

Effects of vegetation restoration in karst areas on soil nitrogen mineralisation

Jianghong Wu, Xianghuan Gong and Yingge Shu

College of Agronomy, Guizhou University, Guiyang, Guizhou, China

ABSTRACT

Background: Nitrogen mineralization plays a critical role in the ecosystem cycle, significantly influencing both the ecosystem function and the nitrogen biogeochemical cycle. Therefore, it is essential to investigate the evolutionary characteristics of soil nitrogen mineralization during the karst vegetation restoration to better understand its importance in the terrestrial nitrogen cycle.

Methods: This study analyzed from various stages of vegetation growth, including a 40-year-old woodland, 20-year-old shrubland, 15-year-old shrubland, 5-year-old grassland, and nearby cropland. The aerobic incubation technique was used for 35 days to evaluate soil N mineralization characteristics and their correlation with soil environmental factors. The study focused on examining the variations in soil N mineralization rate (NMR), N nitrification rate (NR), net nitrification rate (AR), and NH_4^+ -N and NO_3^- -N levels.

Results: Nitrate nitrogen, the primary form of inorganic nitrogen, increased by 19.38% in the 0–40 cm soil layer of the 20-year-old shrubland compared to the cultivated land. Soil NH_4^+ -N levels varied during the incubation period, decreasing by the 14th day and rising again by the 21st day. Soil NO_3^- -N and total inorganic nitrogen levels initially increased, then declined, and eventually stabilized, reaching their highest levels on the 14th day. During vegetation restoration, the soil NR and NMR decreased gradually with increasing incubation time. The 15-year shrub, 20-year shrub, and 40-year woodland showed the potential to increase soil NR and NMR. Furthermore, the 15-year shrub and 20-year shrub also increased soil AR. The Mantel test analysis indicated positive correlations among total nitrogen (TN), total phosphorus (TP), total potassium (TK), silicon (Si), AR, NR, and NMR. While available phosphorus (AP) and NMR demonstrated positive correlations with NR and NMR. Furthermore, TN, TP, TK, and Si were found to be positively correlated with AR, NR, and NMR, whereas AP and NO_3^- -N showed negative correlations with AR, NR, and NMR. It is worth noting that NH_4^+ -N had the greatest effect on AR, while the bulk density (BD) significantly affected the NR. Furthermore, ammonium nitrogen (AN) and soil organic carbon (SOC) were identified as the primary contributors to NMR. This study provides a theoretical basis for comprehending the influence of vegetation restoration on soil nitrogen mineralization and its role in ecosystem restoration.

Submitted 8 May 2024

Accepted 4 November 2024

Published 20 December 2024

Corresponding author

Yingge Shu, maogen958@163.com

Academic editor

Shaw Badenhorst

Additional Information and
Declarations can be found on
page 19

DOI 10.7717/peerj.18582

© Copyright

2024 Wu et al.

Distributed under

Creative Commons CC-BY 4.0

OPEN ACCESS

Subjects Agricultural Science, Soil Science

Keywords Vegetation restoration, Nitrogen mineralization, Environmental factors, Mantel test-Test

INTRODUCTION

Nitrogen is crucial for the synthesis of a wide range of complex organic compounds and is essential for the survival of all living organisms on Earth (McNeill & Unkovich, 2007; Pandey, Panda & Singh, 2024). Soil comprises about 95% of the total nitrogen in terrestrial ecosystems around the globe, and soil nitrogen is considered an essential element that significantly influences plant growth, regulates nutrient cycling, and supports ecosystem functioning (Knops, Bradley & Wedin, 2002; Zhang et al., 2014; Yadav et al., 2021).

Although the majority of nitrogen in the soil is found in organic forms, the nitrogen mineralization rate (NMR), which measures the ratio of organic to inorganic nitrogen, is a key indicator of how efficiently soil nitrogen is converted to a form available for plant uptake (Risch et al., 2020). The process of converting organic nitrogen to inorganic nitrogen, referred to as nitrogen mineralization, directly affects the availability of nitrogen in the soil (Zhong & Makeschin, 2003). This process is critical for plant growth and supports various ecosystem services. Soil microorganisms are responsible for the processes of ammonification and nitrification, which are essential to the mineralization of organic nitrogen (Maslov & Maslova, 2022). Several factors can influence nitrogen mineralization in the soil, including land use, soil characteristics, pH levels, temperature, moisture levels, type of vegetation, apoplastic quality, microbial populations, and human activities (Templer et al., 2005; Hu et al., 2019; Risch et al., 2019; Maslov & Maslova, 2022; Zhang et al., 2022; Li et al., 2023). Changes in nitrogen mineralization affect nitrogen availability (Schlesinger & Bernhardt, 2013), as well as primary productivity, ecosystem functioning, and long-term sustainability (Chen, Zeng & Fahey, 2009; Heitkamp et al., 2008).

Furthermore, nitrogen cycling and transformation processes are significantly influenced by the microbial population in the soil and the soil carbon-to-nitrogen (C:N) ratios (Chen et al., 2019; Padalia et al., 2022; Pandey et al., 2024). Therefore, the characteristics of nitrogen mineralization serve as critical indicators for the assessment of soil quality.

Land use and restoration techniques have been shown to substantially influence soil nitrogen (N) mineralization in numerous studies (Gurlevik & Karatepe, 2016; Li et al., 2018; Wang et al., 2017). These effects are primarily due to variations in plant diversity and abundance, as well as variations in soil physical, chemical, and microbial properties under different restoration techniques (Deng et al., 2014; Rhoades & Coleman, 1999). The impact of vegetation on N mineralization depends on the vegetation type, which influences both the quantity and quality of organic matter and the efficiency of nitrogen uptake by plants (Rahman, Bárcena & Vesterdal, 2017; Unver, küçük & Tufekcioglu, 2014). Various research focused on the impact of land use changes on N transformations (Contosta, Frey & Cooper, 2011; Li et al., 2014). However, there is a debate about how N mineralization rates are affected by vegetation restoration (Li et al., 2014). Some studies reported an increase in N mineralization (Gurlevik & Karatepe, 2016; Wang et al., 2017), while others observed a decrease (Li et al., 2014; Yang et al., 2010), or found no significant change (Zeng et al., 2009). Owen et al. (2003) observed higher soil mineralization rates in forests compared to grasslands attributing to the variations in carbon assimilation among plant functional

groups and differences in soil characteristics. *Wei et al. (2017)* observed that, despite an increase in functional group abundance, root nitrogen content decreased together with higher biomass, resulting in a reduced net soil nitrogen mineralization rate. There are substantial seasonal variations in the availability and turnover of soil nitrogen (*Dujardin et al., 2012*). Microbial activity is directly influenced by environmental factors, including temperature, moisture, and pH (*Unver, kükük & Tufekcioglu, 2014; Ye et al., 2015*).

Dujardin et al. (2012) observed that soil ammonium content reaches its highest level during the summer, due to increased microbial activity. *Hu et al. (2015)* observed similar soil nitrogen transformations in both biocrust-covered soils and bare ground, attributed to decreased microbial abundance and activity in extremely low temperatures. Despite the importance of soil nitrogen mineralization, there is limited research focusing on profiled soils in karst ecosystems. Furthermore, ecosystem responses to influencing factors can vary significantly (*Booth, Stark & Rastetter, 2005; Tapia-Torres et al., 2015; Zhou et al., 2009*), highlighting the necessity for site-specific assessments of nitrogen transformation (*Burke, 1989; Liu et al., 2017*). Moreover, the majority of ecosystems lack a comprehensive understanding of the impact of vegetation restoration on soil nitrogen mineralization and the influence of soil environmental factors on this process. These knowledge gaps limit the precise prediction of nitrogen biogeochemical cycling.

The Southwest Karst region is recognized as one of the world's three major continuous karst distribution areas (*Sheng et al., 2018*). Throughout the latter half of the 20th century, significant carbonate development in this region resulted in shallow soil layers, complex karst ecosystems, high population density, and frequent human activities. These elements contributed to significant vegetation loss and ecosystem degradation (*Wang, Liu & Zhang, 2004*). In response, the Chinese government has initiated various vegetation restoration projects in the region (*Basile-Doelsch, Balesdent & Pellerin, 2020; Chen et al., 2018; Wang et al., 2018*). Despite the increased vegetation cover achieved through these initiatives, the impacts (*Li et al., 2019*) and the underlying mechanisms of long-term restorations on soil inorganic nitrogen accumulation (*Li et al., 2019; Liu et al., 2024*) and nitrogen mineralization remain unclear.

This study analyzed ecosystems at various stages of natural succession following the retirement of agricultural land. The focus was on grasslands retired for 5 and 15 years, shrublands abandoned for 20 years, and woodlands left fallow for 40 years, with comparisons made to actively cultivated arable land as a baseline. This study was based on the hypothesis that vegetation restoration has a major effect on soil N mineralization. This effect was attributed to the continuous build-up of soil organic matter and significant changes in soil environmental factors. To validate this premise, the study aimed to achieve two primary objectives: (1) elucidate the mechanisms through which vegetation restoration affects soil N mineralization and (2) quantify the key soil physico-chemical parameters that influence this process. The primary objective was to verify the effects of vegetation restoration on soil N mineralization, assess the impact of key soil properties, and establish a strong scientific basis to guide ecological rehabilitation and soil management practices.

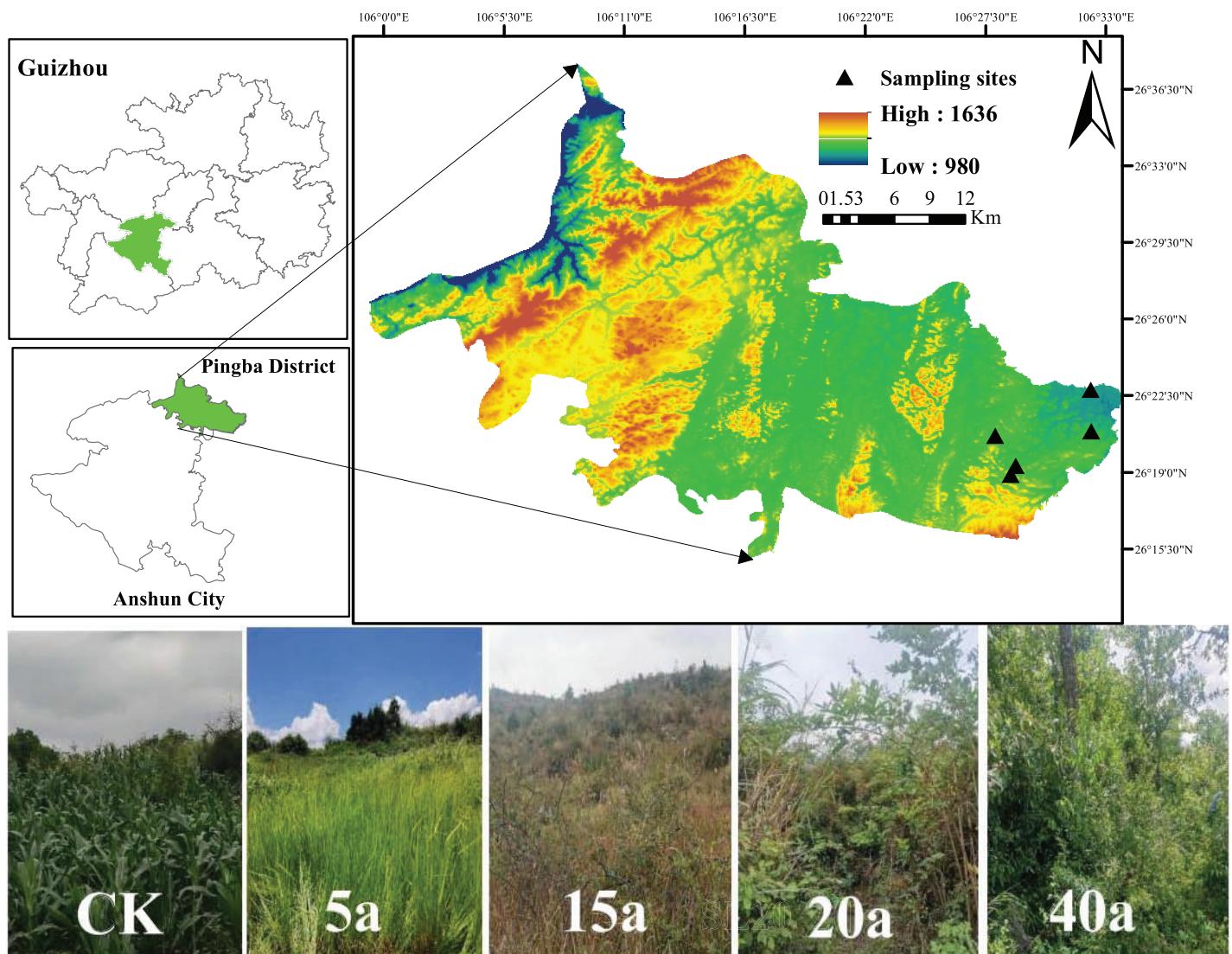


Figure 1 Basic information about the samples. Sampling sites. Map data © 2024 Bigmap.

[Full-size](#) DOI: 10.7717/peerj.18582/fig-1

MATERIALS AND METHODS

Study area

Pingba District ($26^{\circ}15'$ – $26^{\circ}37'40''$ N, $105^{\circ}59'20''$ – $106^{\circ}33'43''$ E), Anshun City, Guizhou Province, lies within subtropical humid monsoon climate zone. The area, with an elevation ranging from 963 to 1,645.6 m and an average annual temperature of 13.3 °C, features complex topography characterized by typical karst landscapes and diverse restored vegetation types. The parent rock of the study area is dominated by limestone, whereas the soil is primarily calcareous (Fig. 1).

