, and K levels, and urease activity can be highly significantly positively correlated (Xiao et al. 2019). In this study, soil TK explained the most variability in soil enzyme activity, explaining 38% of the variation, which might be because K can activate a variety of enzymes.

5 Conclusions

Soil nutrient contents varied with distance from the opencast mine and reached the highest levels at 1550 m from the mine. Soil pH and EC values were the lowest at 1550 m, with values significantly lower than those at other distances. Soil enzyme activity was the lowest at 550 m, but activity was not significantly different from that at other distances. With increasing distance from the mine, soil nutrients, soil enzyme activities, and soil stoichiometric ratios increased

(a)

(b)

(c)
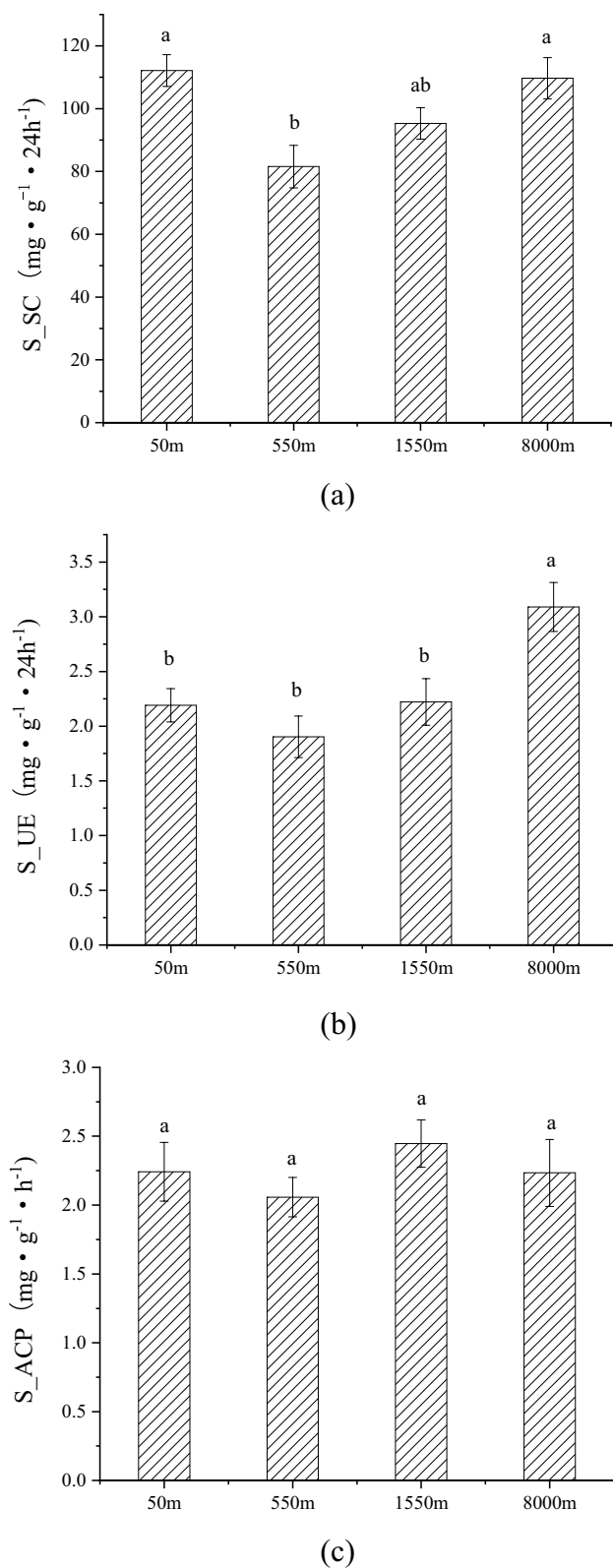
Fig. 3 Soil enzyme activities at different distances from an opencast coal mine. The values are presented mean ± SE), $n = 12$. The x-axis represents the distance from the mining area. In Figures **a–c**, S-SC, soil sucrase; S-UE, soil urease; S-ACP, soil acid phosphatase. Different letters indicate significant differences among sites at $P < 0.05$

(a)

