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Nitrogen Mineralisation Processes in High-Altitude Wet Meadow Soils Along a Vegetation Degradation Gradient and Their Sensitivity to Temperature and Humidity

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Abstract： Nitrogen (N) cycling in alpine wetlands plays a crucial role in global nitrogen cycling and its balance. Although the mechanisms underlying the net nitrogen mineralization rate (Rmin) in degraded soils of alpine wetlands have been extensively studied, research on the effects of temperature and humidity on the Rmin process under different vegetation degradation gradients remains limited. Alpine wet meadows with different vegetation degradation conditions (i.e. undegraded (UD), lightly degraded (LD), moderately degraded (MD), and heavily degraded (HD) were selected to examine effects of temperature, soil moisture, and their interactions on soil net N mineralization. The results indicated that vegetation degradation significantly inhibited the Rmin process, with its rate remaining constant or gradually decreasing as degradation severity increased. Soil moisture significantly affects Rmin. Within the moisture range of 20%-60% FC, Rmin increases with increasing humidity, but decreases gradually beyond 60% FC. Additionally, reduced moisture significantly affects Rmin in soils with different degrees of vegetation degradation. Temperature also significantly affects Rmin. The Q10 values for the four levels of degraded soil are 1.73–2.37 (UD), 0.82–2.98 (LD), 0.93–2.30 (MD), and 1.12–2.10 (HD), respectively. The growth rate of Rmin at all moisture levels decreases with increasing temperature, and the soil nitrogen mineralization process is most sensitive in the 15°C–25°C temperature range. Temperature changes have a greater impact on nitrogen mineralization in MD sites than in UD, LD, and HD sites. Overall, temperature and moisture exhibit synergistic and antagonistic effects on soil nitrogen mineralization, with temperature effects being more pronounced. The optimal temperature for Rmin among the four degradation levels is 20.50–25.00°C, and the optimal moisture condition is 50.00–69.52% FC. These findings provide crucial scientific evidence for understanding soil nitrogen dynamics on the Tibetan Plateau and formulating targeted management measures.

Keywords: Alpine wetland; Vegetation degraded; Nitrogen mineralization; Temperature sensitivity; Moisture sensitivity

1 Introduction

Soil nitrogen availability is a key factor influencing plant productivity and plays a regulatory role in the nitrogen cycle (Wu et al., 2020). Soil nitrogen mineralisation constitutes the primary pathway for converting organic nitrogen into inorganic forms such as ammonium (NH_4^+) and nitrate (NO_3^-), which serve as the principal sources of available nitrogen for plant uptake and microbial growth (Li et al., 2019; Yadav et al., 2021). Globally, terrestrial ecosystems produce approximately 1,450 petagrams of ammonium salts and 330 petagrams of nitrate annually through soil ammonification and nitrification (Kuypers et al., 2018). As significant nitrogen reservoirs, alpine wetlands contribute around 62.12 ± 37.55 petagrams of nitrogen yearly (Nie et al., 2022). However, climate change and human activities have induced vegetation degradation, elevated soil temperatures, and reduced soil moisture in alpine wetland ecosystems. These alterations may influence soil nitrogen mineralisation processes. Consequently, gaining a thorough understanding of soil nitrogen dynamics under varying temperature and moisture conditions resulting from vegetation degradation is crucial for enhancing soil fertility and quality management, as well as maintaining the health of alpine wetland ecosystems.

Soil N mineralisation processes are not constant across time and space, being influenced by multiple factors (LiliLei and Louis M. McDonald, 2019; Hu et al., 2021). The prevailing mechanisms by which environmental factors, soil characteristics, and vegetation degradation affect nitrogen cycling in humid meadows. (He et al., 2025). Hydrological cycles in terrestrial ecosystems are significantly dependent on soil temperature and moisture (Schwinning & Sala, 2004; Song et al., 2007), while climate change (Zhang et al.,

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2020) influences variations in soil temperature and moisture, thereby affecting vegetation growth (Charles E. Sasser et al., 2019; Kenneth S. Miller et al., 2018) induces alterations in soil physical and chemical properties. These changes in soil physicochemical characteristics affect microbial and enzymatic activity (Li et al., 2019), triggering a cascade of reactions. Soil temperature serves as a pivotal driver of nitrogen transformation and availability. Elevated temperatures typically induce alterations in soil microbial activity and physicochemical properties, consequently modifying nitrogen mineralisation rates (McGeough K L et al., 2016). Research indicates that net nitrogen mineralisation rates progressively increase with rising temperatures (Sun et al., 2022). The Q10 coefficient quantifies temperature sensitivity in nitrogen mineralisation, representing the increase in mineralisation rate per 10°C rise in incubation temperature. However, most studies indicate significant variation in Q10 values across ecosystems, ranging from 1.03 to 11.89 (Davidson E A, Janssens I A, 2006). This variability primarily stems from multiple environmental factors, including humidity levels. This indicates the existence of specific temperature thresholds governing soil nitrogen mineralisation processes. Soil moisture represents another critical microclimatic factor significantly influencing nitrification and net nitrogen mineralisation rates (Sierra, 1997; Paul et al., 2003). Humidity levels regulate net nitrogen mineralisation rates by influencing soil aeration, oxygen availability, specific microbial growth rates, and enzyme activity (Curtin et al., 2012). Higher humidity provides favourable conditions for biochemical reactions, accelerating soil nitrogen mineralisation. Previous studies indicate that both excessively high and low moisture levels impair soil nitrogen mineralisation rates (Guntiñas M E et al., 2012). Nitrogen mineralisation peaks when soil moisture approaches field capacity (Stanford and Epstein, 1974), as cultivated soils are most workable at saturation levels near field capacity, where soil pore water films precisely envelop mineral surfaces, maximising substrate desorption and diffusion rates. However, Charles and Sasser reported that nitrogen mineralisation peaked at 60% field capacity (FC) in temperate broadleaf forests, achieved by optimising oxygen diffusion and reducing steric hindrance to advance the moisture peak. Furthermore, existing research confirms significant variations in the effects of soil temperature and moisture on net ammonification and nitrification processes across different ecosystems (Booth et al., 2005; Wang et al., 2006). Nevertheless, the interactive effects of temperature and moisture on soil nitrogen mineralisation remain poorly understood, necessitating region-specific assessments of nitrogen transformation.