Selection of sample plots

The vegetation types and restoration timelines of the area were accurately determined through detailed analysis using Google Historical Image Maps and on-site field surveys.

Table 1 Basic information of the sample site.

Sample type	Recovery years/a	Altitude /m	Longitude and latitude	Predominant species
Cropland	0	1,211	26°20'52"N, 106°32'18"E	<i>Zea mays</i>
Grassland	5	1,217	26°20'59"N, 106°32'18"E	<i>Imperata cylindrical</i>
	15	1,285	26°20'5"N, 106°27'56"E	<i>Imperata cylindrical</i>
Shrubland	20	1,289	26°18'54"N, 106°28'39"E	<i>Pyracantha fortuneana, Artemisia annua, Rubus idaeus L., Zanthoxylum simulans</i>
Woodland	40	1,223	26°19'19"N, 106°29'6"E	<i>CatalpabungeiC.A.Mey, Celtis sinensis Pers</i>

Afterward, a series of carefully chosen sample plots were identified, ensuring minimal variation in crucial factors like the type of restored vegetation, the duration of restoration, the topography, and the soil type. The selected restored vegetation types included grassland, shrub, shrub grassland, and woodland, corresponding to restoration periods of 5, 15, 20, and 40a, respectively. Conversely, adjacent cultivated land was used as a control (CK). The dominant vegetation type in grassland was Leucaena [*Imperata cylindrical* (L.) Beauv]. In shrub areas, key species included pyracantha (*Pyracantha fortuneana*), artemisia (*Artemisia annua*), wild berry (*Rubus idaeus L.*), and wild peppercorn (*Zanthoxylum simulans*). The woodland primarily featured Park and Rowan (*CatalpabungeiC.A.Mey, Celtis sinensis Pers*). While the cultivated land was predominantly planted with maize (*Zea mays*). Further details on the sample plots can be found in [Table 1](#).

Soil sampling

In July 2022, soil samples were collected from the study area following a precise protocol. The surface was first cleared of any debris and humus to maintain sample integrity. Using the "S" sampling method, five different soil horizons (0–5, 5–10, 10–20, 20–30, and 30–40 cm) were obtained from three selected soil profiles. To maintain soil structural integrity during transportation, samples were carefully sealed and laid flat. A total of 75 soil samples were collected and analyzed for their physicochemical properties through detailed laboratory assessments.

Sample analysis and methods

Soil pH was determined using the potentiometric method with a water-to-soil ratio of 2.5:1. Total phosphorus (TP) and total potassium (TK) were analyzed through NaOH dissolution while AN was determined using the alkali diffusion method. Available phosphorus (AP) was determined by the 0. 5 mol·L⁻¹NaHCO₃ method and available potassium (AK) was assessed by ammonium acetate leaching flame photometry. Soil moisture content (SMC) was quantified through dehydration, soil bulk density (BD), and total portfolio porosity (STP) was determined by the ring knife method. Soil texture was

analyzed using the hydrometer method. The soil particles were classified according to the international system (Ge *et al.*, 2019) (sand (Sa) 2–0.02 mm, silt (Si) 0.02–0.002 mm, and clay (Cl) < 0.002 mm). The methodology for specific references to the above indicators was based on guidelines from (Sparks *et al.*, 1996).

The soil's NH_4^+ -N was obtained using a 2 mol·L⁻¹ KCl solution and the indophenol blue colorimetric technique (Lu, 1999). On the other hand, the NO_3^- -N levels were determined through the dual-wavelength ultraviolet spectrophotometric approach along with a correction factor (Norman, Edberg & Stucki, 1985). NH_4^+ -N and NO_3^- -N in soil samples were conducted utilizing the METASH UV-5500 UV-Vis spectrophotometer, a precision instrument sourced from METASH Instruments in Shanghai, China.

Determination of mineralizable nitrogen

Soil organic nitrogen mineralization was assessed through aerobic incubation (Stanford & Smith, 1972; Chenxiao *et al.*, 2024). Initially, 60 g of soil, sieved through a 2 mm mesh, were placed in 250 mL of PE clinker bottle for the incubation process. The soil's moisture content was then adjusted to 30% of its field water-holding capacity was set at 25 °C before being placed in a temperature-controlled incubator (ROX-250B). A 7-day pre-incubation period was carried out to restore soil microbial activity. After the pre-incubation stage, the samples were sealed with black cling film, which was punctured to allow for aeration, and then stored in darkness at 25 °C for 35 days. Aeration was performed every 3 days for 30 min, while moisture levels were carefully monitored by regularly weighing the sample. Destructive sampling was conducted on days 7, 14, 21, 28, and 35 following incubation. On each occasion, 10 g of soil were combined with 35 mL of 2 mol·L⁻¹ KCl solution (in a 5:1 ratio), shaken for 1 h and filtered into plastic containers for subsequent analysis. Ammonium nitrogen content was measured using KCl leaching and colorimetric analysis with indophenol blue. Nitrate nitrogen levels were determined using a dual-wavelength UV spectrophotometric method with a correction factor.

Statistical methods

Experimental data were averaged across three replicates, and statistical analysis was performed using ANOVA with SPSS 27.0. The significance of differences between treatments was evaluated by using the least significant difference (LSD) method. Graphs depicting mean values with standard errors were generated using Origin 2024. Furthermore, the Mantel test was conducted in the R v 4.2.2 (R Core Team, 2022) environment using the dplyr, ggcov, and ggplot2 packages. This test determined the significance of various influencing factors on nitrogen mineralization, offering a detailed analysis of their relative importance.

Calculation of indicators

The formula for calculating the indicator of soil N mineralization characteristics can be written as follows:

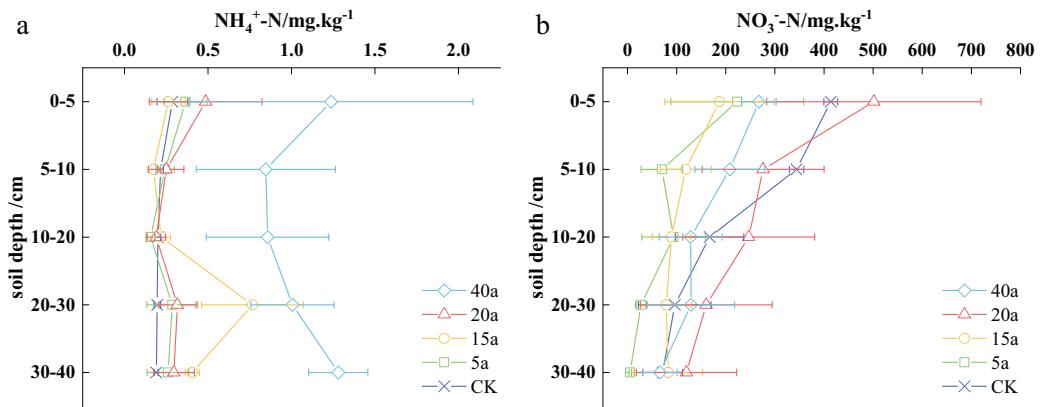


Figure 2 Effects of vegetation restoration on ammonium nitrogen and nitrate nitrogen.

[Full-size](#) DOI: 10.7717/peerj.18582/fig-2

$$\text{Net ammonification amount (mg} \cdot \text{kg}^{-1}) = \text{NH}_4^+ - \text{N content after culture} \\ - \text{NH}_4^+ - \text{N content before culture}$$

$$\text{Net nitrification (mg} \cdot \text{kg}^{-1}) = \text{NO}_3^- - \text{N content after culture} \\ - \text{NO}_3^- - \text{N content before culture}$$

$$\text{Soil mineral nitrogen content (mg} \cdot \text{kg}^{-1}) = \text{NH}_4^+ - \text{N} + \text{NO}_3^- - \text{N}$$

$$\text{Net mineralization (mg} \cdot \text{kg}^{-1}) = \text{soil mineral N content after incubation} \\ - \text{soil mineral N content before incubation}$$

$$\text{Net nitrogen mineralization rate (mg/kg} \cdot \text{d}) = \frac{\text{net mineralisation (mg} \cdot \text{kg}^{-1})}{\text{culture days}}$$

$$\text{Net ammonification rate (mg/kg} \cdot \text{d}) = \frac{\text{net ammonification amount (mg} \cdot \text{kg}^{-1})}{\text{culture days}}$$

$$\text{Net nitrification rate (mg/kg} \cdot \text{d}) = \frac{\text{net nitrification amount (mg} \cdot \text{kg}^{-1})}{\text{culture days}}$$

RESULTS AND ANALYSIS

Effects of vegetation restoration on inorganic nitrogen

The soil NH_4^+ -N content varied from 0.19 to 1.28 $\text{mg} \cdot \text{kg}^{-1}$ across different vegetation restoration sites, with the highest concentration observed in the 40-year-old woodland. In particular, the soil's ammonium nitrogen values were determined as 0.84 to 1.28 $\text{mg} \cdot \text{kg}^{-1}$ for 40-year-old woodlands, 0.19 to 0.48 $\text{mg} \cdot \text{kg}^{-1}$ for 20-year-old shrubs, 0.17 to 0.76 $\text{mg} \cdot \text{kg}^{-1}$ for 15-year-old shrub grasslands, 0.15 to 0.36 $\text{mg} \cdot \text{kg}^{-1}$ for 5-year-old grasslands, and 0.19 to 0.28 $\text{mg} \cdot \text{kg}^{-1}$ for cultivated areas (Fig. 2A).

In the top 5 cm of soil, the ammonium nitrogen content ranged from 0.26 to 1.23 mg·kg⁻¹. Over 40 years, the woodland area demonstrated a notable increase in soil ammonium nitrogen, reaching 1.23 mg·kg⁻¹, which was 3.31 times higher than that found in the cultivated land. The sequence of soil ammonium nitrogen levels can be written as follows: 40-year-old woodland > 20-year-old shrub > 5-year-old grassland > cultivated land > 15-year-old shrub grassland. The described pattern remained consistent in the 5–10 cm soil depth. In the 10–20 cm stratum, the order shifted to the following: 40-year-old woodland > 15-year-old shrubland > cultivated land > 20-year-old shrub > 5-year-old grassland. At greater depths, in the 20–30 and 30–40 cm strata, the sequence changed to the following: 40-year-old woodland > 15-year-old shrubland > 20-year-old shrub > 5-year-old grassland > cultivated land, with increases compared to cultivated land of 4.89, 2.03, 0.58, and 0.41 times, respectively.

The nitrate nitrogen content in the soil ranged from 5.58 to 501.56 mg·kg⁻¹ across various vegetation restoration scenarios. In particular, the highest soil nitrate nitrogen content was observed in the 20-year-old shrubland. The levels of soil nitrate nitrogen in a woodland of 40a, shrub of 20a, shrub grassland of 15a, grassland of 5a, and cultivated land varied from 65.9–267.54, 120.02–501.56, 82.88–187.32, 5.58–223.3, and 71.56–413.96 mg·kg⁻¹, respectively (Fig. 2B).

In the 0–5 cm soil stratum, the soil nitrate-nitrogen content ranged from 187.32 to 501.56 mg·kg⁻¹. The nitrate nitrogen content in the shrub soil after 20 years was significantly higher than that in cultivated land, reaching 501.56 mg·kg⁻¹. This value represented a 21.16% increase compared to the nitrate nitrogen content present in the cultivated land. The following is the observed ranking of nitrate nitrogen performance: shrubs after 20 years > cultivated land > woodland after 40 years > grassland after 5 years > shrubland after 15 years. In the 5–10 cm soil stratum, the order of nitrate nitrogen content can be written as cultivated land > shrubs after 20 years > woodland after 40 years > shrubland after 15 years > grassland after 5 years. In the 10–20 cm soil stratum, the nitrate nitrogen performance is similar to that of the 0–5 cm stratum. In the 20–30 cm soil stratum, the following is the nitrate nitrogen performance: shrubs after 20 years > cultivated land > woodland after 40 years > shrub grassland after 15 years > grassland after 5 years. Finally, in the 30–40 cm soil stratum, the ranking of nitrate nitrogen performance was observed as shrubs after 20 years > shrub grassland after 15 years > cultivated land > woodland after 40 years > grassland after 5 years. Overall, shrub growth in the 0–40 cm soil depth demonstrated a 19.38% increase over 20 years compared to cultivated land.

