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A global synthesis of the rate and temperature sensitivity of soil nitrogen mineralization: latitudinal patterns and mechanisms

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Abstract

Soil net nitrogen (N) mineralization (N_{min}) is a pivotal process in the global N cycle regulating the N availability of plant growth. Understanding the spatial patterns of $N_{min,}$ its temperature sensitivity (Q_{10}) and regulatory mechanisms is critical for improving the management of soil nutrients. In this study, we evaluated 379 peer-reviewed scientific papers to explore how N_{min} and the Q_{10} of N_{min} varied among different ecosystems and regions at the global scale. The results showed that N_{min} varied significantly among different ecosystems with a global average of 2.41 mg N soil kg^{-1} day^{-1}. Furthermore, N_{min} significantly decreased with increasing latitude and altitude. The Q_{10} varied significantly among different ecosystems with a global average of 2.21, ranging from the highest found in forest soils (2.43) and the lowest found for grassland soils (1.67) and significantly increased with increasing latitude. Path analyses indicated that N_{min} was primarily affected by the content of soil organic carbon (C), soil C:N ratio, and clay content, where Q_{10} was primarily influenced by the soil C:N ratio and soil pH. Furthermore, the activation energy (E_a) of soil N mineralization was significantly and negative correlated with the substrate quality index among all ecosystems, indicating the applicability of the carbon quality temperature hypothesis to soil N mineralization at a global scale. These findings provided empirical evidence supporting that soil N availability, under global warming scenarios, is expected to increase stronger in colder regions as compared with that low-latitude regions due to the higher Q_{10}. This may alleviate the restriction of N supply for increased primary productivity at higher latitudes.

Keywords: activation energy, global pattern, mechanism, mineralization, nitrogen availability, substrate quality, temperature sensitivity

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Introduction

Nitrogen (N) availability is a crucial factor limiting primary productivity in many terrestrial ecosystems (Vitousek & Howarth, 1991; Reich *et al.*, 2006; Elser *et al.*, 2007; Yahdjian *et al.*, 2011) by regulating plant growth and affecting plant species competition (Perakis & Kellogg, 2006; Cole *et al.*, 2008). In most ecosystems, the N availability of plants largely depends on the quantity of soil net N mineralization (N_{min}), in which soil organic N is converted to inorganic N by soil microorganisms and small animals (Chapin *et al.*, 2011). Some studies have demonstrated that N_{min} exhibits high spatial and temporal heterogeneity (Knoepp & Swank, 1998), which is regulated by several factors, such as temperature (Guntinas *et al.*, 2012), moisture (Paul *et al.*, 2003), and land-use type (Templer *et al.*, 2005). Given the dynamic global climate changes, with expected increases in global temperature by at least 2 °C by the end of the 21st century (IPCC, 2013), this change in temperature is expected to significantly affect N_{min} and soil N availability, which may influence plant growth and primary productivity in terrestrial ecosystems (IPCC, 2013). However, the pattern of N_{min} at the global scale is unclear, and only a few studies on N_{min} have been conducted at the continental scale (Colman & Schimel, 2013; Liu *et al.*, 2016). Determining whether

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the driving factors for N_{min} are similar at regional and global scales is essential for us understanding of the regulatory mechanisms of N_{min} and is critical for the estimation of soil N availability in natural or anthropogenic ecosystems.

The temperature sensitivity (Q_{10}) of N_{min} is commonly defined as the factor by which N_{min} increases with a 10 °C rise in temperature (Kirschbaum, 1995). This parameter is important to evaluate the feedback of soil N availability in response to climate warming scenarios (Kirschbaum, 1995; Koch *et al*., 2007). Individual studies have shown that Q_{10} varies with vegetation type (Liu *et al*., 2016), substrate quality (Updegraff *et al*., 1995; Koch *et al*., 2007), soil temperature, soil moisture (Kirschbaum, 1995; Sierra, 1997), and soil texture (Zimmermann *et al*., 2012). In natural ecosystems, these factors are spatially heterogeneous and may result in spatial variations in Q_{10} values. However, scientists have commonly considered Q_{10} to be a constant in many models (Manzoni & Porporato, 2009; Wang *et al*., 2010), leading to high levels of uncertainty in projection of feedback between the terrestrial ecosystem N cycle and climate change. At the regional or global scale, some studies have reported the effects of climatic factors, measurement methods, and vegetation types on the Q_{10} of soil N mineralization (Peng *et al*., 2009; Colman & Schimel, 2013; Liu *et al*., 2016). However, no comprehensive evaluation of the spatial variations of Q_{10} with geographic variables has been performed to date. Understanding the geographic patterns and regulatory mechanisms of Q_{10} at a global scale is crucial for better exploring the response of soil N cycling under the scenario of global warming.