Vegetation, as a crucial component of terrestrial ecosystems (Rui et al.,2011), exhibits degradation through declines in biomass and alterations in community structure. These changes frequently stem from the combined effects of climate change (including rising temperatures and precipitation variations) and human disturbances (such as overgrazing) (Pei S, et al., 2008). Vegetation degradation alters soil properties by regulating microbial activity (Jin et al., 2013), leading to shifts in plant species composition. It further influences soil nitrogen mineralisation processes by modifying the input, quality, and quantity of aboveground material (i.e., the surface layer). As a driver of global change, vegetation degradation profoundly impacts soil nitrogen cycling by altering both abiotic and biotic soil characteristics (Kang et al., 2024).Research indicates that vegetation degradation significantly influences the activity of key nitrogen cycle enzymes—such as urease and nitrate reductase—by altering soil moisture and temperature conditions, thereby regulating soil nitrogen mineralisation rates(Chang et al., 2023). Studies indicate that post-vegetation renewal alters soil nutrient balance and mineralisation processes (Lu et al., 2022). Nevertheless, the impact of vegetation degradation on net soil nitrogen mineralisation remains contentious. This is because reduced biomass diminishes vegetation shading, leading to increased evapotranspiration and lower soil moisture

(Dang et al., 2020). Such changes may conversely favour nitrification (Xu et al., 2016). Bai et al. (2020) observed in alpine meadows that grassland degradation reduces net nitrogen mineralisation rates (consistent with our findings), yet simultaneously concluded that nitrification processes diminish—a finding at odds with our results. Although extensive research has examined the effects of vegetation degradation on soil nitrogen mineralisation processes, results may vary due to the influence of temperature, moisture, and their interactions.

The Qinghai-Tibet Plateau (QTP) wetlands cover approximately one-third of the nation's total wetland area (1.06×10^5 km²), with wet meadows constituting 50% of the plateau's wetland cover (Ma et al., 2018; Li et al., 2021). This region exhibits ecological fragility and is particularly sensitive to climate warming and anthropogenic disturbances, leading to a significant reduction in wet meadow areas (Nie et al., 2022). Accompanying vegetation degradation, vegetation cover, density, height, and biomass in wet meadows have markedly declined (Ma et al., 2018), exacerbating soil degradation issues such as increased water and nutrient loss and elevated soil temperatures, which in turn affect soil nitrogen transformation and availability. However, it remains unclear whether the effects of temperature, humidity, and their interactions on net nitrogen mineralisation in alpine wet meadows vary along a vegetation degradation gradient. To address this research gap, this study selected alpine wet meadows with varying degrees of vegetation degradation (undegraded UD, lightly degraded LD, moderately degraded MD, and heavily degraded HD) to investigate the effects of temperature, soil moisture, and their interactions on soil net nitrogen mineralisation. Experimental objectives include: (1) analysing the effects of temperature, moisture, and their interactions on soil net nitrogen mineralisation rates; (2) comparing these effects across the four vegetation degradation plots; (3)Identify the optimal moisture and temperature thresholds for nitrogen mineralization rates under different degradation gradients. We hypothesise that: (1) both temperature and moisture significantly influence wet meadow soil N mineralisation rates, potentially limiting increases under extreme factor combinations; (2) soil N mineralisation rates progressively decrease with increasing vegetation degradation; (3) temperature exerts a greater influence on soil nitrogen mineralisation than moisture.

2 Materials and methods

2.1 Study area overview

The study was conducted in Gagai alpine wet meadow in Gahai-Zecha International Nature Reserve (34°16'N, 102°26'E), Gansu province of China, located on the northeastern edge of the Qinghai Tibet Plateau. The wet meadow, covering about 4.07×10^4 hm², are mostly distributed across the Reserve. The climate of the Reserve is cold temperate continental monsoon, with an average annual temperature of 2.9°C (January: -9.5°C, July:12.4°C), and the mean annual precipitation was 781.8 mm, occurring during the May to September（Ma et al.,2018).Over the last forty years, the region has experienced a significant increase in temperatures and a decrease in rainfall, with temperatures rising by 0.4 °C and rainfall decreasing by 2 mm per decade (Yao et al., 2022；Chylek et al.,2009). Additionally, the wetland in the area has been extensively drained for rangelands since the 1970s, leading to a reduction in soil moisture levels. Overgrazing has occurred due to the pressures of a growing human population and increased social and economic activities over the past few decades，this overgrazing has led to significant vegetation loss (Qin et al., 2016;Sun et al.,2018). Previous studies have identified a clear gradient of vegetation degradation along a moisture gradient in these areas (Ma et al., 2018). UD, LD, MD and HD in the alpine wet meadow were selected based on the plant cover, dominant species, biomass and groundwater level. In UD, the main plant species were Gansu artemisia (Kobresia kansuensis), fern hemp (Potentilla anserina), and scattered early morning glory

(Poa subfastigiata), which had more apomictic and root systems, and shallow seasonal water, with the water table ranging from 20-40 cm. The main plant species were Gansu artemisia (Kobresia kansuensis), echinoderma (Oxy tropis), and wetland plants are the main companion species for LD(Sun et al., 2018). The surface area of bare soil is 5% to 10%, with no standing water and a water table of 40-70 cm. the main plant species at MD were Equisetum aruense and Kobresia humilis, with a surface area of bare soil of 10% to 30%, with no standing water and a water table of less than 70 cm. the surface of the HD is only sporadically covered with vegetation, and there is no vegetation on the surface. Only sporadic cover of vegetation more than 90 percent of the surface is bare, and the surface shows signs of minor wind erosion.