Effects of vegetation restoration on nitrogen mineralization

Variation characteristics of soil ammonium nitrogen

The nitrogen content of NH₄⁺-N in the soil varied from 0.09 to 4.19 mg·kg⁻¹ depending on the stage of vegetation restoration. Specifically, the concentrations varied as follows: 0.25 to 4.19 mg·kg⁻¹ in a 40-year-old forest, 0.19 to 2.54 mg·kg⁻¹ in a 20-year-old shrub area, 0.15 to 2.18 mg·kg⁻¹ in a 15-year-old grassland, 0.10 to 1.13 mg·kg⁻¹ in a 5-year-old field, and 0.09 to 1.17 mg·kg⁻¹ in farmland. The NH₄⁺-N levels in the soil showed a cyclical pattern, characterized by alternating phases of increase, decrease, increase, decrease, and eventual

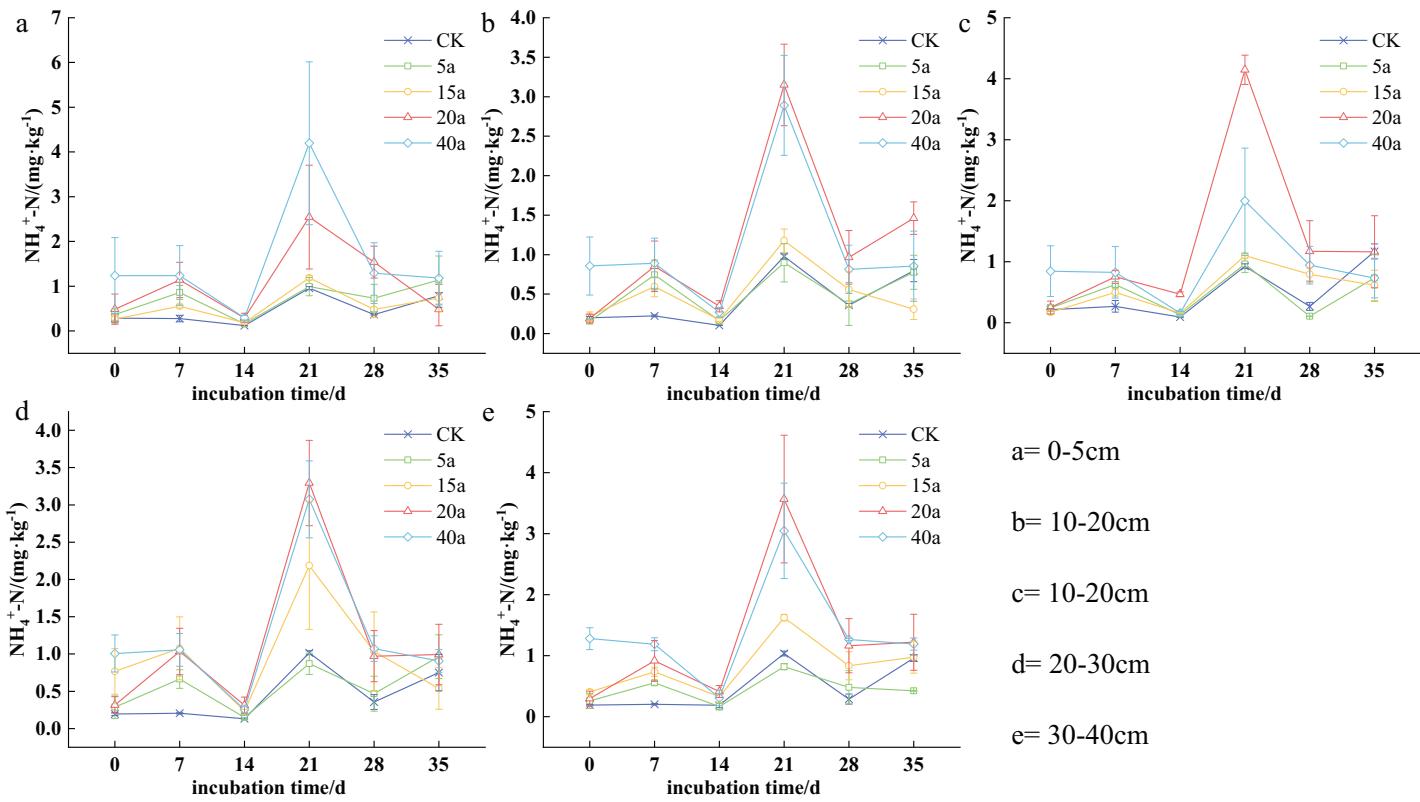


Figure 3 (A-E) Characteristics of soil ammonium nitrogen changes under vegetation restoration.

[Full-size](#) DOI: 10.7717/peerj.18582/fig-3

stabilization over time. After 7 days of cultivation, significant differences were observed between various vegetation types and cultivated land. By the 14th day, the overall content decreased but increased again by the 21st day. Furthermore, $\text{NH}_4^+ \text{-N}$ concentrations were higher in the 0–10 cm topsoil stratum compared to the deeper stratum (10–20, 20–30, 30–40 cm).

In the 0–5 cm soil layer, $\text{NH}_4^+ \text{-N}$ levels reached their lowest point on the 14th day, with no significant statistical differences observed compared to other sampling days. The concentration was found to be highest on the 21st day. The ranking of soil $\text{NH}_4^+ \text{-N}$ was as follows: woodland (40a) > shrub (20a) > shrub grassland (15a) > grassland (5a) > cultivated land. Specifically, woodland (40a) and shrub (20a) increased by 3.39 times and 1.66 times, respectively, compared to cultivated land. In the 5–10 cm soil layer, after the 21st day, the order of $\text{NH}_4^+ \text{-N}$ concentrations was as follows: shrub (20a) > woodland (40a) > shrub grassland (15a) > cultivated land > grassland (5a). In particular, shrub (20a) and woodland (40a) increased by 3.47 times and 1.15 times compared to cultivated land. After 21 days in the 10–20 cm soil stratum, the order of soil $\text{NH}_4^+ \text{-N}$ was determined as shrub (20a) > woodland (40a) > shrub grassland (15a) > grassland (5a) > cultivated land. In this case, shrub (20a) and woodland (40a) demonstrated 2.22 times and 1.95 times increase compared to the cultivated land. This trend continued in the 20–30 cm soil layer, where $\text{NH}_4^+ \text{-N}$ levels in the 20-year-old shrub and 40-year-old woodland were 2.23 times and 2.02 times higher, respectively, compared to the cultivated land. Finally, in the 30–40 cm

soil stratum, the trend remained consistent with previous strata, where shrub (20a) and woodland (40a) increased by 2.44 and 1.94 times upon comparison with cultivated land (Fig. 3).

Variation characteristics of soil nitrate nitrogen

Soil nitrogen content varied significantly among different vegetation restoration types, ranging from 14.20 to 868.06 mg·kg⁻¹. Specifically, the levels ranged from 53.84 to 868.06 mg·kg⁻¹ in 40a woodland, 120.02 to 680.38 mg·kg⁻¹ in 20a shrubs, 72.94 to 454.58 mg·kg⁻¹ in 15a shrub grassland, 14.08 to 676.29 mg·kg⁻¹ in 5a grassland, and 34.26 to 560.42 mg·kg⁻¹ in cultivated land. As time progressed, soil nitrogen content generally increased with the duration of cultivation, peaking on the 14th day. Furthermore, nitrogen levels were consistently higher in the top 0–10 cm soil stratum compared to the deeper strata (10–20, 20–30, and 30–40 cm).

The highest concentration of soil NO₃⁻-N was observed on the 14th day of cultivation. In the top 0–5 cm soil stratum, soil NO₃⁻-N levels were observed as follows: 40a woodland > 20a shrubs > cultivated land > 15a shrub grassland > 5a grassland, with 40a woodland and 20a shrubs demonstrating a respective increase of 0.44 and 0.39 times compared to cultivated land. In the case of the 5–10 cm soil stratum, the order shifted to the following: 20a shrubs > cultivated land > 40a woodland > 15a shrub grassland > 5a grassland, with shrubs showing a 0.13 times increase compared to cultivated land in 20a. The described trend persisted in the 10–20 cm soil stratum, with shrubs showing a 0.46 times increase compared to cultivated land in 20 years. In the 20–30 cm soil stratum, soil NO₃⁻-N levels ranked as follows: 20a shrubs > 40a woodland > 15a shrubland > cultivated land > 5a grassland, where 40a woodland and 20a shrubs demonstrated a respective increase of 0.71 and 0.92 fold compared to cultivated land. The pattern remained consistent in the 30–40 cm soil stratum, with 40a woodland and 20a shrubs showing a 0.17 and 1.36 times increase, respectively, compared to the cultivated land (Fig. 4).

Vegetation restoration on net ammonification rate

The results depicted in Fig. 5 revealed that the soil's net ammonification rate followed a fluctuating pattern over time: it initially decreased, then increased, subsequently declined, and finally stabilized. On the 14th day, the soil's net ammonification rate reached its lowest level during cultivation, while the highest concentration was observed on the 21st day. Notably, the ammonification levels on the 35th day were found to be lower than those observed on the 7th day. With the increase in the cultivation period, the soil's ammonification impact was reduced, resulting in a decrease in the net ammonification rate. Throughout cultivation, the net soil mineralization rate increased in the following order: 40a woodland, cultivated land, 5a grassland, 15a shrub grassland, and 20a shrub grassland, with an average value of 7.36, 11.18, 21.11, 21.71, and 58.26 mg/(kg·d), respectively. Compared to cultivated land, the net mineralization rate increased by 0.94 times for 15-year-old shrub grassland and 4.21 times for 20-year-old shrub grassland.

During the first 7 days of planting, the soil net nitrification rate (AR) size at different depths followed a consistent order: 20a shrubs > 5a grassland > 15 shrubland > cultivated

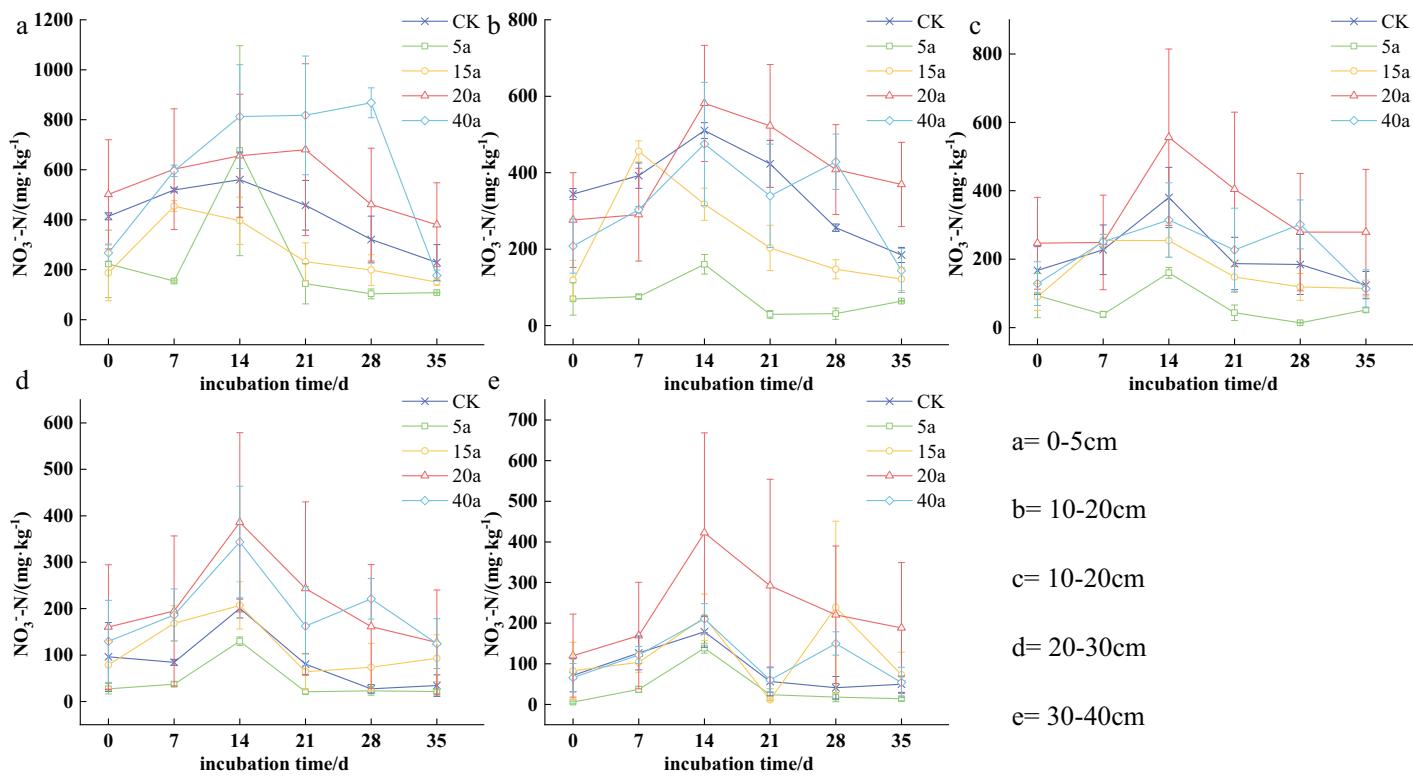


Figure 4 (A-E) Characteristics of soil nitrate-nitrogen changes under vegetation restoration.