(b)
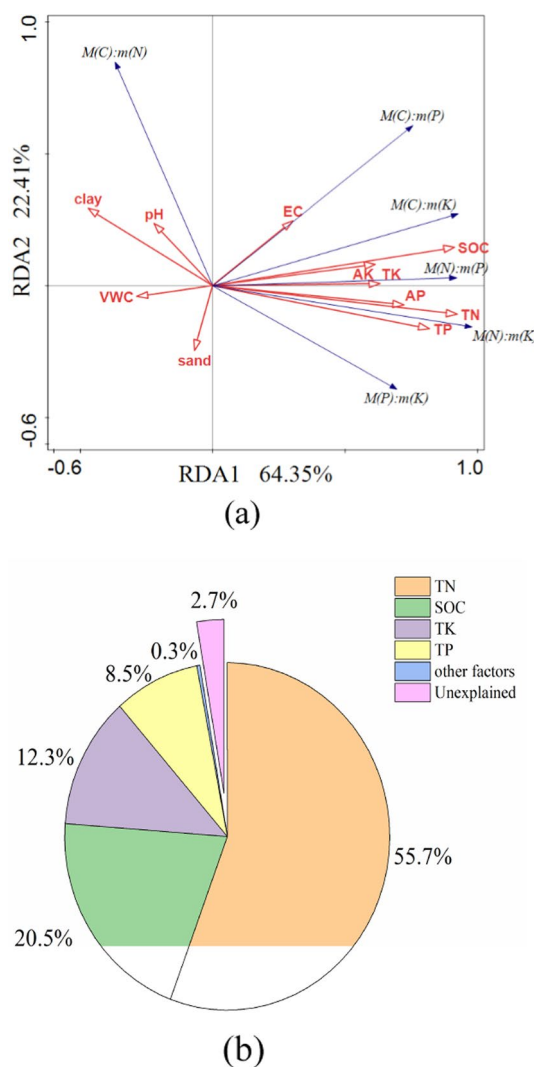
Fig. 4 Redundancy analysis (RDA) of soil chemometric ratios and soil physicochemical properties and cumulative interpretation of soil factors. In Figures **a** and **b** C:N, soil organic carbon (C):soil total nitrogen (N); C:P, soil organic C:soil total phosphorus (P); C:K, soil organic C:soil total potassium (K); N:P, soil total N:soil total P; N:K, soil total N:soil total K; P:K, soil total P:soil total K; *VWC* variable water content of soil, *EC* electrical conductivity, *SOC* soil organic matter carbon, *TN* total nitrogen, *TP* total phosphorus, *TK* total potassium, *AP* available phosphorus, *AK* available potassium

significantly, which might be related to dust production during the expansion of mining. Redundancy analysis showed that soil N and SOC contents explained the most variation in soil stoichiometric ratios and that soil TK explain the most variation in soil enzyme activities. Coal dust from the opencast mining might be the main factor affecting soil enzyme activities and soil stoichiometric characteristics. This study can serve as a foundation to guide the next step in studies on the influence of mining areas on soil properties and processes.

(a)

(b)
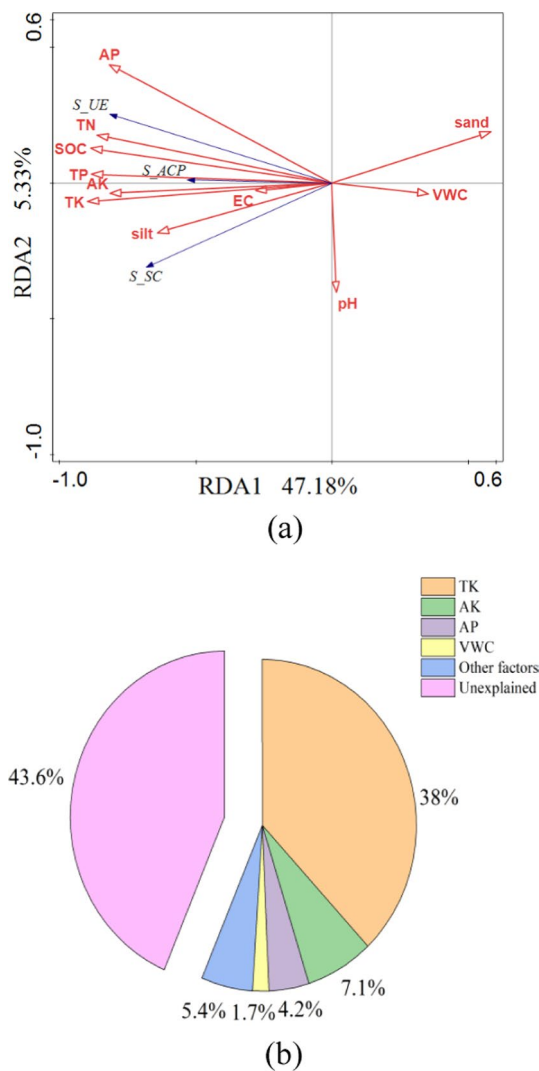
Fig. 5 Redundancy analysis (RDA) of soil enzyme activities and soil physicochemical properties and cumulative interpretation of soil factors. In Figures **a** and **b** *S-SC* soil sucrose, *S-UE* soil urease, *S-ACP* soil acid phosphatase, *VWC* variable water content of soil, *EC* electrical conductivity, *SOC* soil organic matter carbon, *TN* total nitrogen, *TP* total phosphorus, *TK* total potassium, *AP* available phosphorus, *AK* available potassium