Table.1 basic soil characteristics of the four level of degradation. Values are shown as mean ± SD

Soilproperties	**UD**	**LD**	**MD**	**HD**
Soil organic carbon ($g·kg^{-1}$)	61.22±1.91a	61.30±13.06a	36.822±4.65b	32.27±7.69b
Soil total nitrogen ($g·kg^{-1}$)	4.00±0.25a	3.68±0.10a	2.61±0.05b	1.87±0.24c
Total soil phosphorus($g·kg^{-1}$)	2.45±0.01a	2.35±0.22ab	2.06±0.21bc	1.98±0.15c
N:P ratio	1.63±0.09a	1.56±0.11a	1.28±0.13b	0.95±0.14c
C:N ratio	56.48±65.92a	28.87±93.74a	25.28±48.36a	13.17±51.3a
MBN ($g·kg^{-1}$)	39.01±1.34a	33.38±1.94b	35.53±2.58ab	26.94±2.06c
MBC ($g·kg^{-1}$)	46.80±14.63a	31.42±16.51a	42.67±31.30a	50.22±13.0a
Bulk density ($g·cm^{-3}$)	0.36±0.01c	0.39±0.02c	0.62±0.05a	0.56±0.03b
URE($\mu mol· g^{-1}· h^{-1}$)	0.79±0.07b	0.69±0.02b	0.62±0.02ab	0.62±0.04a
NIR($\mu mol· g^{-1}· h^{-1}$)	0.61±0.01b	0.50±0.01ab	0.30±0.14ab	0.14±0.08a

2.2 Soil sampling and incubation methods

Three independent replicate plots were established within the study area as spatial replicates, corresponding to different degrees of vegetation degradation. In each plot with varying levels of degradation, five sampling points were randomly selected to collect surface soil (0–10 cm). To obtain representative soil materials for each degradation level, soil samples from all plots of the same degradation level were mixed to form a composite sample. The cultivation experiment mainly aimed to elucidate the response of the nitrogen mineralization process in soils of different degradation levels to the interaction between temperature and moisture. The N mineralization characteristics of wet meadow soils under different moisture and temperature conditions were determined using a laboratory non-leaching incubation experiment(Xiong et al.,2011). Laboratory incubation was conducted at three temperature levels (15, 25 and 35℃) and four moisture levels (20%, 40%, 60% and 80%FC). A total of 144 soil samples were used in the experiment (4 degraded levels×3 temperatures×4 moisture levels ×3 replications).The 100g soil sample was put into 300 mL plastic beaker, according to the degree of degradation of each wetland field water holding capacity, the moisture content was adjusted to the experimental design of the moisture content with distilled water, sealed with plastic wrap, and tied 2-3 small holes on the plastic wrap to maintain moderate air permeability, and put into the incubator at 15℃, 25℃, 35℃ for cultivation. During the incubation period, the water in the bottle was replenished every 2-3d by weighing, and destructive sampling was carried out, and the plastic beaker was taken out from the incubator at 0 d, 3 d, 7 d, 14 d, 28 d, and 49 d of incubation in order. Five grams of fresh soil was weighed for each soil sample, and the nitrate-ammonium nitrogen in the soil was extracted with 2 mol/L KCL solution, and then the nitrogen mineralization rate in the soil was determined by using a Kjeldahl Nitrogen Analyzer (Ma et al., 2020).

2.3 Soil sampling measurements and calculations

Cumulative soil N mineralization is equal to the sum of the N mineralization of each sample taken throughout the incubation time (mg·kg^{-1}), and net soil nitrogen mineralization is the difference between the mineralized nitrogen before and after incubation(mg·kg^{-1}).

$$\Delta t_i = t_{i+1} - t_i \quad (1)$$

$$\Delta N_{R\min} = \frac{\Delta c\left(NH_4^{\ +} - N\right)_i + \Delta c\left(NO_3^{\ -} - N\right)_i}{\Delta t_i} \quad (2)$$

Where: Δt_i denotes the time interval, $\Delta c\left(NH_4^{\ +} - N\right)_i$ denotes the amount of change in ammonium N in mg·kg^{-1}, $\Delta c\left(NO_3^{\ -} - N\right)_i$ denotes the amount of change in nitrate N in mg·kg^{-1}, and $\Delta N_{R\min}$ denotes the rate of N mineralization in mg·kg^{-1}·d^{-1}.

Stanford and Smith's single-compartment model (Stanford G, Smith S. J. 1972) is one of the most commonly used models for kinetic analysis of N mineralization and is used to study N mineralization in soil throughout the incubation period. The model is usually represented in the following form:

$$N_t = N_0 (1 - e^{-kt}) \quad (3)$$

In the formula, N_t is the accumulated amount of soil mineralization (mg·kg^{-1}); N_0 is the N mineralization potential (mg·kg^{-1}), which is the maximum value of the amount of organic nitrogen that can be mineralized into inorganic N in the soil under a certain condition, and characterizes the size of the potential of N supply in the soil; k is the rate constant of mineralization (d^{-1}), which is the ratio of mineralized N to the mineralized N in the soil per unit of time, reflecting the rapidity of mineralization of organic N in soil and the size of N supply rate in the soil; t is the incubation time (day); The measured ammonium N accumulation data were fitted to obtain the parameters N_0 and k of the kinetic model for the soil-level response of wetlands with different degradation levels at different temperatures.