Full-size DOI: 10.7717/peerj.18582/fig-4

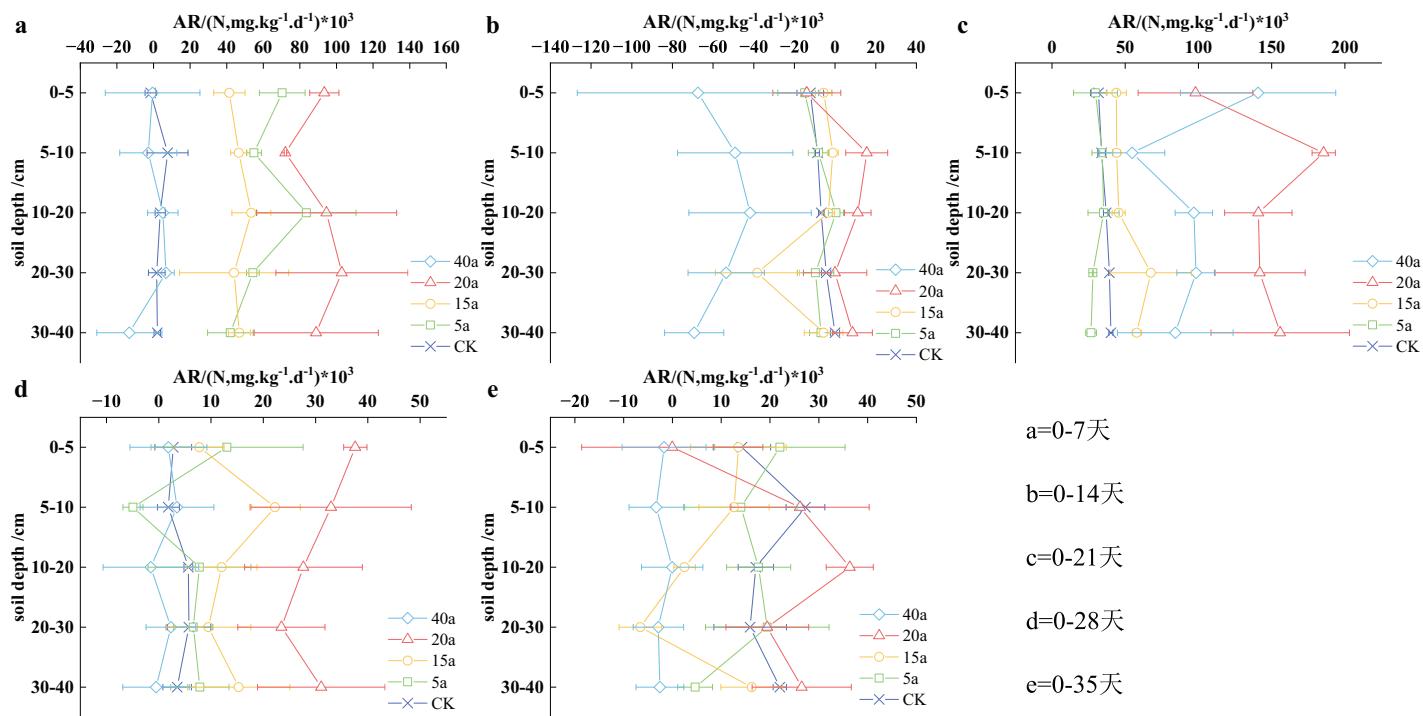


Figure 5 (A-E) Characteristics of net soil ammonification rate under vegetation restoration.

Full-size DOI: 10.7717/peerj.18582/fig-5

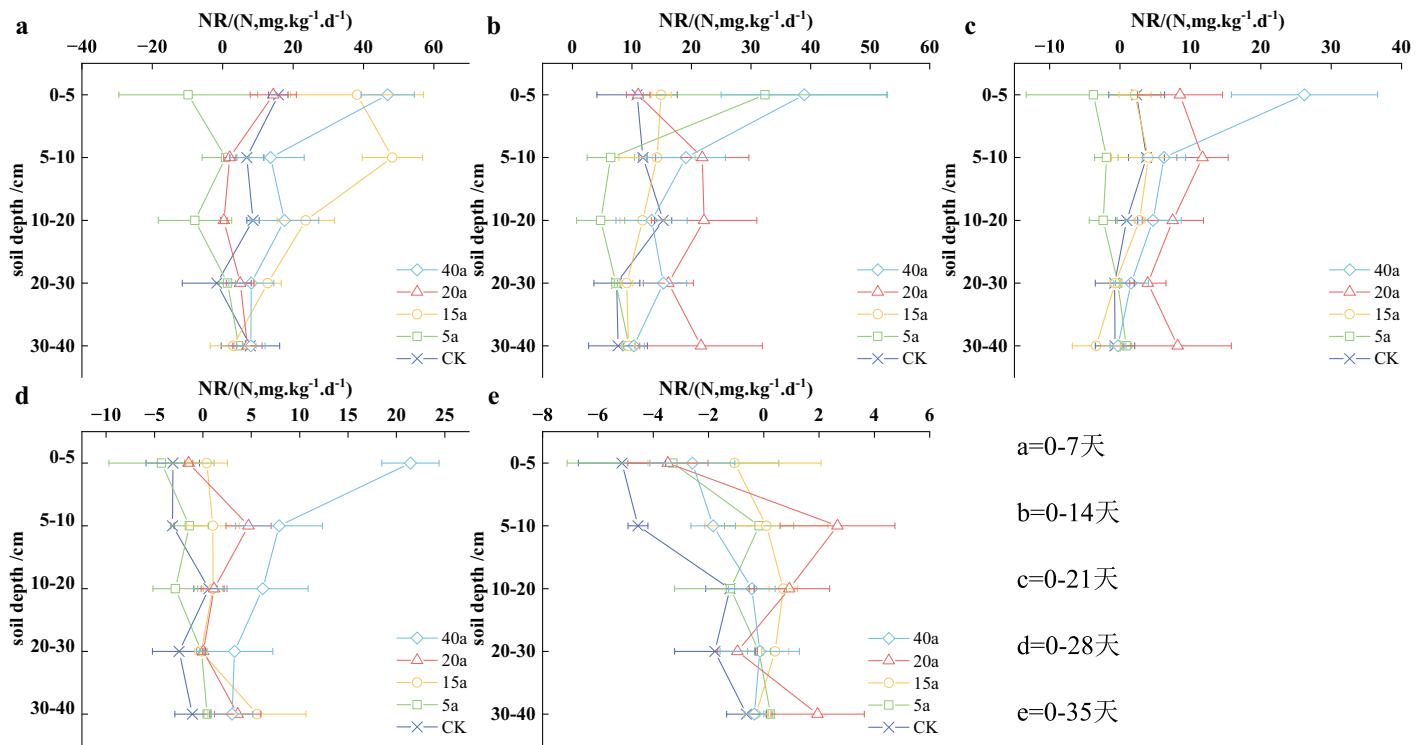


Figure 6 (A-E) Characteristics of net soil nitrification rate under vegetation restoration.

Full-size DOI: 10.7717/peerj.18582/fig-6

land > 40a woodland. Specifically, 20a shrubs, 5a grassland, and 15a shrub vegetation demonstrated significantly higher measurements than cultivated land. With the increase in cultivation to 14 days, woodland in 40a showed the lowest measurement, compared to other vegetation types. On the other hand, 20a shrubs displayed the highest measurement, with no significant differences observed among the other vegetation types. After 21 days of cultivation, the soil AR size ranked as follows: 20a shrub > 40a woodland > 15a shrubland > cultivated land > 5a grassland, with a notable difference between shrubs and cultivated land in 20a. By the 28th day, the sequence of soil AR size remained consistent across the strata: 20a shrubs > 15a shrubland > 5a grassland > cultivated land > 40a woodland, with considerable differences observed between shrubs and cultivated land in 20a. With increase in planting till day 35, the soil AR size in the 0–5 cm stratum was determined as follows: 5a grassland > 15a shrub vegetation > cultivated land > 20a shrubs > 40a woodland, whereas in the 5–10, 10–20, 20–30, and 30–40 cm strata, the arrangement was observed as follows: 20a shrubs > cultivated land > 5a grassland > 15 shrub vegetation > 40a woodland.

Vegetation restoration on net nitrification rate

Figure 6 illustrates a progressive decrease in the soil net nitrification rate over time. The peak rate was observed at 7 days of cultivation, with the lowest rate recorded at 35 days. Furthermore, the soil net nitrification rate consistently decreased over the culture period, indicating a reduction in soil nitrification with prolonged cultivation time. Throughout the cultivation process, the net soil mineralization rate decreased sequentially in a 40-year-old

woodland, 15-year-old shrubland, a 20-year-old shrub, cultivated land, and a 5-year-old grassland, with an average value of 10.63, 7.91, 6.81, 2.94, and 1.16 mg/(kg·d) respectively. Woodland aged 40 years, shrubland aged 15 years, and shrubs aged 20 years demonstrated respective increases of 2.62 times, 1.69 times, and 1.32 times, compared to cultivated land.

During the initial 0–7 days of soil incubation, the size of soil NR in the 0–5 cm stratum followed the order of 40a woodland > 15a scrub grassland > cropland > 20a shrub > 5a grassland, with 40a woodland showing significantly higher N nitrification rate (NR) than cropland. In the subsequent 5–10, 10–20, and 20–30 cm stratum, the soil NR size was ranked as follows: 15a scrub grassland > 40a woodland > cropland > 20a shrub > 5a grassland, with 15a scrub grassland, demonstrated remarkably higher NR than cropland. However, in the 30–40 cm stratum, no significant differences were observed in vegetation recovery. For the case of 0–14 days of incubation, in the 0–5 cm stratum, the soil NR size was determined as follows: 40a woodland > 5a grassland > 15a shrub meadow > 20a shrub > cropland, with 40a woodland showing significantly higher NR than cropland. In the subsequent stratum (5–10, 10–20, and 20–30 cm), the soil NR size showed the following sequence: 20a shrub > 40a woodland > cropland > 15a shrub meadow > 5a grassland, with 20a shrub showing significant superiority over cropland. In the 30–40 cm stratum, no significant differences were observed among the various types of vegetation restoration.

During the initial 0–21 days of incubation, the soil NR size in the 0–5 cm stratum was ranked as follows: 40a woodland > 20a shrub > 15a shrub meadow > cropland > 5a grassland, with 40a woodland demonstrating significant superiority over cropland. In the subsequent stratum (5–10, 10–20, 20–30, and 30–40 cm), the overall trend for soil NR size can be written as 20a shrub > 40a woodland > 15a shrub meadow > cropland > 5a grassland. Lastly, at 0–28 days of incubation, the 0–5 cm stratum showed a soil NR size sequence of 40a woodland > 15a shrub meadow > 20a shrub > cropland > 5a grassland, with 40a woodland showing significantly higher NR than cropland. In the subsequent stratum (5–10, 10–20, and 20–30 cm), the overall soil NR size was ranked as follows: 40a woodland > 20a shrub > 15a shrub meadow > cropland > 5a grassland. In the stratum of soil measuring 30–40 cm, there were no significant differences observed in plant life. Following an incubation period of 0–35 days, the ranking of NR size in the soil stratum of 0–5 cm was observed in the following order: 15a meadow of shrubs > 40a forested area > 20a shrubbery > 5a grassy meadow > cultivated land. For the stratum of soil measuring 5–10 and 10–20 cm, the NR size ranking can be written as follows: 20a shrubbery > 15a meadow of shrubs > 5a grassy meadow > 40a forested area > cultivated land. However, in the stratum of soil measuring 20–30 and 30–40 cm, no significant disparities were observed in vegetation regeneration.

Vegetation restoration on net nitrogen mineralization rate

The nitrogen mineralization rate in the soil reflects the changes in inorganic nitrogen over time. This research evaluated the nitrogen mineralization rate at varying time intervals, ranging from 0–7 to 0–35 days. [Figure 7](#) illustrates a distinct decrease in nitrogen mineralization throughout vegetation restoration, with a peak value of 46.86 ± 7.55 mg/(kg·d) observed on the 7th day in a 40-year-old forest area. The ranking of nitrogen

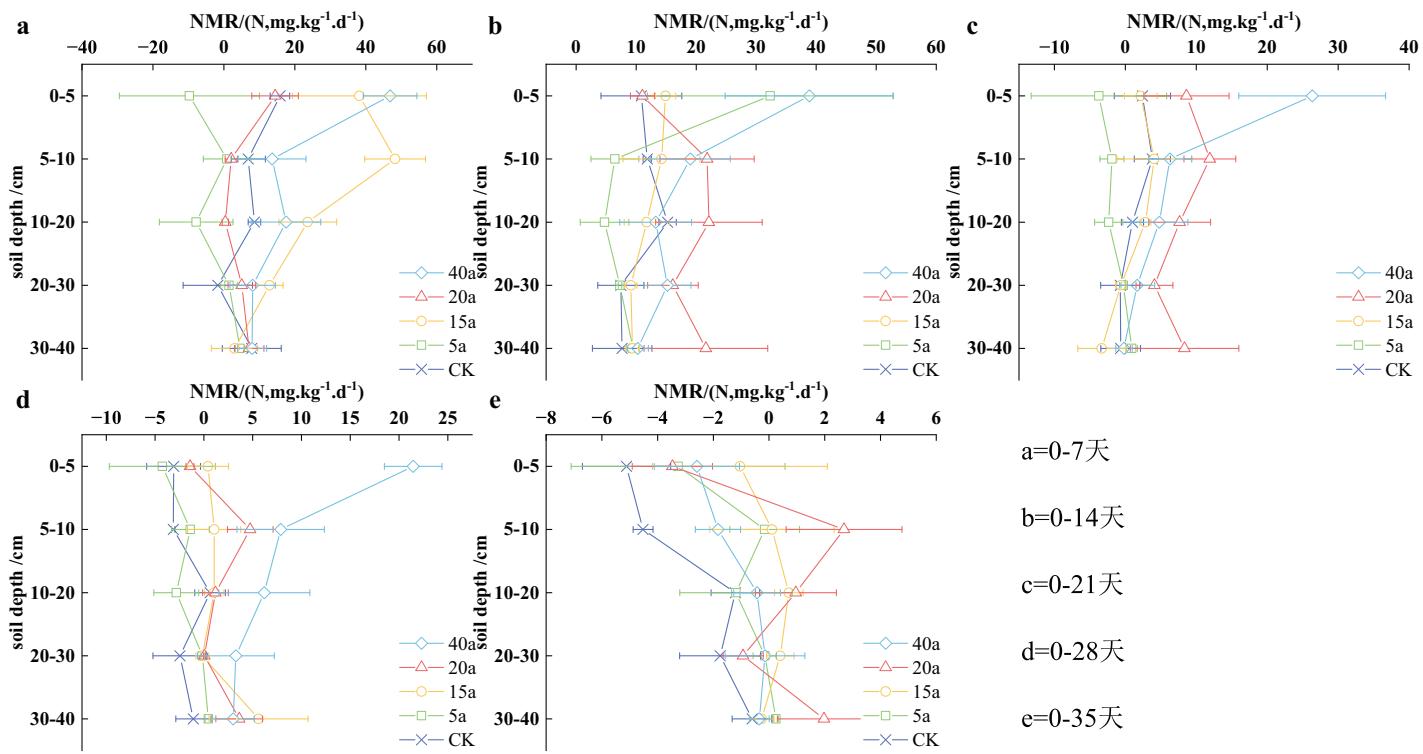


Figure 7 (A-E) Characteristics of net soil nitrogen mineralisation rate under vegetation restoration.