As the decomposition of soil organic matter (SOM) is largely affected by substrate quality (Fierer *et al*., 2005), according to enzyme kinetics, SOM that is more biochemically recalcitrant has a higher Q_{10} value (Xu *et al*., 2010). On the basis of the Arrhenius equation, the values of Q_{10} may increase with increasing activation energy (E_a) of a chemical reaction (Arrhenius, 1889). Therefore, the enzymatic decomposition of biochemically recalcitrant substrates (higher requirement of E_a) should generally be more sensitive to temperature changes than that of more labile substrates (high-quality substrates) (Craine *et al*., 2010), resulting in an inverse relationship between substrate quality and Q_{10}, also referred to as the carbon quality temperature (CQT) hypothesis (Fierer *et al*., 2005; Davidson & Janssens, 2006). Other studies have supported the CQT hypothesis for litter decomposition, soil carbon (C) mineralization in laboratory incubation experiments, and soil respiration in the field (Davidson & Janssens, 2006; Craine *et al*., 2010; Quan *et al*., 2014; Wang *et al*., 2014; Li *et al*., 2015). Because soil C and N mineralization are closely coupled (Gilmour *et al*., 1985; Quan *et al*., 2014), and the substrate quality of C mineralization is positively correlated with the substrate quality of N mineralization (Koch *et al*., 2007), we assumed that N_{min} would also be subjected to CQT hypothesis. Because labile substrates [such as dissolved organic carbon (DOC)] gradually decrease with increasing altitude (Gutiérrez-Girón *et al*., 2015), we assumed that the Q_{10} values of N_{min} would increase at higher latitudes worldwide in response to changes in organic substrate quality.

To better understand how N_{min} and its Q_{10} vary among different ecosystems and regions at the global scale, a global dataset of N_{min} in laboratory incubation experiments was collected. Specifically, the main objectives of this study were to analyze the spatial patterns and influencing factors of N_{min} and its Q_{10} at global scale and to verify the mechanisms controlling Q_{10} with respect to soil substrate quality and soil microorganisms.

Materials and methods

Literature survey and data extraction

Soil net N mineralization (N_{min}) is the balance of soil gross N mineralization and soil gross immobilization, which is calculated as the change in NH_4^+-N plus NO_3^--N during incubation and is used to describe soil N availability for plants (Stanford & Smith, 1972). In this study, peer-reviewed papers on N_{min} under laboratory incubation experiments were collected from the Web of Science (www.webofknowledge.com) and China National Knowledge Infrastructure (http://epub.cnki.net) from 1980 to 2015. A total of 379 papers describing N_{min} and 54 papers describing temperature sensitivity (Q_{10}) of N_{min} were collected.

The original data of N_{min} were first extracted from reported tables or graphs using GetData Graph Digitizer software (http://getdata-graph-digitizer.com) or calculated using the change in NH_4^+-N plus NO_3^--N during incubation. At the same time, other auxiliary data, such as geographic information (latitude, longitude, and altitude), climate information (mean annual air temperature [MAT] and mean annual precipitation [MAP]), soil texture (sand, silt, and clay fractions), soil chemical properties (soil pH, soil organic C [SOC], soil total N [TN], soil C:N ratio, soil DOC, soil dissolved organic N, and soil initial inorganic N [NO_3^--N and NH_4^+-N]), and soil microbial properties (microbial biomass C [MBC], microbial biomass N [MBN], and MBC:MBN ratio) were collected from the same literature.