The sensitivity of the N mineralization rate Rmin to the temperature Δ(Q10), the ratio of constant rates measured at temperatures differing by 10 °C is calculated as follows:

$$Q_{10} = \left(\frac{R_{T2}}{R_{T1}}\right)^{\frac{10}{T2-T1}} \quad (4)$$

where N_{T1} and N_{T2} are the soil net nitrification rates (mg·kg^{-1}·d^{-1}) at incubation temperatures T1 and T2, respectively.

2.4 Statistical analyses

Statistical analysis was conducted using SPSS 25.0 (SPSS Institute, Inc., Chicago, IL, USA). One-way analysis of variance (ANOVA) was employed to test for statistical differences in soil properties and soil nitrogen mineralisation rates under varying soil temperature and moisture levels. LSD tests were used at a significance level of 0.05. Variance analysis of moisture and humidity effects on soil nitrogen mineralisation was performed using the vegan and tidyverse packages, with residuals representing the unexplained portion of the model. Four-way analysis of variance (ANOVA) assessed interactions among all experimental variables—soil temperature, soil moisture, incubation time, and vegetation degradation levels—on soil properties and nitrogen mineralisation rates. Pearson correlation analysis examined relationships between all measured variables. All statistical analyses were conducted at a significance level of α = 0.05. Variance decomposition plots were generated using R software, while other graphs were produced using Origin 2022.

3 Result

3.1 Variations of soil nitrogen mineralization rates under different soil temperatures and moisture level

As the incubation period increases, the rate of mineralization gradually decreases. Soil temperature and moisture significantly affect nitrogen mineralization rates under four levels of grassland degradation (Fig.1). Nitrogen mineralization rates rise with increasing soil temperature, peaking at 35°C. Compared to undegraded grassland (UD), mineralization rates in lightly degraded (LD), moderately degraded (MD), and severely degraded (HD) grasslands decreased by 3.26–32.28%, 5.67–45.55%, and 9.05–52.95%, respectively. Soil temperature, moisture content, degradation severity, incubation time, and their interactions had a significant impact on soil nitrogen mineralization rates ($P < .001$) (Table 2). Across different degradation levels, N values increased with temperature (see Table 3), reaching a maximum at 35°C. N values were significantly higher under high humidity (60% FC, 80% FC) compared to low humidity (20% FC, 40% FC) conditions. The N value was highest under 60% FC humidity conditions among all treatments.

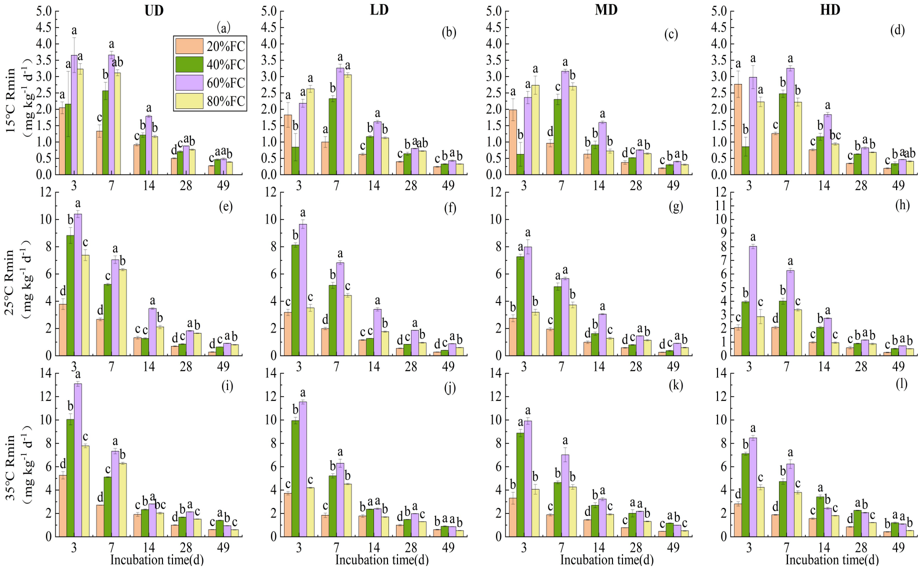

Figure. 1 N mineralization rates (Rmin) of four vegetation degradation degrees over the incubation period under different soil temperature and moisture conditions

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Table.2 Analysis of variance (ANOVA) of soil N mineralization rate under the interaction of temperature, moisture, degradation, and incubation time

	df	equalize the square	F	P
M	3	149.118	1583.269	0.000
T	2	238.162	2528.695	0.000
D	3	19.93	211.605	0.000
I	4	526.615	5591.363	0.000
M * T	6	19.294	204.855	0.000
M * D	9	1.278	13.565	0.000
M * I	12	24.277	257.76	0.000
T * D	6	2.425	25.745	0.000
T * I	8	44.562	473.137	0.000
D * I	12	6.679	70.919	0.000
M*T * D	18	0.682	7.239	0.000
M *T * I	24	6.941	73.7	0.000
M* D* I	36	0.833	8.842	0.000
T * D * I	24	1.152	12.227	0.000
M* T * D * I	72	0.323	3.434	0.000

（M : moisture, T : temperature, D :degree of degradation, I : incubation time）

Table.3 First-order kinetic modelling of soil N mineralization in different wetland degradation stages. Values are shown as mean ± SD