Full-size DOI: 10.7717/peerj.18582/fig-7

mineralization rates in the 0–40 cm soil stratum can be written as follows: shrub grassland aged 15 years > woodland aged 40 years > cultivated land > shrubland aged 20 years > grassland aged 5 years. The reduction in nitrogen mineralization was associated with longer cultivation periods, resulting in a slower nitrogen mineralization process in the soil.

Throughout the cultivation period, the nitrogen mineralization rates in woodland aged 40 years, shrubland aged 15 years, shrubland aged 20 years, grassland aged 5 years, and cultivated land decreased progressively, with average values of 10.64, 7.93, 6.87, 2.95, and 1.18 mg/(kg·d) respectively. In comparison, nitrogen mineralization rates in 40-year-old woodland, 15-year-old shrubland, and 20-year-old shrubland were determined to be 8.01, 5.72, and 4.82 times higher, respectively than those observed in cultivated land. Overall, vegetation restoration has the potential to significantly enhance soil nitrogen mineralization rates.

During the initial 7 days of cultivation, the highest soil nitrogen mineralization rate was recorded at 46.86 ± 7.55 mg/(kg·d) in a 40-year-old woodland area, while the lowest value was found to be negative in a 5-year-old grassland region. In the 0–40 cm soil stratum, the NMR values showed the following order: 15a shrub grassland > 40a woodland > cultivated land > 20a shrub > 5a grassland. Specifically, in the 0–5 cm soil stratum, the sequence of soil NMR values can be written as 40a woodland > 15a shrubland > cultivated land > 20a shrub > 5a grassland, with 40a woodland showing significantly higher values compared to cultivated land and 5a grassland demonstrating negative values. In the 5–10

and 10–20 cm soil stratum, the soil NMR trends were determined to be consistent with those observed in the 0–40 cm soil stratum. However, no significant difference was observed between the 20–30 and 30–40 cm soil stratum.

During the initial 2 weeks of planting, the soil NMR levels varied from $38.85 \pm 14.00 \text{ mg/(kg-d)}$ in the 40a forest area to $4.74 \pm 4.04 \text{ mg/(kg-d)}$ in 5a grassy terrain. The sequence of nitrogen mineral rates in the 0–40 cm soil stratum was determined as follows: 40a woodland > 20a shrub > 5a grassland > 15a shrubland > farmland. In the top 5 cm soil stratum, the soil NMR hierarchy was determined as follows: 40a woodland > 5a grassland > 15a shrubland > 20a shrubs > farmland. For the case of 5–10 cm soil stratum, the soil NMR performance showed the following ranking: 20a shrubs > 40a woodland > 15a shrubland > farmland > 5a grassland. In the 10–20 cm soil stratum, the soil NMR pattern demonstrated the following order: 20a shrubs > farmland > 40a woodland > 15a shrubland > 5a grassland.

Significant differences were observed between 20a shrubland, 40a woodland, and farmland in the 20–30 and 30–40 cm soil segments.

Within the first 21 days of planting, the highest soil NMR value was recorded as $26.33 \pm 10.34 \text{ mg/(kg-d)}$ in the 40a woodland. In the 0–40 cm soil stratum, the following sequence of soil NMR values was observed: 40a woodland > 20a shrubs > land under cultivation > 15a shrub grassland > 5a grassland. For the soil stratum of 0–5 cm, the soil NMR values were found to be similar to those observed in the 0–40 cm stratum, with 40a woodland demonstrating significantly higher values compared to cultivated land. In the soil stratum of 5–10, 10–20, 20–30, and 30–40 cm, the following sequence of soil NMR values was observed: 20a shrub > 40a woodland > 15a shrub grassland > land under cultivation > 5a grassland.

Throughout the first 28 days of plant growth, the 40-acre woodland area demonstrated significantly larger soil NMR values in the top 5 cm stratum compared to other vegetation types. As the cultivation increased till day 35, the soil NMR dimensions in the top 5 cm stratum were ranked in the following order: shrub grassland spanning 15 acres > woodland area of 40 acres > shrub area of 20 acres > grassland area of 5 acres > cultivated land. In the 5–10, 10–20, 20–30, and 30–40 cm soil stratum, the overall soil NMR dimensions were observed in the following order: shrub area of 20 acres > shrub grassland spanning 15 acres > woodland area of 40 acres > grassland area of 5 acres > cultivated land.

During the incubation period across different plant regenerations, soil ammonification rates were significantly lower than nitrification rates, demonstrating an increasing trend that contrasted with the declining pattern of soil nitrification. The predominant net mineralization form in the soil was nitrification, consistent with established findings on soil nitrification processes.

Effects of environmental factors on vegetation restoration

Analysis of the Mantel test revealed the positive correlation between AR and total nitrogen (TN), total phosphorous (TP), total potassium (TK), ammonium nitrogen (AN), AK, soil organic carbon (SOC), silicon (Si), NH_4^+ -N; NR and TN, TP, TK, Si, BD, STP, SMC; NMR and TN, TP, TK, AN, AK, SOC, Si, Sa, pH. In contrast, AR, NR, and NMR showed negative

correlations with NO_3^- -N and Ap. The findings suggest that soil mineralization processes in the study area were primarily influenced by TN, TP, TK, and Si, with ammonium (NH_4^+ -N) having the most significant effect on AR, BD affected the NR, and ammonium nitrogen (AN) and SOC influenced the NMR. Moreover, NH_4^+ -N showed a positive correlation with TK, AK, and C, while NO_3^- -N was positively associated with TN, AP, and SOC.

DISCUSSION

Effects of vegetation restoration on inorganic nitrogen

Subtropical and tropical forests are generally considered phosphorus-limited, while temperate and boreal forests are often nitrogen-limited (Elser *et al.*, 2007). Recent research by Zhang *et al.* (2015) and Lan, Hu & Fu (2020) has shown that karst landscapes in subtropical regions can exhibit nitrogen-limited conditions as vegetation begins to regenerate. The detection of NO_3^- -N as the primary form of inorganic nitrogen in this study was consistent with the results of Hu *et al.* (2021), showing a 19.38% increase in shrub areas compared to cultivated areas. The observed increase in NO_3^- -N was associated with vegetation recovery, which enhanced the accumulation of plant debris and roots in the soil. This process improves soil permeability and stimulates bacterial and microbial activities, ultimately leading to higher nitrogen concentrations. The higher levels of NO_3^- -N in woodlands compared to grassland samples observed in this study supported the findings reported by Xing *et al.* (2013), contrasting grassland ecosystems with a wide variety of trees, shrubs, and grasses (Li *et al.*, 2019; Dong *et al.*, 2022a). Woodlands often contain more apoplastic substances with lesser C/N ratios, leading to the presence of greater mineral N in the surface soil (Pang *et al.*, 2020; Babur *et al.*, 2022). The research findings revealed a significant variation in nitrate N levels between the upper and lower soil strata. (Karki, Bargali & Bargali, 2021; Dong *et al.*, 2022b; Siwach *et al.*, 2023). This variation was attributed to the rich oxygen environment, abundant organic matter, and diverse array of microorganisms in the topsoil, which facilitated the nitrification process. In the soil stratum ranging from 0–40 cm, the ranking of soil ammonium nitrogen levels was as determined as follows: woodland > shrub-grassland > shrub > grassland > arable land, with increases of 4.89, 2.03, 0.58, and 0.41 times respectively compared to arable land. These variations were linked to the continuous decomposition of plant matter during the process of vegetation restoration, ongoing mineralization of organic nitrogen in the soil, accumulation of inorganic nitrogen, and the increase in NH_4^+ -N content.

Effects of vegetation restoration on nitrogen mineralization

Restoring vegetation significantly enhances the uptake and consumption of ammonium and nitrate nitrogen in the soil (Maslov & Maslova, 2022; Wang *et al.*, 2023). According to Loeb *et al.* (2009), the rate of nitrogen mineralization is crucial for supplying these essential nutrients. Over time, soil accumulates various nitrogen species, leading to substantial nitrogen reserves. The rate of net mineralization is a key metric for the assessment of soil nitrogen effectiveness (Zhang *et al.*, 2021b). They also revealed that inorganic nitrogen concentrations in the soil varied from 14.50 to 869.36 $\text{mg}\cdot\text{kg}^{-1}$ across different vegetation

restoration conditions. As the incubation period increased, the levels of inorganic nitrogen in the soil generally showed a pattern of increase, followed by a decrease and eventual stabilization, peaking on the 14th day, consistent with the trends observed in nitrate nitrogen. The adsorption and utilization of NO_3^- -N in the soil are restricted by its negatively charged nature, resulting in the majority of NO_3^- -N remaining in the soil solution without being effectively consumed. Soil nitrification processes consume ammonium nitrogen from the soil and external fertilizers, reducing the loss due to ammonia volatilization and leading to NO_3^- -N accumulation in the soil. The study highlighted the presence of higher concentrations of inorganic nitrogen in the upper 0-10 cm soil stratum compared to the deeper stratum. Surface soils have a higher capacity to absorb external organic N, leading to more rapid accumulation. In contrast, with increase in soil depth, permeability generally decreases, which slows down the aging and decomposition processes of soil organic matter (Qiu *et al.*, 2021). This results in decreased organic matter availability for decomposition and plant uptake, causing a reduction in microbial populations and activity, which could potentially lower the rate of N mineralization (He *et al.*, 2021). Soil surface temperature variations significantly affect microbial activity, whereas deeper soil strata are less influenced by these changes (Naylor, McClure & Jansson, 2022). The research demonstrates that NO_3^- -N is the primary form of inorganic nitrogen. Initially, vegetation absorbs NO_3^- -N, resulting in a significantly lower net residual of NO_3^- -N in areas with dense vegetation compared to those with sparse vegetation (Li *et al.*, 2017). The loss rate of NO_3^- -N exceeded that of NH_4^+ -N, while the relatively high levels of NH_4^+ -N in soils across varying locations contributed to the sustained nitrogen content in the soil (Sainju *et al.*, 2006). Soil inorganic N levels increased gradually during vegetation mineralization recovery but decreased with increasing the recovery period. This trend resulted from the gradual stabilization of organic matter and apoplastic material in the soil, coupled with decreased microbial activity during the process of vegetation restoration. Therefore, the mineralization processes slowed down, leading to varying concentrations of inorganic nitrogen over time as the restoration period progressed.

Factors affecting soil nitrogen mineralization

Vegetation plays an essential role in the nitrogen cycle and is vital for soil health (Manral *et al.*, 2020). It enhances water retention, improves soil aeration and infiltration rates, and contributes to better soil texture (Zhang *et al.*, 2021a). These improvements can directly influence the structure and operation of plants (Pandey *et al.*, 2023). Furthermore, the contributions from vegetation debris and decomposition processes play a crucial role in determining soil nutrient levels (Awasthi *et al.*, 2022; Pandey *et al.*, 2024). Land use patterns considerably affect the fertility and stability of an ecosystem, serving as a crucial source of nutrients due to their rapid turnover (Padalia *et al.*, 2018). Moreover, plants, along with cultural practices, can alter the soil environment by influencing the microclimate and generating detritus (Trentini *et al.*, 2018). They contribute to nutrient redistribution (Wu *et al.*, 2021), enhance N₂ fixation (Li *et al.*, 2021), improve soil biota (Cai *et al.*, 2022), and influence soil physicochemical characteristics (Qiu *et al.*, 2022; Lyu