Author contributions YB and NG conceived and designed the study. Sampling in the experiment and data analysis were performed by NG, YZ, XL, and ZS. The first draft of the manuscript was written by NG and YB.

Availability of data and materials The data sets generated and analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

References

Akhtar K, Wang W, Ren G, Khan A, Feng Y, Yang G (2018) Changes in soil enzymes, soil properties, and maize crop productivity under wheat straw mulching in Guanzhong, China. Soil Tillage Res 182:94–102. https://doi.org/10.1016/j.still.2018.05.007

Bai X, Wang B, An S, Zeng Q, Zhang H (2019) Response of forest species to C:N:P in the plant–litter–soil system and stoichiometric homeostasis of plant tissues during afforestation on the Loess Plateau, China. Catena (amsterdam) 183:104186. https://doi.org/10.1016/j.catena.2019.104186

Bandick AK, Dick RP (1999) Field management effects on soil enzyme activities. Soil Biol Biochem 31:1471–1479. https://doi.org/10.1016/S0038-0717(99)00051-6

Bastida F, Moreno J, Hernández T, García C (2006) Microbiological activity in a soil 15 years after its devegetation. Soil Biol Biochem 38:2503–2507. https://doi.org/10.1016/j.soilbio.2006.02.022

Bhattacharya SS, Kim K-H, Das S, Uchimiya M, Jeon BH, Kwon E, Szulejko JE (2016) A review on the role of organic inputs in maintaining the soil carbon pool of the terrestrial ecosystem. J Environ Manag 167:214–227. https://doi.org/10.1016/j.jenvman.2015.09.042

Bing H, Wu Y, Zhou J, Li R, Wang J (2016) Historical trends of anthropogenic metals in Eastern Tibetan Plateau as reconstructed from alpine lake sediments over the last century. Chemosphere 148:211–219. https://doi.org/10.1016/j.chemosphere.2016.01.042

Boughattas I, Hattab S, Alphonse V, Livet A, Giusti-Miller S, Boussetta H, Banni M, Bousserrhine N (2019) Use of earthworms *Eisenia andrei* on the bioremediation of contaminated area in north of Tunisia and microbial soil enzymes as bioindicator of change on heavy metals speciation. J Soils Sediments 19:296–309. https://doi.org/10.1007/s11368-018-2038-8

Chadwick OA, Derry LA, Vitousek PM, Huebert BJ, Hedin LO (1999) Changing sources of nutrients during four million years of ecosystem development. Nature 397:491–497. https://doi.org/10.1038/17276

Cleveland CC, Liptzin D (2007) C:N:P stoichiometry in soil: Is there a "redfield ratio" for the microbial biomass? Biogeochemistry 85:235–252

Cui Y, Fang L, Guo X, Wang X, Zhang Y, Li P, Zhang X (2018) Ecoenzymatic stoichiometry and microbial nutrient limitation in rhizosphere soil in the arid area of the northern Loess Plateau, China. Soil Biol Biochem 116:11–21. https://doi.org/10.1016/j.soilbio.2017.09.025

Cui YX, Fang LC, Deng L, Guo XB, Han F, Ju WL, Wang X, Chen HS, Tan WF, Zhang XC (2019) Patterns of soil microbial nutrient limitations and their roles in the variation of soil organic carbon across a precipitation gradient in an arid and semi-arid region. Sci Total Environ 658:1440–1451. https://doi.org/10.1016/j.scitotenv.2018.12.289