		15°C		25°C		35°C	
moisture	Degradation	N_0(mg·kg^{-1})	K(d^{-1})	N_0(mg·kg^{-})	K(d^{-1})	N_0(mg·kg^{-})	K(d^{-1})
20%FC	UD	1.14Ca	0.0185Ba	1.97Da	0.0452Aa	2.16Da	0.0304Ca
	LD	0.90Db	0.0156Ca	1.7Ca	0.0419Aa	1.91Db	0.0308Ba
	MD	0.85Db	0.0138Ca	1.41Cb	0.0239Bb	1.69Db	0.0239Cb
	HD	0.96Cab	0.0137Ca	1.32Ca	0.0227Cb	1.67Cc	0.0237Cb
40%FC	UD	1.71Ba	0.02898Ac	2.8Bb	0.0428Aa	4.38Ba	0.0677Aa
	LD	1.41Cab	0.0207Bc	2.48Bb	0.0290Bb	3.79Bb	0.0454Ab
	MD	1.23Cb	0.0192Bb	2.46Bb	0.0246Bb	4.3Ba	0.0655Aa
	HD	1.44Bab	0.0221Ba	2.45Bb	0.0323Bb	4.58Aa	0.0644Aa
60%FC	UD	2.24Aa	0.0338Aa	4.59Aa	0.0422Ac	4.83Aa	0.0513Ba
	LD	1.95Abc	0.0281Aab	4.49Aa	0.0480Ab	4.3Ab	0.0433Ab

	MD	1.89Ac	0.0254Ac	3.92Ab	0.0582Aa	4.77Aa	0.05442Ba
	HD	2.10Aab	0.0294Aab	3.56Ac	0.0439Abc	4.39Bb	0.0497Ba
80%FC	UD	1.80Ba	0.0202Ba	3.71Ba	0.0369Aa	1.91Ca	0.0274Ca
	LD	1.65Bab	0.0161Cb	2.5Bb	0.0249Bb	2.66Cb	0.0223Cb
	MD	1.43Bc	0.0149Bb	2.35Bb	0.0250Bb	2.67Cb	0.0214Cb
	HD	1.52Bbc	0.0197BCa	1.94Cc	0.0211Cb	2.55Bb	0.0218Cb

3.2 The impact of water and temperature interactions on nitrogen mineralization in soils with varying degrees of degradation

The variance decomposition analysis revealed that soil nitrogen mineralization is predominantly influenced by temperature factors (9.90%、9.41%、11.90%、10.71%). In general , temperature exerts a greater impact on soil nitrogen mineralization than moisture (Fig. 2), indicating that the mineralization rate is more strongly regulated by temperature than that by water availability. Fig.3 shows the response surface plots of N mineralization rate under the combined effect of moisture and temperature, fitted to the known data to obtain the optimum moisture and temperature for the soil under each degradation level: 21.32°C, 69.52%FC under UD, 22.76°C, 50.00%FC under LD, 25.00°C, 50.00%FC under MD, and 20.50°C, 60.92%FC under HD. Both moisture and temperature curves showed a steeper curve in Fig.3, increasing and then decreasing, which had a significant effect on the soil N mineralization rate.Tab.4, the contribution of temperature to soil N mineralization was the highest(48.16%), followed by the interaction of mositure and temperature (39.84%), moisture was the lowest(12%).

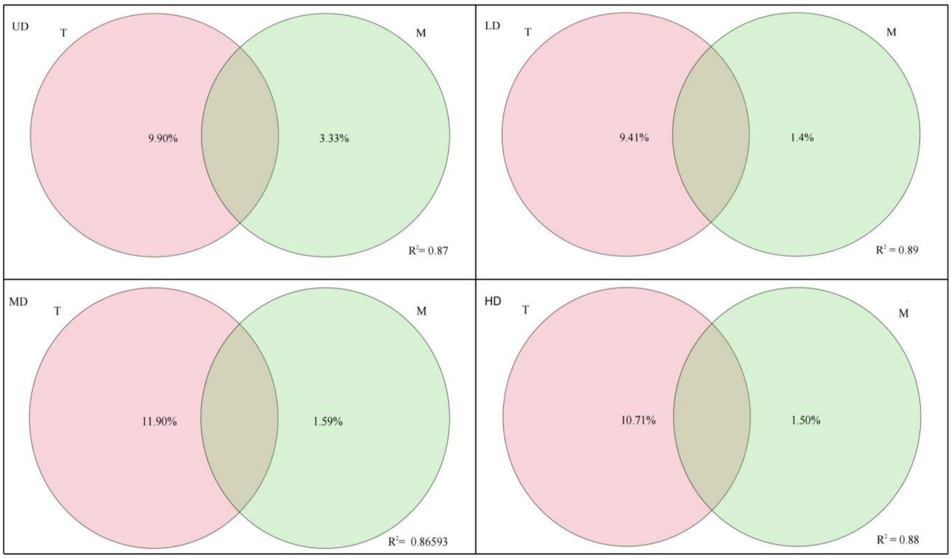

Figure 2. Variance Decomposition Analysis of Soil Nitrogen Mineralization by Temperature and Moisture Duration under Different Degradation Gradients

（Note: M : moisture, T : temperature.The non-overlapping areas of the circles represent the individual contributions of each factor to changes in nitrogen mineralization content, while the overlapping areas represent their combined effects; variance contributions of ≤0 are not labeled in the diagra ）