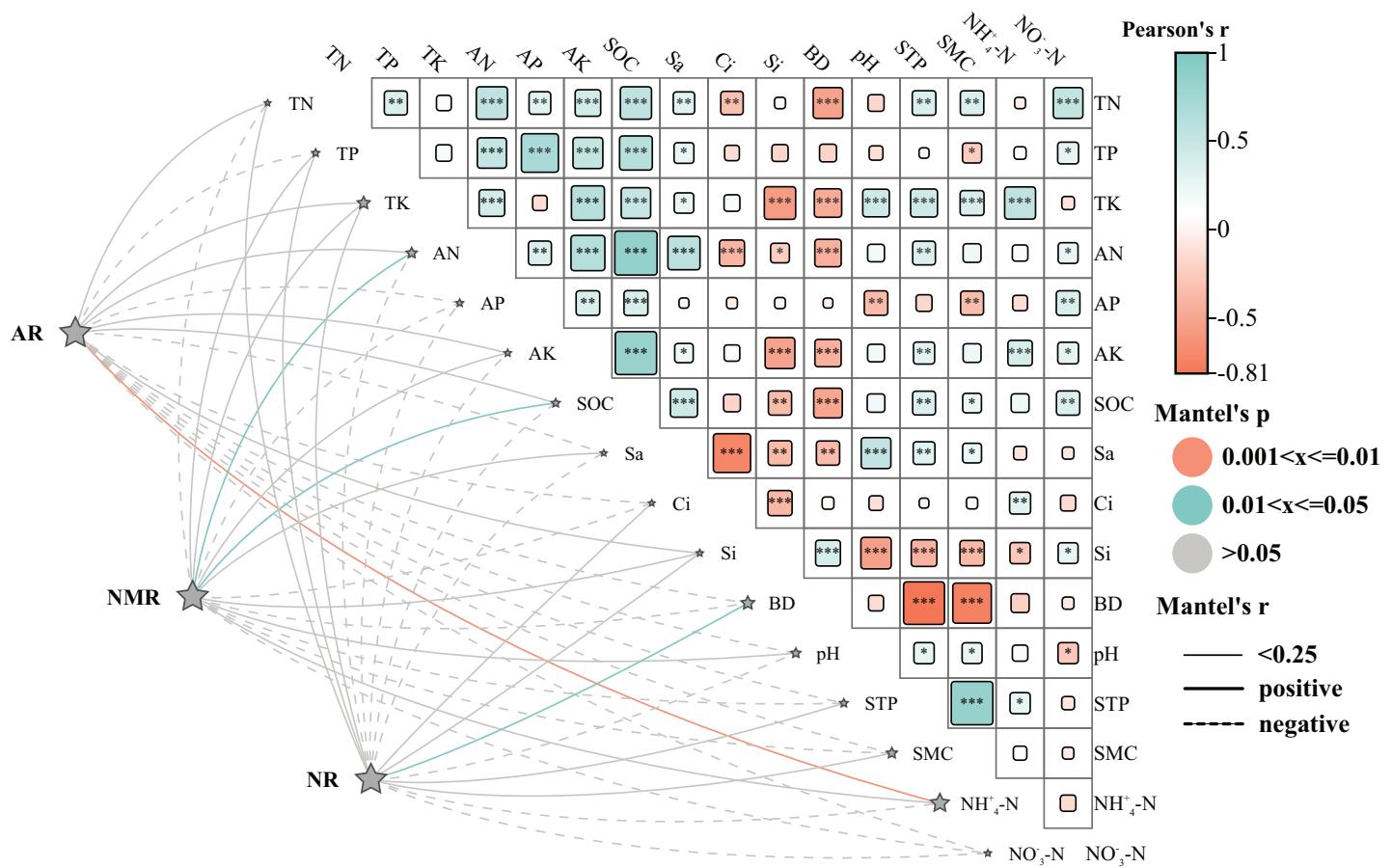


Figure 8 Effects of environmental factors on nitrogen mineralisation. Abbreviations: The heat map's rectangular shapes illustrate the correlations between soil physicochemical factors. The line's thickness represents Mantel's *r*-test correlation coefficient magnitude, with solid lines indicating positive correlations and dashed lines representing negative correlations. The line colors in the heat map represent Mantel's *p*-test value (grey signifies $*P < 0.05$, cyan denotes $**P < 0.01$, orange represents $***P < 0.001$). These correlations examine various organic nitrogen fractions and environmental factors such as AR (net ammonification rate), NR (net nitrification rate), NMR (net nitrogen mineralization rate), SOC (soil organic carbon), pH, BD (looseness), STP (total porosity), Cl (clayey grains), Si (silt grains), Sa (sandy grains), SMC (water content), TN (total nitrogen), AN (alkali dissolved nitrogen), AP (quick phosphorus), AK (quick potassium), NH₄⁺-N (ammoniacal nitrogen), and NO₃⁻-N (nitrate-nitrogen).

Full-size DOI: 10.7717/peerj.18582/fig-8

et al., 2023). The Mantel test analysis revealed positive correlations of TN, TP, TK, and Si with soil AR, NR, and NMR (Fig. 8), consistent with the findings reported by *Li et al.* (2019). However, pH showed a negative correlation with AR and NR, indicating that substrate abundance and favorable conditions can enhance soil N mineralization (*Li et al.*, 2018), a critical factor in regulating soil N availability (*Wei et al.*, 2011). N transformations including mineralization and nitrification greatly influence soil N availability. Sa showed a negative correlation with AR and NR, aligning with studies that suggest clay-rich, fine-textured soils typically contain a higher amount of microbial biomass, organic carbon, and nitrogen compared to coarse-textured soils, thereby enhancing overall N mineralization (*Ding et al.*, 2021). Total N mineralization was significantly higher in soils with elevated levels of fines and clays (*Elrys et al.*, 2023). SMC was negatively correlated with soil NO₃⁻-N, possibly due to increased NO₃⁻-N depletion in soils with higher moisture

contents (*Srivastava et al., 2015*). Furthermore, alkaline soils hinder the decomposition of organic matter, leading to reduced soil N mineralization (*Beltran-Hernandez et al., 1999*). This was consistent with the observed negative relationship between pH and soil AR and NR parameters. Soil inorganic N levels play a crucial role in soil nutrient dynamics, with soil NMR indirectly affecting SOC and serving as an important indicator of soil fertility in revegetated ecosystems (*Wei et al., 2009*). Factors affecting soil N transformations vary across ecosystems, primarily due to variations in climate, vegetation, and land use history (*Burke, 1989; Li et al., 2014; Maithani et al., 1998*).

CONCLUSION

(1) Over 20 years, shrubs demonstrated a 19.38% increase in inorganic nitrogen at the 0–40 cm depth, primarily in the form of nitrate nitrogen, compared to cultivated areas.

(2) As the duration of incubation increased, soil NH_4^+ -N levels showed a distinct pattern: an initial rise, followed by a decrease, a subsequent spike, another decrease, and finally, stabilization. On the 14th day of incubation, the NH_4^+ -N content reached its lowest point, while it peaked on the 21st day. In contrast, the soil NO_3^- -N and total inorganic nitrogen showed a pattern of increase, decrease, and stabilization, with their highest levels observed on 14 days of incubation. Furthermore, the NO_3^- -N, NO_3^- -N, and organic nitrogen levels in the upper 0–10 cm stratum of soil exceeded those in the deeper stratum (10–20, 20–30, and 30–40 cm).

(3) Under vegetation restoration, the soil NR and NMR gradually decrease with incubation time. However, soil NR and NMR increased in 15-year shrub, 20-year shrub, and 40-year woodland areas. Moreover, the 15-year shrub and 20-year shrub conditions led to higher soil AR.

(4) The analysis of the Mantel test showed positive correlations between TN, TP, TK, and Si with soil AR, NR, and NMR. Among these, NH_4^+ -N had the most significant impact on AR, BD had the most pronounced influence on NR, and AN and SOC were identified as the key driving forces of NMR.

ADDITIONAL INFORMATION AND DECLARATIONS

Funding

This work was funded by the Ministry of Agriculture and Rural China (Z2023365) and the National Natural Science Foundation of China (31460133). The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

Grant Disclosures

The following grant information was disclosed by the authors:

Ministry of Agriculture and Rural China: Z2023365.

National Natural Science Foundation of China: 31460133.

Competing Interests

The authors declare that they have no competing interests.

Author Contributions

- Jianghong Wu conceived and designed the experiments, performed the experiments, analyzed the data, prepared figures and/or tables, and approved the final draft.
- Xianghuan Gong conceived and designed the experiments, analyzed the data, authored or reviewed drafts of the article, and approved the final draft.
- Yingge Shu conceived and designed the experiments, authored or reviewed drafts of the article, and approved the final draft.

Data Availability

The following information was supplied regarding data availability:

The raw data is available in the [Supplemental File](#).

Supplemental Information

Supplemental information for this article can be found online at <http://dx.doi.org/10.7717/peerj.18582#supplemental-information>.

REFERENCES

- Awasthi P, Bargali K, Bargali SS, Khatri K.** 2022. Nutrient return through decomposing *Coriaria nepalensis* litter in degraded hills of Kumaun Himalaya, India. *Frontiers in Forests and Global Change* 5:293 DOI [10.3389/ffgc.2022.1008939](https://doi.org/10.3389/ffgc.2022.1008939).
- Babur E, Dindaroğlu T, Riaz M, Uslu OS.** 2022. Seasonal variations in litter layers' characteristics control microbial respiration and microbial carbon utilization under mature pine, cedar, and beech forest stands in the eastern mediterranean karstic ecosystems. *Microbial Ecology* 84(1):153–167 DOI [10.1007/s00248-021-01842-4](https://doi.org/10.1007/s00248-021-01842-4).
- Basile-Doelsch I, Balesdent J, Pellerin S.** 2020. Reviews and syntheses: the mechanisms underlying carbon storage in soil. *Biogeosciences* 17(21):5223–5242 DOI [10.5194/bg-17-5223-2020](https://doi.org/10.5194/bg-17-5223-2020).
- Beltran-Hernandez RI, Coss-Munoz E, Luna-Guido ML, Mercado-Garcia F, Siebe C, Dendooven L.** 1999. Carbon and nitrogen dynamics in alkaline saline soil of the former Lake Texcoco (Mexico) as affected by application of sewage sludge. *European Journal of Soil Science* 50:601–608 DOI [10.1046/j.1365-2389.1999.00270.x](https://doi.org/10.1046/j.1365-2389.1999.00270.x).
- Booth MS, Stark JM, Rastetter E.** 2005. Controls on nitrogen cycling in terrestrial ecosystems: a synthetic analysis of literature data. *Ecological Monographs* 75(2):139–157 DOI [10.1890/04-0988](https://doi.org/10.1890/04-0988).
- Burke IC.** 1989. Control of nitrogen mineralization a sagebrush steppe landscape. *Ecology* 70(4):1115–1126 DOI [10.2307/1941380](https://doi.org/10.2307/1941380).
- Cai X, Zhang D, Wang Y, Diao L, Cheng X, Luo Y, An S, Yang W.** 2022. Shift in soil microbial communities along ~160 years of natural vegetation restoration on the Loess Plateau of China. *Applied Soil Ecology* 173:104394 DOI [10.1016/j.apsoil.2022.104394](https://doi.org/10.1016/j.apsoil.2022.104394).
- Chen S, Wang W, Xu W, Wang Y, Wan H, Chen D, Tang Z, Tang X, Zhou G, Xie Z, Zhou D, Shangguan Z, Huang J, He J-S, Wang Y, Sheng J, Tang L, Li X, Dong M, Wu Y, Wang Q, Wang Z, Wu J, Chapin FS, Bai Y.** 2018. Plant diversity enhances productivity and soil carbon

storage. *Proceedings of the National Academy of Sciences of the United States of America* **115**:4027–4032 DOI [10.1073/pnas.1700298114](https://doi.org/10.1073/pnas.1700298114).

- Chen L, Wen Y, Zeng J, Wang H, Wang J, Dell B, Liu S.** 2019. Differential responses of net N mineralization and nitrification to throughfall reduction in a *Castanopsis hystrix* plantation in southern China. *Forest Ecosystems* **6**:14 DOI [10.1186/s40663-019-0174-2](https://doi.org/10.1186/s40663-019-0174-2).
- Chen FS, Zeng DH, Fahey TJ.** 2009. Changes in soil nitrogen availability due to stand development and management practices on semi-arid sandy lands, in northern China. *Land Degradation & Development* **20**(5):481–491 DOI [10.1002/ldr.924](https://doi.org/10.1002/ldr.924).
- Chenxiao D, Jiabei L, Shufang W, Hao F.** 2024. Effects of combined application of organic and inorganic fertilizers on nitrogen mineralization in different soil types in northwest China. *Transactions of the Chinese Society for Agricultural Machinery* **55**:344–355 DOI [10.6041/j.issn.1000-1298.2024.05.033](https://doi.org/10.6041/j.issn.1000-1298.2024.05.033).
- Contosta AR, Frey SD, Cooper AB.** 2011. Seasonal dynamics of soil respiration and N mineralization in chronically warmed and fertilized soils. *Ecosphere* **2**:art36 DOI [10.1890/ES10-00133.1](https://doi.org/10.1890/ES10-00133.1).
- Deng Q, Cheng X, Yang Y, Zhang Q, Luo Y.** 2014. Carbon-nitrogen interactions during afforestation in central China. *Soil Biology and Biochemistry* **69**:119–122 DOI [10.1016/j.soilbio.2013.10.053](https://doi.org/10.1016/j.soilbio.2013.10.053).
- Ding SJ, Zhang XF, Yang WL, Xin XL, Zhu AN, Huang SM.** 2021. Soil nutrients and aggregate composition of four soils with contrasting textures in a long-term experiment. *Eurasian Soil Science* **54**(11):1746–1755 DOI [10.1134/S1064229321110041](https://doi.org/10.1134/S1064229321110041).
- Dong L, Berg B, Gu W, Wang Z, Sun T.** 2022a. Effects of different forms of nitrogen addition on microbial extracellular enzyme activity in temperate grassland soil. *Ecological Processes* **11**(1):36 DOI [10.1186/s13717-022-00380-2](https://doi.org/10.1186/s13717-022-00380-2).
- Dong Y, Yang JL, Zhao XR, Yang SH, Mulder J, Dörsch P, Zhang GL.** 2022b. Nitrate leaching and N accumulation in a typical subtropical red soil with N fertilization. *Geoderma* **407**(4):115559 DOI [10.1016/j.geoderma.2021.115559](https://doi.org/10.1016/j.geoderma.2021.115559).
- Dujardin G, Bureau F, Vincelas-Akpa M, Decaëns T, Langlois E.** 2012. Soil functioning in a mosaic of herbaceous communities of a chalky environment: temporal variations of water availability and N dynamics. *Plant and Soil* **360**(1–2):197–213 DOI [10.1007/s11104-012-1234-3](https://doi.org/10.1007/s11104-012-1234-3).
- Elrys AS, Zhu Q, Jiang C, Liu J, Sobhy HHH, Shen Q, Uwiragiye Y, Wu Y, El-Tarably KA, Meng L, Müller C, Zhang J.** 2023. Global soil nitrogen cycle pattern and nitrogen enrichment effects: Tropical versus subtropical forests. *Global Change Biology* **29**(7):1905–1921 DOI [10.1111/gcb.16603](https://doi.org/10.1111/gcb.16603).
- Elser JJ, Bracken MES, Cleland EE, Gruner DS, Harpole WS, Hillebrand H, Ngai JT, Seabloom EW, Shurin JB, Smith JE.** 2007. Global analysis of nitrogen and phosphorus limitation of primary producers in freshwater, marine and terrestrial ecosystems. *Ecology Letters* **10**(12):1135–1142 DOI [10.1111/j.1461-0248.2007.01113.x](https://doi.org/10.1111/j.1461-0248.2007.01113.x).
- Ge N, Wei X, Wang X, Liu X, Shao M, Jia X, Li X, Zhang Q.** 2019. Soil texture determines the distribution of aggregate-associated carbon, nitrogen and phosphorous under two contrasting land use types in the Loess Plateau. *CATENA* **172**(1):148–157 DOI [10.1016/j.catena.2018.08.021](https://doi.org/10.1016/j.catena.2018.08.021).
- Gurlevik N, Karatepe Y.** 2016. Long-term effects of afforestation on soil characteristics and net nitrogen mineralization in sandy soils. *Austrian Journal of Forest Science* **133**:187–202.
- He W, Zhang M, Jin G, Sui X, Zhang T, Song F.** 2021. Effects of nitrogen deposition on nitrogen-mineralizing enzyme activity and soil microbial community structure in a Korean pine plantation. *Microbial Ecology* **81**(2):410–424 DOI [10.1007/s00248-020-01595-6](https://doi.org/10.1007/s00248-020-01595-6).