Datta A, Gujre N, Gupta D, Agnihotri R, Mitra S (2021) Application of enzymes as a diagnostic tool for soils as affected by municipal solid wastes. J Environ Manag 286:112169. https://doi.org/10.1016/j.jenvman.2021.112169

de Vries FT, Manning PRB, Tallowin J, Mortimer SR, Pilgrim ES, Harrison KA, Hobbs PJ, Quirk H, Shipley B, Cornelissen JH, Kattge J, Bardgett RD (2012) Abiotic drivers and plant traits explain landscape-scale patterns in soil microbial communities. Ecol Lett 15:1230–1239. https://doi.org/10.1111/j.1461-0248.2012.01844.x

Dong K, Hao G, Yang N, Zhang JL, Ding XF, Ren HQ, Shen JF, Wang JL, Jiang L, Zhao NX (2019) Community assembly mechanisms and succession processes significantly differ among treatments during the restoration of *Stipa grandis—Leymus chinensis* communities. Sci Rep 9:9. https://doi.org/10.1038/s41598-019-52734-0

Helton AM, Ardon M, Bernhardt ES (2015) Thermodynamic constraints on the utility of ecological stoichiometry for explaining global biogeochemical patterns. Ecol Lett 18:1049–1056. https://doi.org/10.1111/ele.12487

Hessen D, Elser J, Sterner R, Urabe J (2013) Ecological stoichiometry: an elementary approach using basic principles. Limnol Oceanogr 58:2219–2236. https://doi.org/10.4319/lo.2013.58.6.2219

Hinojosa MB, Albert-Belda E, Gómez-Muñoz B, Moreno JM (2021) High fire frequency reduces soil fertility underneath woody plant canopies of Mediterranean ecosystems. Sci Total Environ 752:141877. https://doi.org/10.1016/j.scitotenv.2020.141877

Houlton BZ, Morford SL, Dahlgren RA (2018) Convergent evidence for widespread rock nitrogen sources in Earth's surface environment. Science 360:58–62

Kalembasa SJ, Jenkinson DS (1973) A comparative study of titrimetric and gravimetric methods for the determination of organic carbon in soil. J Sci Food Agric 24:1085–1090

Kayet N, Pathak K, Chakrabarty A, Kumar S, Chowdary VM, Singh CP, Sahoo S, Basumatary S (2019a) Assessment of foliar dust using Hyperion and Landsat satellite imagery for mine environmental monitoring in an open cast iron ore mining areas. J Clean Prod 218:993–1006. https://doi.org/10.1016/j.jclepro.2019.01.305

Kayet N, Pathak K, Chakrabarty A, Singh CP, Chowdary VM, Kumar S, Sahoo S (2019b) Forest health assessment for geo-environmental planning and management in hilltop mining areas using Hyperion and Landsat data. Ecol Indic 106:105471. https://doi.org/10.1016/j.ecolind.2019.105471

Khan A, Lu G, Ayaz M, Zhang H, Wang R, Lv F, Yang X, Sun B, Zhang S (2018) Phosphorus efficiency, soil phosphorus dynamics and critical phosphorus level under long-term fertilization for single and double cropping systems. Agric Ecosyst Environ 256:1–11. https://doi.org/10.1016/j.agee.2018.01.006

Kooch Y, Sanji R, Tabari M (2019) The effect of vegetation change in C and N contents in litter and soil organic fractions of a Northern Iran temperate forest. Catena (amsterdam) 178:32–39. https://doi.org/10.1016/j.catena.2019.03.009

Lal R (2004) Soil carbon sequestration impacts on global climate change and food security. Science 304:1623–1627

Lauber CL, Strickland MS, Bradford MA, Fierer N (2008) The influence of soil properties on the structure of bacterial and fungal communities across land-use types. Soil Biol Biochem 40:2407–2415. https://doi.org/10.1016/j.soilbio.2008.05.021

Li J, Pu L, Han M, Zhu M, Zhang R, Xiang Y (2014) Soil salinization research in China: advances and prospects. J Geograph Sci 24:943–960. https://doi.org/10.1007/s11442-014-1130-2

Li Z, Zhao B, Olk DC, Jia Z, Mao J, Cai Y, Zhang J (2018) Contributions of residue-C and -N to plant growth and soil organic matter pools under planted and unplanted conditions. Soil Biol Biochem 120:91–104. https://doi.org/10.1016/j.soilbio.2018.02.005