Data assembly

To explore the spatial patterns and influencing factors of the potential N_{min} under optimal conditions, data stemming from optimal laboratory incubation at 20–30 °C and 60–80% field capacity for 2 weeks were used to determine the N_{min} and

Q_{10}. Soil mineral N was extracted with 0.05 M K_2SO_4. In total, 506 datasets from 379 publications were selected to identify data for N_{min} (Appendix S1), and 123 datasets from 54 publications were selected for the analysis of Q_{10} (Appendix S1).

All sites were classified into different ecosystems according to the dominant vegetation composition (e.g., croplands, grasslands, forests, shrub lands, wetlands, and tundra). Overall, these sites spanned from 46.32°S to 68.63°N in latitude and from 159.5°W to 175.97°E in longitude across the Asian (201 sites), European (108 sites), North American (131 sites), South American (13 sites), African (15 sites), and Oceanian regions (38 sites). These sites covered five major climate zones, that is, tropical, subtropical, temperate, boreal, and subarctic, and included eight biomes, that is, evergreen broad-leaved forests (17 sites), evergreen needle-leaved forests (31 sites), deciduous broad-leaved forests (nine sites), tropical forest (three sites), grasslands (68 sites), croplands (338 sites), shrub lands (21 sites), and wetlands (11 sites), as shown in Fig. 1.

Data calculations

Q_{10} data were selected to reflect the responses of N_{min} as the temperature increased by 10 °C and were calculated according to Eqn 1 (Fissore *et al.*, 2013):

$$Q_{10} = (N_2/N_1)^{[10/(T_2-T_1)]} \qquad (1)$$

where N_1 and N_2 are the soil net N mineralization rate (mg N soil kg^{-1} day^{-1}) at incubation temperatures T_1 and T_2 (°C), respectively.