- Heitkamp F, Glatzel S, Michalzik B, Fischer E, Gerold G. 2008.** Soil microbiochemical properties as indicators for success of heathland restoration after military disturbance. *Land Degradation & Development* **19**(4):408–420 DOI [10.1002/ldr.848](https://doi.org/10.1002/ldr.848).
- Hu T, Hu H, Li F, Zhao B, Wu S, Zhu G, Sun L. 2019.** Long-term effects of post-fire restoration types on nitrogen mineralisation in a Dahurian larch (*Larix gmelinii*) forest in boreal China. *Science of the Total Environment* **679**:237–247 DOI [10.1016/j.scitotenv.2019.05.008](https://doi.org/10.1016/j.scitotenv.2019.05.008).
- Hu R, Wang X, Pan Y, Zhang Y, Zhang H, Chen N. 2015.** Seasonal variation of net N mineralization under different biological soil crusts in Tengger Desert, North China. *CATENA* **127**:9–16 DOI [10.1016/j.catena.2014.12.012](https://doi.org/10.1016/j.catena.2014.12.012).
- Hu P, Zhao Y, Xiao D, Xu Z, Zhang W, Xiao J, Wang K. 2021.** Dynamics of soil nitrogen availability following vegetation restoration along a climatic gradient of a subtropical karst region in China. *Journal of Soils and Sediments* **21**(6):2167–2178 DOI [10.1007/s11368-021-02915-0](https://doi.org/10.1007/s11368-021-02915-0).
- Karki H, Bargali K, Bargali SS. 2021.** Spatial and temporal trends in soil N-mineralization rates under the agroforestry systems in Bhabhar belt of Kumaun Himalaya, India. *Agroforestry Systems* **95**(8):1603–1617 DOI [10.1007/s10457-021-00669-9](https://doi.org/10.1007/s10457-021-00669-9).
- Knops JMH, Bradley KL, Wedin DA. 2002.** Mechanisms of plant species impacts on ecosystem nitrogen cycling. *Ecology Letters* **5**(3):454–466 DOI [10.1046/j.1461-0248.2002.00332.x](https://doi.org/10.1046/j.1461-0248.2002.00332.x).
- Lan J, Hu N, Fu W. 2020.** Soil carbon-nitrogen coupled accumulation following the natural vegetation restoration of abandoned farmlands in a karst rocky desertification region. *Ecological Engineering* **158**(11):106033 DOI [10.1016/j.ecoleng.2020.106033](https://doi.org/10.1016/j.ecoleng.2020.106033).
- Li C, Li C, Zhao L, Ma Y, Tong X, Deng J, Ren C, Han X, Yang G. 2019.** Dynamics of storage and relative availability of soil inorganic nitrogen along revegetation chronosequence in the loess hilly region of China. *Soil and Tillage Research* **187**(4):11–20 DOI [10.1016/j.still.2018.11.006](https://doi.org/10.1016/j.still.2018.11.006).
- Li X, Wang A, Huang D, Qian H, Luo X, Chen W, Huang Q. 2023.** Patterns and drivers of soil net nitrogen mineralization and its temperature sensitivity across eastern China. *Plant and Soil* **485**(1–2):475–488 DOI [10.1007/s11104-022-05843-1](https://doi.org/10.1007/s11104-022-05843-1).
- Li Z, Wanqin Y, Yue K, Ruoyang H, Yang K, Liyan Z, Tan B, Xu Z. 2017.** Effects of temperature on soil nitrogen mineralization in three subalpine forests of western Sichuan, China. *Acta Ecologica Sinica* **37**(12):4045–4052 DOI [10.13287/j.1001-9332.201706.027](https://doi.org/10.13287/j.1001-9332.201706.027).
- Li X, Yang H, Shi W, Li Y, Guo Q. 2018.** Afforestation with xerophytic shrubs accelerates soil net nitrogen nitrification and mineralization in the Tengger Desert, Northern China. *CATENA* **169**(2):11–20 DOI [10.1016/j.catena.2018.05.026](https://doi.org/10.1016/j.catena.2018.05.026).
- Li D, Zhang X, Dungait JAJ, Wen X, Quine TA, Wang Q. 2021.** Changes in the biological N₂-fixation rates and diazotrophic community as vegetation recovers on abandoned farmland in a karst region of China. *Applied Soil Ecology* **158**:103808 DOI [10.1016/j.apsoil.2020.103808](https://doi.org/10.1016/j.apsoil.2020.103808).
- Li M, Zhou X, Zhang Q, Cheng X. 2014.** Consequences of afforestation for soil nitrogen dynamics in central China. *Agriculture, Ecosystems & Environment* **183**:40–46 DOI [10.1016/j.agee.2013.10.018](https://doi.org/10.1016/j.agee.2013.10.018).
- Liu Y, Wang C, He N, Wen X, Gao Y, Li S, Niu S, Butterbach-Bahl K, Luo Y, Yu G. 2017.** A global synthesis of the rate and temperature sensitivity of soil nitrogen mineralization: latitudinal patterns and mechanisms. *Global Change Biology* **23**(1):455–464 DOI [10.1111/gcb.13372](https://doi.org/10.1111/gcb.13372).
- Liu L, Zhu Q, Yang L, Elrys AS, Sun J, Ni K, Meng L, Zhu T, Müller C. 2024.** Afforestation increases soil inorganic N supply capacity and lowers plant N limitation in subtropical karst areas. *Geoderma* **443**:116848 DOI [10.1016/j.geoderma.2024.116848](https://doi.org/10.1016/j.geoderma.2024.116848).

- Loeb R, Kuijpers L, Peters RCJH, Lamers LPM, Roelofs JGM.** 2009. Nutrient limitation along eutrophic rivers? Roles of N, P and K input in a species-rich floodplain hay meadow. *Applied Vegetation Science* **12**(3):362–375 DOI [10.1111/j.1654-109X.2009.01034.x](https://doi.org/10.1111/j.1654-109X.2009.01034.x).
- Lu R.** 1999. *Soil and agro-chemical analytical methods*. Beijing: China Agricultural Science and Technology Press, 146–195.
- Lyu D, Liu Q, Xie T, Yang Y.** 2023. Impacts of different types of vegetation restoration on the physicochemical properties of sandy soil. *Forests* **14**(9):1740 DOI [10.3390/f14091740](https://doi.org/10.3390/f14091740).
- Maithani K, Arunachalam A, Tripathi RS, Pandey HN.** 1998. Nitrogen mineralization as influenced by climate, soil and vegetation in a subtropical humid forest in northeast India. *Forest Ecology and Management* **109**(1–3):91–101 DOI [10.1016/S0378-1127\(98\)00246-1](https://doi.org/10.1016/S0378-1127(98)00246-1).
- Manral V, Bargali K, Bargali SS, Shahi C.** 2020. Changes in soil biochemical properties following replacement of Banj oak forest with Chir pine in Central Himalaya, India. *Ecological Processes* **9**(1):30 DOI [10.1186/s13717-020-00235-8](https://doi.org/10.1186/s13717-020-00235-8).
- Maslov MN, Maslova OA.** 2022. Soil nitrogen mineralization and its sensitivity to temperature and moisture in temperate peatlands under different land-use management practices. *CATENA* **210**:105922 DOI [10.1016/j.catena.2021.105922](https://doi.org/10.1016/j.catena.2021.105922).
- McNeill A, Unkovich M.** 2007. The nitrogen cycle in terrestrial ecosystems. In: Marschner P, Rengel Z, eds. *Nutrient Cycling in Terrestrial Ecosystems*. Berlin, Heidelberg: Springer, 37–64.
- Naylor D, McClure R, Jansson J.** 2022. Trends in microbial community composition and function by soil depth. *Microorganisms* **10**(3):540 DOI [10.3390/microorganisms10030540](https://doi.org/10.3390/microorganisms10030540).
- Norman RJ, Edberg JC, Stucki JW.** 1985. Determination of nitrate in soil extracts by dual-wavelength ultraviolet spectrophotometry. *Soil Science Society of America Journal* **49**(5):1182–1185 DOI [10.2136/sssaj1985.03615995004900050022x](https://doi.org/10.2136/sssaj1985.03615995004900050022x).
- Owen JS, Wang MK, Sun HL, King HB, Wang CH, Chuang CF.** 2003. Comparison of soil nitrogen mineralization and nitrification in a mixed grassland and forested ecosystem in central Taiwan. *Plant and Soil* **251**:167–174 DOI [10.1023/A:1022980731416](https://doi.org/10.1023/A:1022980731416).
- Padalia K, Bargali SS, Bargali K, Khulbe K.** 2018. Microbial biomass carbon and nitrogen in relation to cropping systems in Central Himalaya, India. *Current Science* **115**:1741–1750 DOI [10.18520/cs/v115/i9/1741-1750](https://doi.org/10.18520/cs/v115/i9/1741-1750).
- Padalia K, Bargali SS, Bargali K, Manral V.** 2022. Soil microbial biomass phosphorus under different land use systems of Central Himalaya. *Tropical Ecology* **63**:30–48 DOI [10.1007/s42965-021-00184-z](https://doi.org/10.1007/s42965-021-00184-z).
- Pandey R, Bargali SS, Bargali K, Karki H, Chaturvedi RK.** 2024. Dynamics of nitrogen mineralization and fine root decomposition in sub-tropical Shorea robusta Gaertner f. forests of Central Himalaya, India. *Science of the Total Environment* **921**:170896 DOI [10.1016/j.scitotenv.2024.170896](https://doi.org/10.1016/j.scitotenv.2024.170896).
- Pandey V, Panda SK, Singh VK.** 2024. Preparation and characterization of high-strength insulating porous bricks by reusing coal mine overburden waste, red mud and rice husk. *Journal of Cleaner Production* **469**:143134 DOI [10.1016/j.jclepro.2024.143134](https://doi.org/10.1016/j.jclepro.2024.143134).
- Pandey S, Rai S, Bisht AS, Rai A.** 2023. Establishing linkages of soil carbon dynamics with microbes mediated ecological restoration of degraded ecosystems in Indian Himalayan Region. In: Mishra G, Giri K, Nath AJ, Francaviglia R, eds. *Soil Carbon Dynamics in Indian Himalayan Region*. Singapore: Springer Nature, 125–145.
- Pang Y, Tian J, Zhao X, Chao Z, Wang Y, Zhang X, Wang D.** 2020. The linkages of plant, litter and soil C:N:P stoichiometry and nutrient stock in different secondary mixed forest types in the Qinling Mountains, China. *PeerJ* **8**(4):e9274 DOI [10.7717/peerj.9274](https://doi.org/10.7717/peerj.9274).