Li L, Liu Y, Xiao T, Hou F (2021) Different responses of soil C:N:P stoichiometry to stocking rate and nitrogen addition level in an alpine meadow on the Qinghai-Tibetan Plateau. Appl Soil Ecol 165:103961. https://doi.org/10.1016/j.apsoil.2021.103961

Liu J, Gou X, Zhang F, Bian R, Yin D (2021) Spatial patterns in the C:N:P stoichiometry in Qinghai spruce and the soil across the Qilian Mountains, China. Catena (Amsterdam). https://doi.org/10.1016/j.catena.2020.104814

McDonald GK (1992) Effects of nitrogenous fertilizer on the growth, grain yield and grain protein concentration of wheat. Aust J Agric Res 43:949–967. https://doi.org/10.1071/AR9920949

McLauchlan KK, Hobbie SE, Post WM (2006) Conversion from agriculture to grassland builds soil organic matter on decadal timescales. Ecol Appl 16:143–153. https://doi.org/10.1890/04-1650

Méndez M, Karlsson PS (2005) Nutrient stoichiometry in *Pinguicula vulgaris*: nutrient availability, plant size, and reproductive status. Ecology 86:982–991

Nadimi-Goki M, Bini C, Wahsha M, Kato Y, Fornasier F (2018) Enzyme dynamics in contaminated paddy soils under different cropping patterns (NE Italy). J Soils Sediments 18:2157–2171. https://doi.org/10.1007/s11368-017-1830-1

Pausch J, Kuzyakov Y (2018) Carbon input by roots into the soil: quantification of rhizodeposition from root to ecosystem scale. Glob Chang Biol 24:1–12. https://doi.org/10.1111/gcb.13850

Pettigrew WT (2008) Potassium influences on yield and quality production for maize, wheat, soybean and cotton. Physiol Plant 133:670–681. https://doi.org/10.1111/j.1399-3054.2008.01073.x

Qiu L, Bi Y, Jiang B, Wang Z, Zhang Y, Zhakypbek Y (2018) Arbuscular mycorrhizal fungi ameliorate the chemical properties and enzyme activities of rhizosphere soil in reclaimed mining subsidence in northwestern China. J Arid Land 11:135–147. https://doi.org/10.1007/s40333-018-0019-9

Roldán A, Salinas-García JR, Alguacil MM, Caravaca F (2005) Changes in soil enzyme activity, fertility, aggregation and C sequestration mediated by conservation tillage practices and water regime in a maize field. Appl Soil Ecol 30:11–20. https://doi.org/10.1016/j.apsoil.2005.01.004

Rutigliano FA, Castaldi S, D'Ascoli R, Papa S, Carfora A, Marzaioli R, Fioretto A (2009) Soil activities related to nitrogen cycle under three plant cover types in Mediterranean environment. Appl Soil Ecol 43:40–46. https://doi.org/10.1016/j.apsoil.2009.05.010

Sardans J, Rivas-Ubach A, Peñuelas J (2012) The C:N:P stoichiometry of organisms and ecosystems in a changing world: a review and perspectives. Perspect Plant Ecol Evol Syst 14:33–47. https://doi.org/10.1016/j.ppees.2011.08.002

Sasmito SD, Kuzyakov Y, Lubis AA, Murdiyarso D, Borchard N (2020) Organic carbon burial and sources in soils of coastal mudflat and mangrove ecosystems. Catena (amsterdam) 187:104414. https://doi.org/10.1016/j.catena.2019.104414

Suo C, Li YP, Mei H, Lv J, Sun J, Nie S (2021) Towards sustainability for China's energy system through developing an energy-climate-water nexus model. Renew Sustain Energy Rev 135:110394. https://doi.org/10.1016/j.rser.2020.110394

Tarafdar JC, Marschner H (1994) Phosphatase activity in the rhizosphere and hyphosphere of VA mycorrhizal wheat supplied with inorganic and organic phosphorus. Soil Biol Biochem 26:387–395

Tian H, Chen G, Chi Z, Melillo JM, Hall C (2010) Pattern and variation of C:N:P ratios in China's soils: a synthesis of observational data. Biogeochemistry 98:139–151

Troelstra SR, Lotz LAP, Wagenaar R, Sluimer L (1990) Temporal and spatial variability in soil nutrient status of a former beach plain. Plant Soil 127:1–12. https://doi.org/10.1007/BF00010831