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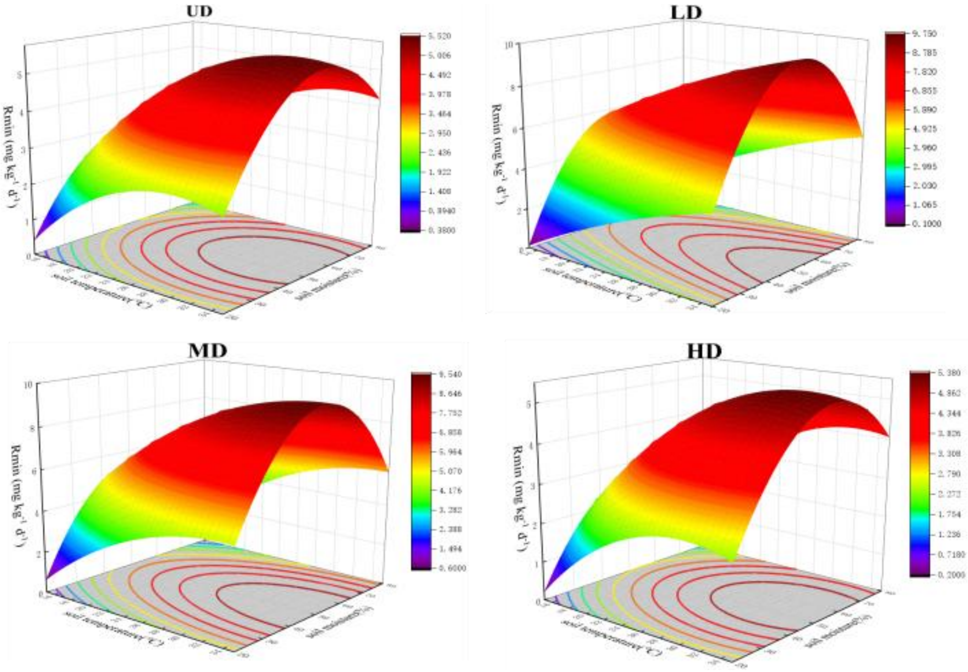

Figure. 3 Relationship among soil temperature (T), soil moisture (M), and the Rmin for different wetland degradation stages

Table.4 Linear mixed effect model of water and temperature on soil nitrogen mineralization rate

	F	P	I.prrc(%)
T	5.133	0.003	48.16
M	1.321	0.187	12
T*M	0.873	0.383	39.84

(note: Significance levels $p < 0.001$)

3.3 Temperature sensitivity of soil N mineralization

The temperature sensitivity (Q10) of soil N mineralization rates ranged from 25°C/15°C > 35°C/25°C, and between 15°C and 25°C, the effect of temperature on soil N mineralization rates was higher than that of 25°C-35°C(Tab.5).The Q10 value did not depend on the vegetation degradation(Tab.6).

Table.5Temperature sensitivity of soil N mineralization coefficients (Q10) at different moisture levels

Degradation	Moisture	25°C/15°C	35°C/25°C
UD	20%FC	1.73	1.31
	40%FC	2.37	1.22
	60%FC	2.26	1.11
	80%FC	2.11	1.00
LD	20%FC	0.82	1.25
	40%FC	2.98	1.26
	60%FC	2.73	1.02
	80%FC	1.57	1.09
MD	20%FC	1.57	1.21

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	40%FC	0.93	1.28
	60%FC	2.30	1.22
	80%FC	1.40	1.22
HD	20%FC	1.12	1.26
	40%FC	2.10	1.63
	60%FC	2.02	1.07
	80%FC	1.33	1.35

Table.6 Effects of factors on the Q10 of soil N mineralization

Variables	Factors	Degrees of freedom	F value	P
Q10	temperature	1	12.469	0.001
	moisture	3	4.49	0.005
	Degradation	3	0.517	0.672

(note:Significance levels $p < 0.001$)

4 Discussion

4.1 Effect of vegetation degradation on the rate of soil N mineralization

Vegetation degradation constitutes a significant manifestation of ecosystem decline, exerting profound impacts on ecosystem functions and nitrogen cycling processes (Liu et al., 2018). In this study, at cultivation temperatures of 15°C, 25°C, and 35°C, soil nitrogen mineralisation rates exhibited an increasing trend across four degradation levels as moisture content rose. However, when moisture content exceeded 60% field capacity (FC), further increases led to a decline in mineralisation rates, consistent with findings by Zhang et al. (2018). Within the 20%–60% FC range, moisture content enhanced soil nitrogen mineralisation rates; this primarily occurred because lower moisture content favoured nitrifying bacterial growth, thereby accelerating soil nitrogen transformation. Conversely, beyond this range, restricted oxygen diffusion and transport within the soil inhibit nitrifying bacterial proliferation, reducing nitrification rates and consequently diminishing overall mineralisation (Joergensen et al., 1990). Among the four soil degradation levels, the highest potential mineralisation capacity (4.77 $mg \cdot kg^{-1}$) was observed at 60% FC and 35°C . Although the nitrogen mineralisation reaction rate constant (k) showed no significant differences among soils with varying degradation levels under identical temperature conditions, the nitrogen mineralisation potential (N_0) exhibited marked variations; higher N_0 values correlated with faster mineralisation rates (Zand-Parsa et al., 2007). Temperature exerted a significant influence on nitrogen mineralisation rates across soils of varying degradation levels (Table 3), partially supporting our hypothesis. At all three incubation temperatures and moisture conditions, the nitrogen mineralisation rate in undisturbed (UD) soil typically peaked on the third incubation day before gradually declining. This pattern indicates that nitrogen mineralisation in undisturbed soils exhibits relatively low sensitivity to moisture fluctuations, potentially linked to their higher intrinsic moisture content. High moisture conditions accelerate nitrogen transformation by altering soil permeability, promoting soluble substance diffusion, and reshaping microbial communities. As incubation progresses, diminishing substrate availability leads to a corresponding reduction in nitrogen mineralisation rates (Agehara et al., 2005). In contrast, soils subjected to more severe vegetation degradation reached peak nitrogen mineralisation on day 7, with degradation intensity amplifying moisture's influence on this process; severely degraded soils exhibited the most pronounced response. Vegetation degradation markedly suppressed nitrogen mineralisation, with mineralisation rates either remaining constant or gradually declining throughout degradation, consistent with findings by Li et al. (2021). In densely vegetated wet meadows, soil disturbance caused by animal activity altered soil distribution, disrupted plant root systems, reduced microbial activity, and increased soil moisture evaporation (Wang, 2018). This lowered soil moisture content, enhanced soil permeability, and ultimately reduced nitrogen mineralisation rates.