- Qiu D, Xu R, Wu C, Mu X, Zhao G, Gao P.** 2022. Vegetation restoration improves soil hydrological properties by regulating soil physicochemical properties in the Loess Plateau, China. *Journal of Hydrology* **609**(3–4):127730 DOI [10.1016/j.jhydrol.2022.127730](https://doi.org/10.1016/j.jhydrol.2022.127730).
- Qiu L, Zhu H, Liu J, Yao Y, Wang X, Rong G, Zhao X, Shao M, Wei X.** 2021. Soil erosion significantly reduces organic carbon and nitrogen mineralization in a simulated experiment. *Agriculture, Ecosystems & Environment* **307**(G1):107232 DOI [10.1016/j.agee.2020.107232](https://doi.org/10.1016/j.agee.2020.107232).
- Rahman MM, Bárcena TG, Vesterdal L.** 2017. Tree species and time since afforestation drive soil C and N mineralization on former cropland. *Geoderma* **305**:153–161 DOI [10.1016/j.geoderma.2017.06.002](https://doi.org/10.1016/j.geoderma.2017.06.002).
- R Core Team.** 2022. *R: a language and environment for statistical computing*. Version 4.2.2. Vienna: R Foundation for Statistical Computing. Available at <https://www.r-project.org>.
- Rhoades CC, Coleman DC.** 1999. Nitrogen mineralization and nitrification following land conversion in montane Ecuador. *Soil Biology and Biochemistry* **31**(10):1347–1354 DOI [10.1016/S0038-0717\(99\)00037-1](https://doi.org/10.1016/S0038-0717(99)00037-1).
- Risch AC, Zimmermann S, Moser B, Schütz M, Hagedorn F, Firn J, Fay PA, Adler PB, Biederman LA, Blair JM, Borer ET, Broadbent AAD, Brown CS, Cadotte MW, Caldeira MC, Davies KF, di Virgilio A, Eisenhauer N, Eskelinen A, Knops JMH, MacDougall AS, McCulley RL, Melbourne BA, Moore JL, Power SA, Prober SM, Seabloom EW, Siebert J, Silveira ML, Speziale KL, Stevens CJ, Tognetti PM, Virtanen R, Yahdjian L, Ochoa-Hueso R.** 2020. Global impacts of fertilization and herbivore removal on soil net nitrogen mineralization are modulated by local climate and soil properties. *Global Change Biology* **26**(12):7173–7185 DOI [10.1111/gcb.15308](https://doi.org/10.1111/gcb.15308).
- Risch AC, Zimmermann S, Ochoa-Hueso R, Schütz M, Frey B, Firn JL, Fay PA, Hagedorn F, Borer ET, Seabloom EW, Harpole WS, Knops JMH, McCulley RL, Broadbent AAD, Stevens CJ, Silveira ML, Adler PB, Báez S, Biederman LA, Blair JM, Brown CS, Caldeira MC, Collins SL, Daleo P, di Virgilio A, Ebeling A, Eisenhauer N, Esch E, Eskelinen A, Hagenah N, Hautier Y, Kirkman KP, MacDougall AS, Moore JL, Power SA, Prober SM, Roscher C, Sankaran M, Siebert J, Speziale KL, Tognetti PM, Virtanen R, Yahdjian L, Moser B.** 2019. Soil net nitrogen mineralisation across global grasslands. *Nature Communications* **10**(1):1–10 DOI [10.1038/s41467-019-12948-2](https://doi.org/10.1038/s41467-019-12948-2).
- Sainju UM, Terrill TH, Gelaye S, Singh BP.** 2006. Soil carbon and nitrogen pools under long-term productivity of rhizoma peanut and perennial weeds management systems: (Kohlenstoff- und Stickstoffpools im Boden bei Langzeitanbau von Futterleguminosen (*Arachis glabrata* Benth.) bzw. mehrjährigen Grasanbausystemen). *Archives of Agronomy and Soil Science* **52**(1):45–59 DOI [10.1080/03650340500421729](https://doi.org/10.1080/03650340500421729).
- Schlesinger W, Bernhardt E.** 2013. *Biogeochemistry: an analysis of global change*. Third Edition. Cambridge: Academic Press, 1–672 DOI [10.1029/98EO00015](https://doi.org/10.1029/98EO00015).
- Sheng M, Xiong K, Wang L, Li X, Li R, Tian X.** 2018. Response of soil physical and chemical properties to Rocky desertification succession in South China Karst. *Carbonates and Evaporites* **33**(1):15–28 DOI [10.1007/s13146-016-0295-4](https://doi.org/10.1007/s13146-016-0295-4).
- Siwach A, Kaushal S, Sarma K, Baishya R.** 2023. Interplay of moss cover and seasonal variation regulate soil physicochemical properties and net nitrogen mineralization rates in Central Himalayas, India. *Journal of Environmental Management* **345**(1):118839 DOI [10.1016/j.jenvman.2023.118839](https://doi.org/10.1016/j.jenvman.2023.118839).
- Sparks DL, Page AL, Helmke PA, Loepert RH, Soltanpour PN, Tabatabai MA, Johnston CT, Sumner ME (eds.).** 1996. Methods of soil analysis: part 3 chemical methods. In: *SSSA Book Series*. Madison, WI, USA: Soil Science Society of America, American Society of Agronomy.

- Srivastava P, Raghubanshi AS, Singh R, Tripathi SN.** 2015. Soil carbon efflux and sequestration as a function of relative availability of inorganic N pools in dry tropical agroecosystem. *Applied Soil Ecology* **96**:1–6 DOI [10.1016/j.apsoil.2015.04.019](https://doi.org/10.1016/j.apsoil.2015.04.019).
- Stanford G, Smith SJ.** 1972. Nitrogen mineralization potentials of soils. *Soil Science Society of America Journal* **36**(3):465–472 DOI [10.2136/sssaj1972.03615995003600030029x](https://doi.org/10.2136/sssaj1972.03615995003600030029x).
- Tapia-Torres Y, López-Lozano NE, Souza V, García-Oliva F.** 2015. Vegetation-soil system controls soil mechanisms for nitrogen transformations in an oligotrophic Mexican desert. *Journal of Arid Environments* **114**:62–69 DOI [10.1016/j.jaridenv.2014.11.007](https://doi.org/10.1016/j.jaridenv.2014.11.007).
- Templer PH, Groffman PM, Flecker AS, Power AG.** 2005. Land use change and soil nutrient transformations in the Los Haitises region of the Dominican Republic. *Soil Biology and Biochemistry* **37**(2):215–225 DOI [10.1016/j.soilbio.2004.07.031](https://doi.org/10.1016/j.soilbio.2004.07.031).
- Trentini CP, Villagra M, Gómez Pámies D, Bernava Laborde V, Bedano JC, Campanello PI.** 2018. Effect of nitrogen addition and litter removal on understory vegetation, soil mesofauna, and litter decomposition in loblolly pine plantations in subtropical Argentina. *Forest Ecology and Management* **429**(2):133–142 DOI [10.1016/j.foreco.2018.07.012](https://doi.org/10.1016/j.foreco.2018.07.012).
- Unver MC, kücüük M, Tufekcioglu A.** 2014. Temperature influence on N mineralisation potential in different land uses in Artvin. *Journal of Environmental Protection and Ecology* **15**:991–998.
- Wang H, Deng N, Wu D, Hu S.** 2017. Quantitative response relationships between net nitrogen transformation rates and nitrogen functional genes during artificial vegetation restoration following agricultural abandonment. *Scientific Reports* **7**:7752 DOI [10.1038/s41598-017-08016-8](https://doi.org/10.1038/s41598-017-08016-8).
- Wang SJ, Liu QM, Zhang DF.** 2004. Karst rocky desertification in southwestern China: geomorphology, landuse, impact and rehabilitation. *Land Degradation & Development* **15**(2):115–121 DOI [10.1002/ldr.592](https://doi.org/10.1002/ldr.592).
- Wang L, Wang P, Sheng M, Tian J.** 2018. Ecological stoichiometry and environmental influencing factors of soil nutrients in the karst rocky desertification ecosystem, southwest China. *Global Ecology and Conservation* **16**(10):e00449 DOI [10.1016/j.gecco.2018.e00449](https://doi.org/10.1016/j.gecco.2018.e00449).
- Wang J, Wu L, Xiao Q, Huang Y, Liu K, Wu Y, Li D, Duan Y, Zhang W.** 2023. Long-term manuring enhances soil gross nitrogen mineralization and ammonium immobilization in subtropical area. *Agriculture, Ecosystems & Environment* **348**(8):108439 DOI [10.1016/j.agee.2023.108439](https://doi.org/10.1016/j.agee.2023.108439).
- Wei X, Reich PB, Hobbie SE, Kazanski CE.** 2017. Disentangling species and functional group richness effects on soil N cycling in a grassland ecosystem. *Global Change Biology* **23**(11):4717–4727 DOI [10.1111/gcb.13757](https://doi.org/10.1111/gcb.13757).
- Wei X, Shao M, Fu X, Horton R, Li Y, Zhang X.** 2009. Distribution of soil organic C, N and P in three adjacent land use patterns in the northern Loess Plateau. *China Biogeochemistry* **96**(1–3):149–162 DOI [10.1007/s10533-009-9350-8](https://doi.org/10.1007/s10533-009-9350-8).
- Wei X, Shao M, Fu X, Ågren GI, Yin X.** 2011. The effects of land use on soil N mineralization during the growing season on the northern Loess Plateau of China. *Geoderma* **160**(3–4):590–598 DOI [10.1016/j.geoderma.2010.11.007](https://doi.org/10.1016/j.geoderma.2010.11.007).
- Wu C, Deng L, Huang C, Chen Y, Peng C.** 2021. Effects of vegetation restoration on soil nutrients, plant diversity, and its spatiotemporal heterogeneity in a desert-oasis ecotone. *Land Degradation & Development* **32**(2):670–683 DOI [10.1002/ldr.3690](https://doi.org/10.1002/ldr.3690).
- Xing X, Huang Y, An S, Zhang H.** 2013. Soil nitrogen concentrations and transformations under different vegetation types in forested zones of the Loess Gully Region. *Acta Ecologica Sinica* **33**:7181–7189 DOI [10.5846/stxb](https://doi.org/10.5846/stxb).

- Yadav AN, Kour D, Kaur T, Devi R, Yadav A, Dikilitas M, Abdel-Azeem AM, Ahluwalia AS, Saxena AK.** 2021. Biodiversity, and biotechnological contribution of beneficial soil microbiomes for nutrient cycling, plant growth improvement and nutrient uptake. *Biocatalysis and Agricultural Biotechnology* 33:102009 DOI [10.1016/j.bcab.2021.102009](https://doi.org/10.1016/j.bcab.2021.102009).
- Yang L, Zhang F, Gao Q, Mao R, Liu X.** 2010. Impact of land-use types on soil nitrogen net mineralization in the sandstorm and water source area of Beijing, China. *CATENA* 82(1):15–22 DOI [10.1016/j.catena.2010.04.004](https://doi.org/10.1016/j.catena.2010.04.004).
- Ye C, Cheng X, Liu W, Zhang Q.** 2015. Revegetation impacts soil nitrogen dynamics in the water level fluctuation zone of the Three Gorges Reservoir, China. *Science of the Total Environment* 517:76–85 DOI [10.1016/j.scitotenv.2015.02.068](https://doi.org/10.1016/j.scitotenv.2015.02.068).
- Zeng DH, Hu YL, Chang SX, Fan ZP.** 2009. Land cover change effects on soil chemical and biological properties after planting Mongolian pine (*Pinus sylvestris* var. *mongolica*) in sandy lands in Keerqin, northeastern China. *Plant and Soil* 317(1–2):121–133 DOI [10.1007/s11104-008-9793-z](https://doi.org/10.1007/s11104-008-9793-z).
- Zhang Y, Wang K, Wang J, Liu C, Shangguan Z.** 2021a. Changes in soil water holding capacity and water availability following vegetation restoration on the Chinese Loess Plateau. *Scientific Reports* 11(1):9692 DOI [10.1038/s41598-021-88914-0](https://doi.org/10.1038/s41598-021-88914-0).
- Zhang L, Yang Y, Jiao Z, Chen Z, Shen Y, Liu Y, Zhang L, Wang L, Liu S, Wu Q, Li H.** 2022. Response of soil net nitrogen mineralization to a litter in three Subalpine forests. *Forests* 13(4):597 DOI [10.3390/f13040597](https://doi.org/10.3390/f13040597).
- Zhang S, Zhang X, Liu Z, Sun Y, Liu W, Dai L, Fu S.** 2014. Spatial heterogeneity of soil organic matter and soil total nitrogen in a Mollisol watershed of Northeast China. *Environmental Earth Sciences* 72(1):275–288 DOI [10.1007/s12665-014-3081-4](https://doi.org/10.1007/s12665-014-3081-4).
- Zhang W, Zhao J, Pan F, Li D, Chen H, Wang K.** 2015. Changes in nitrogen and phosphorus limitation during secondary succession in a karst region in southwest China. *Plant and Soil* 391(1–2):77–91 DOI [10.1007/s11104-015-2406-8](https://doi.org/10.1007/s11104-015-2406-8).
- Zhang X, Zhu B, Yu F, Cheng W.** 2021b. Plant inputs mediate the linkage between soil carbon and net nitrogen mineralization. *Science of the Total Environment* 790:148208 DOI [10.1016/j.scitotenv.2021.148208](https://doi.org/10.1016/j.scitotenv.2021.148208).
- Zhong Z, Makeschin F.** 2003. Soluble organic nitrogen in temperate forest soils. *Soil Biology and Biochemistry* 35(2):333–338 DOI [10.1016/S0038-0717\(02\)00252-3](https://doi.org/10.1016/S0038-0717(02)00252-3).
- Zhou L, Huang J, Lü F, Han X.** 2009. Effects of prescribed burning and seasonal and interannual climate variation on nitrogen mineralization in a typical steppe in Inner Mongolia. *Soil Biology and Biochemistry* 41(4):796–803 DOI [10.1016/j.soilbio.2009.01.019](https://doi.org/10.1016/j.soilbio.2009.01.019).