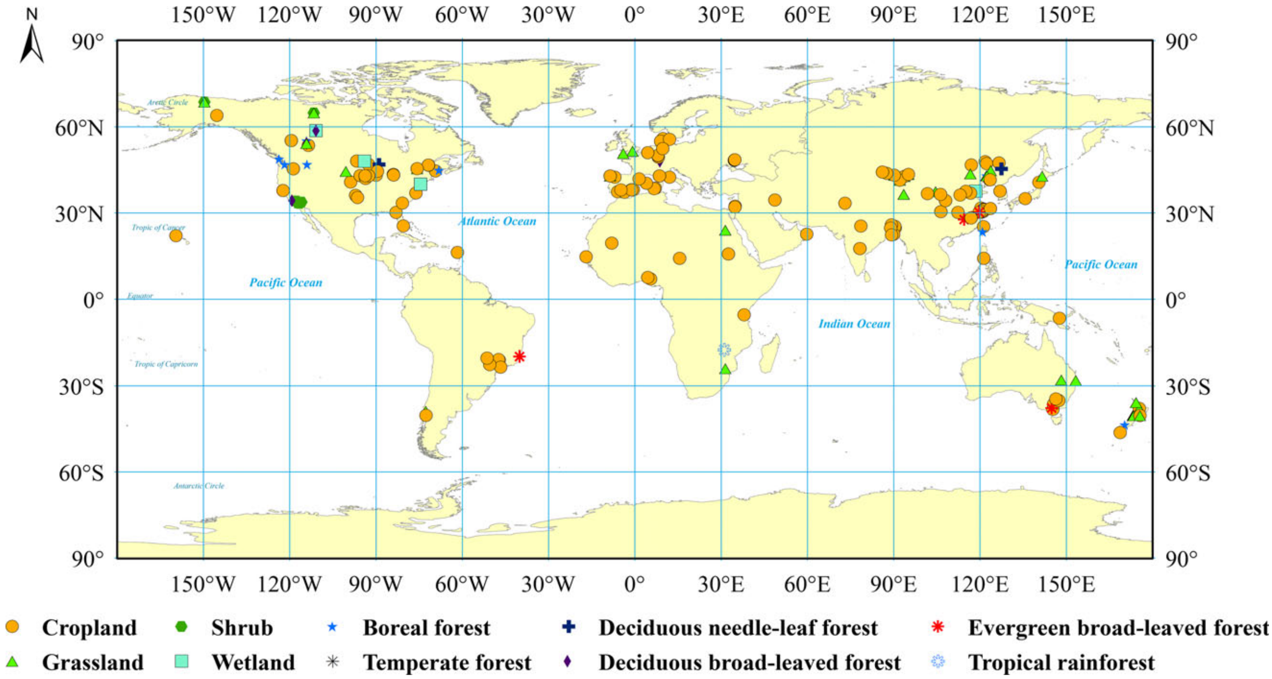

Fig. 1 Distribution of the studying sites in different ecosystems on the global scale.

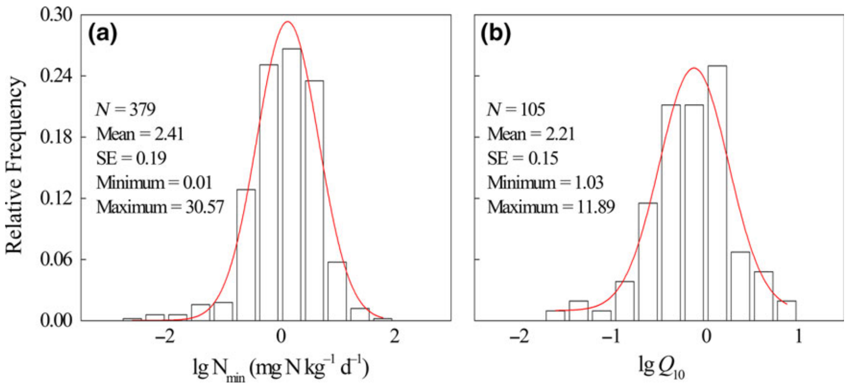

Fig. 2 Frequency distributions of soil net nitrogen mineralization (N_{min}, a) and temperature sensitivity (Q_{10}, b) on the global scale.

To determine whether the CQT hypothesis was applicable to N_{min} at the global scale, we calculated the activation energy (E_a) of N_{min} according to Eqn 3 (Craine *et al.*, 2010):

$$N = A \times e^{\frac{-E_a}{RT}} \quad (2)$$

$$E_a = N \times \ln(Q_{10})/(\frac{1}{T_1} - \frac{1}{T_2}) \quad (3)$$

where N represents the soil net N mineralization rate (mg N soil kg^{-1} day^{-1}), A is an exponential fit parameter, R is the gas constant (8.314 J mol^{-1} K^{-1}), and T_1 and T_2 are temperatures (K) indicating the 10 °C temperature range for the corresponding Q_{10}.

The parameter A in Eqn 2 was used to represent substrate quality, providing an index of overall substrate quality (availability and lability) of SOM that is catabolized by soil microorganisms at a given point in time (Fierer *et al.*, 2005; Koch *et al.*, 2007).

Statistical analysis

The normality of the data was evaluated using the Kolmogorov–Smirnov test, and logarithmic transformation was used to stabilize the distribution to approximate normality when the data did not exhibit normal distribution. Differences in N_{min} and Q_{10} among different ecosystems and regions were tested using one-way analysis of variance (ANOVA), with least significant differences for multiple comparisons. Regression and correlation analyses were used to determine the associations of climate factors, soil properties, and microbial properties with N_{min} and Q_{10}. The best-fitted functions were determined using the Akaike information criterion and Bayesian information criterion (Aho *et al.*, 2014). Additionally, path analyses were used to discriminate the direct and indirect factors influencing N_{min} and Q_{10}. All statistical analyses were conducted using SPSS software (SPSS for Windows, Version 13.0; Chicago, IL, USA). Graphs were drawn using Origin software (Version 8.5; Northampton, MA, USA) and ERSI ArcGIS software (Version 10.1; Redlands, CA, USA). Differences with P values <0.05 were considered significant.