Van Sundert K, Van Sundert K, Radujkovi D, Cools N, De Vos B, Sophia E, Fernández-Martínez M, Janssens IA, Meril P, Peuelas J, Sardans J, Stendahl J, Terrer C, Vicca S et al (2020) Towards comparable assessment of the soil nutrient status across scales-review and development of nutrient metrics. Glob Chang Biol 26:392–409. https://doi.org/10.1111/gcb.14802

Walker TW, Syers JK (1976) The fate of phosphorus during pedogenesis. Geoderma 15:1–19

Wang R, Zhang Y, He P, Yin J, Yang J, Liu H, Cai J, Shi Z, Feng X, Dijkstra FA, Han X, Jiang Y (2018) Intensity and frequency of nitrogen addition alter soil chemical properties depending on mowing management in a temperate steppe. J Environ Manag 224:77–86. https://doi.org/10.1016/j.jenvman.2018.07.036

Wang C, Sun Y, Chen HYH, Ruan H (2021a) Effects of elevated CO2 on the C: N stoichiometry of plants, soils, and microorganisms in terrestrial ecosystems. Catena (amsterdam) 201:105219. https://doi.org/10.1016/j.catena.2021.105219

Wang L, Xie J, Luo Z, Niu Y, Coulter JA, Zhang R, Lingling L (2021b) Forage yield, water use efficiency, and soil fertility response to alfalfa growing age in the semiarid Loess Plateau of China. Agric Water Manag 243:106415. https://doi.org/10.1016/j.agwat.2020.106415

Xiao L, Huang Y, Zeng Q, Zhao J, Zhou J (2018) Soil enzyme activities and microbial biomass response to crop types on the terraces of the Loess Plateau, China. J Soils Sediments 18:1971–1980. https://doi.org/10.1007/s11368-018-1969-4

Xiao L, Bi YL, Du SZ, Wang Y, Guo C (2019) Effects of re-vegetation type and arbuscular mycorrhizal fungal inoculation on soil enzyme activities and microbial biomass in coal mining subsidence areas of Northern China. Catena (amsterdam) 177:202–209. https://doi.org/10.1016/j.catena.2019.02.019

Xiao L, Liu G, Li P, Li Q, Xue S (2020) Ecoenzymatic stoichiometry and microbial nutrient limitation during secondary succession of natural grassland on the Loess Plateau, China. Soil Tillage Res 200:104605. https://doi.org/10.1016/j.still.2020.104605

Yang X, Wang Y, Sun M, Wang R, Zheng P (2018) Exploring the environmental pressures in urban sectors: an energy-water-carbon nexus perspective. Appl Energy 228:2298–2307. https://doi.org/10.1016/j.apenergy.2018.07.090

Yang D, Song L, Jin G (2019a) The soil C:N:P stoichiometry is more sensitive than the leaf C:N:P stoichiometry to nitrogen addition: a four-year nitrogen addition experiment in a *Pinus koraiensis* plantation. Plant Soil 442:183–198. https://doi.org/10.1007/s11104-019-04165-z

Yang X, Dong Q, Chu H, Ding C, Yu Y, Zhang C, Yan Z, Yang Z (2019b) Different responses of soil element contents and their stoichiometry (C:N:P) to yak grazing and Tibetan sheep grazing in an alpine grassland on the eastern Qinghai-Tibetan Plateau. Agric Ecosyst Environ 285(8):106628. https://doi.org/10.1016/j.agee.2019.106628

Younger PL, Wolkersdorfer C, ERMITE-Consortium (2004) Mining impacts on the fresh water environment: technical and managerial guidelines for catchment scale management. Mine Water Environ 23:s2–s80. https://doi.org/10.1007/s10230-004-0028-0

Zhang BL, Luo H, Lv LH, Wang J, Zhang BS (2018) Analysis of ecological environment impact of coal exploitation and utilization. In: 2nd International conference on energy engineering and environmental protection (EEEP), Sanya, P R China, Nov 20–22 2017. IOP conference series-earth and environmental science. Iop Publishing Ltd., Bristol. https://doi.org/10.1088/1755-1315/121/3/032002

Zhang M, Wang J, Li S (2019) Tempo-spatial changes and main anthropogenic influence factors of vegetation fractional coverage in a large-scale opencast coal mine area from 1992 to 2015. J Clean Prod 232:940–952. https://doi.org/10.1016/j.jclepro.2019.05.334