4.2 Effect of soil temperature and moisture on the rate of soil N mineralization

Temperature significantly influences soil microbial activity, shaping microbial community structure and regulating soil nitrogen transformation processes (Wang et al., 2017). Nitrification and ammonification in soil nitrogen mineralization are known to be temperature-dependent, with higher temperatures boosting soil microbial activity and accelerating net nitrogen mineralization rates (Guntiñas M E et al., 2012). Our study observed a consistent increase in both the rate and quantity of soil nitrogen mineralization with rising temperatures, aligning with previous findings (Rustad et al., 2002), suggesting that elevated temperatures can enhance microbial activity and expedite nitrogen cycling. Moreover, at higher temperatures, the ratio of net nitrification to net nitrogen mineralization rose, indicating that thermophilic nitrifying bacteria, such as certain fungi and actinomycetes, exhibit optimal activity within the 25–35°C range (Macduff et al., 1985). Nevertheless, the response of soil nitrogen mineralization to varying temperature conditions displays variability. Specifically, as the incubation temperature increases, the soil nitrogen mineralization potential of the MD treatment group notably surpasses that of the UD, LD, and HD treatment groups. This disparity may be attributed to the heightened vegetation degradation in the MD treatment group, resulting in reduced ground vegetation cover, thereby stimulating microbial activity and enhancing enzymatic processes within microbial cells under elevated temperatures. The nitrogen mineralization quantity and rate derived from extended incubation at 25°C exceeded those at 15°C. This difference can be attributed to the rapid conversion of mineral nitrogen in the soil, given that nitrate nitrogen exhibits weak adsorption by soil colloids (Hu et al., 2018). Utilizing a first-order kinetic model (Table 3) further validates that elevated temperatures are associated with increased soil nitrogen mineralization potential (N). A notable enhancement is observed at 25°C compared to 15°C, with a subsequent rise at 35°C compared to 25°C, aligning with the conclusions drawn by Shan et al. (2018). Nevertheless, data simulations (Table 5) indicate that while soil nitrogen mineralization rates at 15°C and 25°C surpass those at 35°C, the rate does not exhibit a linear increment beyond the optimal temperature. This observation implies that at 35°C, microbial activity and decomposition functions may be impeded, consequently suppressing the nitrogen mineralization rate (Guntiñas M E et al., 2012). Moisture represents another pivotal factor influencing soil nitrogen mineralization by regulating soil aeration, the diffusion of soluble substrates, and the composition of microbial communities (Li et al., 2023). Studies have demonstrated that within the soil moisture range of 40% to 100% of field capacity (FC), nitrogen mineralization rates in forest and grassland soils increase with higher moisture levels (Rex et al., 2021). This underscores the substantial impact of moisture content on nitrogen mineralization rates (Table 3). It is noteworthy that under varying moisture content conditions, soil nitrogen mineralization rates peak between the third and seventh days with increasing indoor humidity and temperature. This temporal trend may be attributed to an initial pre-nitrification phase and heightened activity of nitrifying bacteria (Maslov et al., 2022). However, post the seventh day, nitrogen mineralization rates start to decrease, possibly due to nutrient depletion. These results indicate that soil nitrogen mineralization displays notable variability in response to changes in temperature and humidity levels across different stages of vegetation degradation.

4.3 Temperature sensitivity of soil N mineralization

The correlation between soil moisture and temperature significantly influences the nitrogen mineralization process. Experimental findings demonstrate that these factors collectively affect the temperature sensitivity of nitrogen mineralization. At lower temperatures (15°C), nitrogen mineralization rates were lower across all moisture gradients compared to higher temperatures (25°C and 35°C), indicating that elevated temperatures enhance nitrogen mineralization irrespective of moisture levels, consistent with Wang et al.(2006) previous research. Moreover, under low moisture levels (20% FC), nitrogen mineralization rates were lower across all temperature gradients compared to higher moisture levels (40% FC, 60% FC, and 80% FC). However, at elevated moisture levels (40% FC and 60% FC), nitrogen mineralization rates notably decreased. These outcomes suggest that nitrogen mineralization processes are restricted under both extremely low and high moisture conditions, with moderate moisture levels being optimal for mineralization. In the wet meadow areas of the Qinghai-Tibet Plateau, both low temperatures and abnormal soil moisture levels significantly affect microbial activity and nitrogen mineralization processes. As temperature rises (Table 5), the dependency of nitrogen mineralization rates on moisture content also increases. This trend is likely due to lower temperatures constraining soil microbial activity, thereby diminishing the nitrogen mineralization process's responsiveness to moisture variations. Conversely, with increasing temperature, the primary factor influencing nitrogen mineralization seems to transition from moisture to temperature, aligning with the observations of Xiao et al. (2023). A synergistic regulatory interplay exists between moisture and temperature, where elevated temperature can alleviate the detrimental impacts of excessive moisture on nitrogen mineralization. Beyond a soil moisture level of 60% field capacity (FC), further increments in moisture result in reduced nitrogen mineralization rates. Nevertheless, under the combined influence of moisture and temperature, rates recorded at 25°C and 35°C under moisture levels exceeding 60% FC were notably higher than those at 15°C. Moisture partially mitigates the inhibitory impact of low temperature on mineralization. Specifically, at 15°C, the nitrogen mineralization rate at 80% field capacity (FC) surpasses that at 40% FC. Conversely, at 25°C and 35°C, the rate at 80% FC gradually declines compared to that at 40% FC. Statistical analysis reveals that temperature exerts a more pronounced effect on nitrogen mineralization than moisture. This finding aligns with Gonçalves et al.(1994) observation that moisture's limitation on mineralization microorganisms is less severe than that of temperature. Furthermore, response surface analysis at the four degradation levels demonstrates that the interplay between moisture and temperature significantly impacts soil nitrogen mineralization. The temperature effect curve exhibits an initial rise followed by a decline. Response surface fitting analysis revealed distinct optimal moisture-temperature conditions for each soil degradation level: UD group (21.32°C, 69.52% FC), LD group (22.76°C, 50.00% FC), MD group (25.00°C, 50.00% FC), and HD group (20.50°C, 60.92% FC). The study delineated the optimal temperature range for soil nitrogen mineralization across the four degradation levels as 20.50°C to 25°C, with an ideal moisture content range of 50% to 70% of field capacity, aligning with the findings of Guntiñas M E et al. Additionally, these results are in agreement with previous research indicating a peak temperature sensitivity at 25°C and an ideal moisture content range of 80% to 100% of field capacity for nitrogen mineralization in various soil types. Notably, this study identified 60% FC as the inflection point for moisture content, with optimal conditions approximately 6.52% FC higher, possibly due to enhanced soil moisture and vegetation growth in the UD group, mitigating the impact of lower temperatures on microbial and enzymatic activity associated with mineralization processes. Augmenting moisture levels can counteract the suppressive effect of low temperatures on microbial and enzymatic functions (Cheng et al., 2012). Under low (LD) and moderate (MD) degradation conditions characterized by high temperatures and poor vegetation growth, optimal moisture content conditions were observed below the moisture content inflection point. Maintaining moisture content below 60% of field capacity (FC) under these conditions resulted in maximizing soil nitrogen (N)