Results

Spatial patterns and factors influencing N_{min}

N_{min} varied widely on the global scale, ranging from 0.01 to 30.57 mg N soil kg^{-1} day^{-1}, with an average of 2.41 mg N soil kg^{-1} day^{-1} (Fig. 2a). Additionally, N_{min} differed significantly among different regions, ranging from an average of 1.6 mg N soil kg^{-1} day^{-1} in North America to 2.72 mg N soil kg^{-1} day^{-1} in Asia (Table 1). Furthermore, N_{min} differed significantly among ecosystems (P < 0.05), with the lowest observed in soils of shrub ecosystems (0.4 mg N soil kg^{-1} day^{-1}) and the highest observed in soils of wetland ecosystems (6.1 mg N soil kg^{-1} day^{-1}; Table 1, Fig. 3a).

Table 1 Statistics of soil net nitrogen mineralization (N_{min}) in different ecosystems and regions

N_{min}	Cropland			Grassland			Forest			Wetland			Shrub			Total			
	Mean	SE	*N*†	Mean	SE	*N*	Mean	SE	*N*	Mean	SE	*N*	Mean	SE	*N*	Mean	SE	*N*	*P* value
North American	1.46	0.16	75	0.99	0.18	15	2.39	0.73	11	7.10	1.90	9	0.40	0.08	21	1.60	0.21	131	0.01
South American	2.14	0.49	8	3.18	–	1	0.78	0.01	4	–	–	None	–	–	None	1.80	0.36	13	0.04
European	2.19	0.26	80	3.25	0.65	12	2.77	0.66	15	2.90	–	1	–	–	None	2.40	0.23	108	0.39
African	2.41	0.68	9	1.15	0.29	4	0.49	–	1	–	–	None	–	–	None	1.87	0.46	14	0.35
Asian	2.96	0.34	157	0.82	0.15	20	2.40	0.41	24	0.27	–	1	–	–	None	2.72	0.28	202	0.23
Oceanian	0.88	0.19	14	2.62	0.45	16	2.49	0.65	8	–	–	None	–	–	None	1.95	0.27	38	0.01
Global	2.59	0.26	343	1.76	0.20	68	2.16	0.27	63	6.10	1.69	11	0.40	0.08	21	2.41	0.19	506	0.01

†*N* represents the number of study site, – represents none value, the ecosystem type that only has one observation did not involve in the statistical analysis.

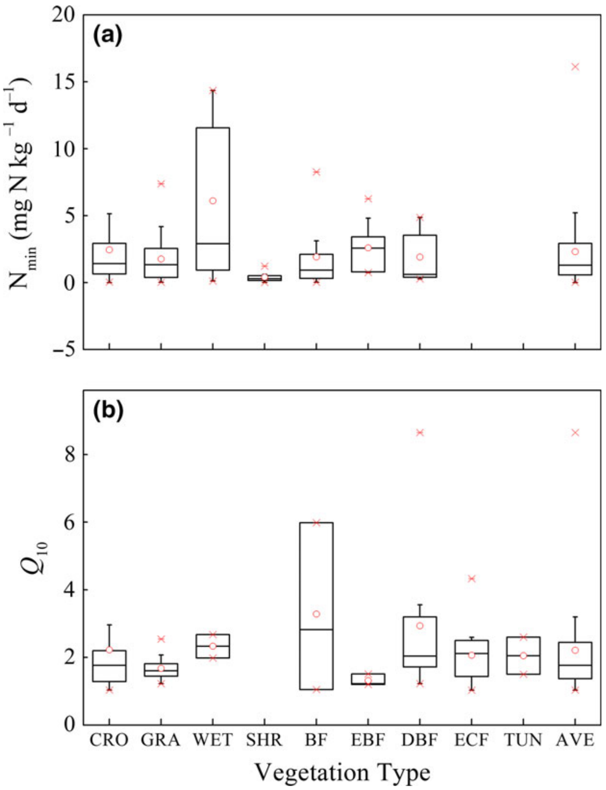

Fig. 3 Changes in soil net nitrogen mineralization (N_{min}) and temperature sensitivity (Q_{10}) among different ecosystems on the global scale. The boxes show the 25% and 75% percentiles, and the lines and red dots represent the mean and median, respectively. CRO, cropland; GRA, grassland; WET, wetland; SHR, shrub; BF, boreal forest; EBF, evergreen broadleaved forest; DBF, deciduous broadleaved forest; ECF, evergreen coniferous forest; TUN, tundra; AVE, average value.