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mineralization rates with increasing temperature. Elevated temperatures were found to counterbalance the negative impacts of excessive or insufficient moisture levels, indicating a synergistic relationship between temperature and soil nitrogen mineralization, while moisture exhibited an antagonistic effect. This study determined the optimal temperature and moisture parameters for enhancing soil nitrogen mineralization across four degradation levels. Soil N mineralization was most responsive to temperatures ranging from 20.50 to 25°C, with the ideal moisture range falling between 50% and 69.52% FC. Throughout the experiment, when moisture levels were optimal, they surpassed the inflection point. As temperatures exceeded the optimal range by 9.52% FC, the regulatory influence of moisture became more pronounced. Even when not within the optimal range, moisture continued to exert its crucial regulatory function, supporting the hypothesis that temperature exerts a greater impact on soil nitrogen mineralization rates compared to moisture. In diverse soil types and environmental settings, temperature and moisture collaboratively influence soil nitrogen mineralization through synergistic and antagonistic interactions (Xiao et al., 2023).

The Q10 value, indicating an exponential increase in soil nitrogen mineralization rates with a 10°C temperature rise, serves as a crucial indicator of soil nitrogen's temperature sensitivity and a key parameter for evaluating soil nitrogen transformation under future climate scenarios (Liu et al., 2020). Soil nitrogen mineralization processes in various ecosystems display distinct responses to temperature variations. This study established Q10 value ranges for four degradation levels: 1.73 to 2.37, .82 to 2.98, .93 to 2.30, and 1.12 to 2.10. As temperatures rise, the exponential growth in net soil nitrogen mineralization rates diminishes progressively across the four wetland degradation levels, aligning with Koch et al.(2007) findings. Higher Q10 values indicate that temperatures significantly boost nitrogen mineralization rates in degraded GaHa wetland grassland soils within the 15–25°C range. However, in the 25–35°C range, while temperature continues to enhance nitrogen mineralization, the impact is less pronounced. This suggests that nitrogen mineralization rates in GaHa wetland grassland soils are more responsive to temperature changes within the 15–25°C range. Consequently, while moderate disturbance can enhance the nitrogen mineralization potential of high-altitude wetland soils, this effect is constrained, implying a certain level of resilience in high-altitude wetland ecosystems to minor external perturbations.

5 Conclusions

Temperature and moisture conditions significantly affected soil N mineralization rates. Vegetation degradation significantly inhibited the soil N mineralization process, and the N mineralization rate remained constant or gradually decreased with increasing degradation. Moisture conditions had a greater effect on soil N mineralization rate in UD, and temperature had a greater effect on N mineralization rate in MD. Q10 values varied between 1.73-2.37, 0.82-2.98, 0.93-2.30, and 1.12-2.01 for the four different degradation levels respectively, soil N mineralization rate in the QTP wet meadow were more responsive to the sensitivity of temperature between 15-25°C. Soil N mineralization rate was promoted by increasing moisture in the moisture range of 20%FC to 60%FC, whereas increasing moisture above 60%FC inhibited the N mineralization process. At 25°C, N0 at 60% FC was 1.33-1.78 times higher than 20% FC at the four degradation gradients, and N0 at 60%FC was 0.24-0.83 times higher than 80%FC. Data fitting yielded optimum water temperature conditions for soil N mineralization rates at different levels of degradation between 20.50-25°C and 50-69.52%FC, respectively. At 25°C, the rate of N mineralization across the degradation gradient was maximum at 60% FC, which was 4.73 mg·kg-1(UD), 4.53mg·kg-1(LD), 3.81mg·kg-1 (MD), 3.79 mg·kg-1(HD). The validation revealed that temperature had a higher effect on soil

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N mineralization rate than moisture.Temperature and soil moisture have synergistic and antagonistic effects on soil N mineralization, depending on soil type and climatic conditions.

CRediT authorship contribution statement

Yiqiu Wang: conceptualization, data curation, formal analysis, methodology, software, visualization,writing-review & editing. Weiwei Ma:conceptualization, methodology, funding acquisition, supervision, writing-review & editing. Shuzhuo Li: supervision, validation. Jianfang Wang:data curation, formal analysis.Jianan Du: data curation, formal analysis, software.Wanpeng He: data curation, formal analysis, investigation.Wenhua Chang: data curation, formal analysis.Jiachen Chang: data curation, resources.Guang Li:data curation, resources.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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