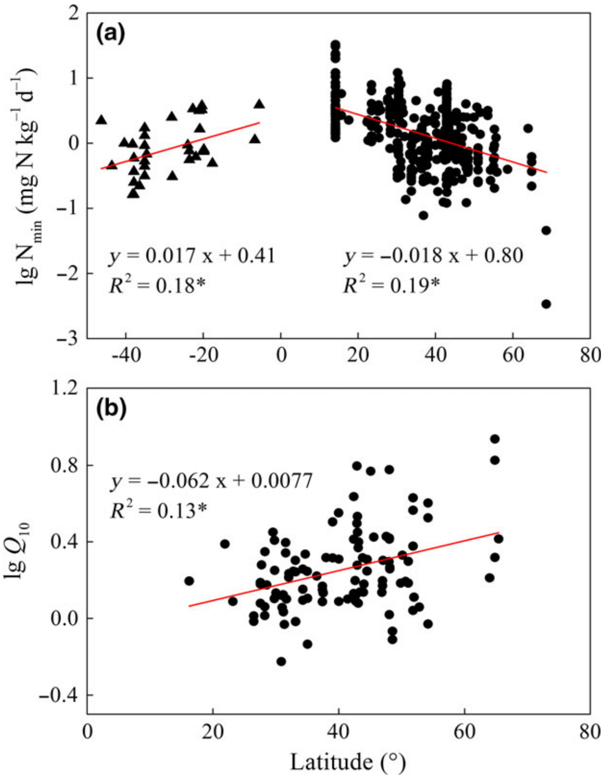

Fig. 4 Latitude patterns of soil net nitrogen mineralization (N_{min}) and temperature sensitivity (Q_{10}) with increasing latitude.

N_{min} was negatively correlated with latitude ($P < 0.05$, Fig. 4a), irrespective of the Northern Hemisphere and Southern Hemisphere. Furthermore, N_{min} decreased significantly with increasing altitude at the global scale (Fig. S2).

The correlation matrix analysis showed that N_{min} was significantly influenced by multiple factors (Table 3). Climate (MAT and MAP), soil texture (clay content), soil chemical properties (SOC, TN, and initial NH_4^+-N concentration), and soil microbial properties (MBC and MBN) were positively correlated with N_{min}, whereas soil pH, soil C:N ratio, soil MBC:MBN ratio, and soil initial NO_3^--N concentration were negatively correlated with N_{min} (Fig. S5). The results of path analysis indicated that SOC, soil C: N ratio, soil pH, and soil clay fraction were direct factors influencing N_{min}, together explaining 30% of the variation in N_{min} (Fig. 6a). MAT and MAP affected the N_{min} indirectly due to long-term effects on soil physical and chemical properties as well as the microbial community composition.

Spatial variations and main factors influencing Q_{10}

The Q_{10} values of N_{min} varied from 1.03 to 11.89, with an average of 2.21 (Fig. 2b and Table 2). The mean Q_{10} was not significantly different among different regions (Table 2). However, Q_{10} differed significantly among different ecosystems ($P < 0.05$; Table 2). Soils of forest ecosystems had the highest Q_{10}, while soils of grassland ecosystems had the lowest Q_{10} (Fig. 3b and Table 2). Furthermore, the values of Q_{10} increased significantly with latitude in the Northern Hemisphere (Fig. 4b; such an analysis was not conducted in the Southern Hemisphere due to insufficiency data for Q_{10}).

The Q_{10} values were positively correlated with SOC, soil silt content, and soil C:N ratio, and negatively correlated with soil pH, soil sand content, and initial inorganic N content (Fig. 5 and Table 4). Path analysis indicated that soil pH was the most important direct factor influencing Q_{10}, accounting for 67% of the variation in Q_{10} (Fig. 6b). Together, SOC content, soil clay content, soil pH, and soil C:N ratio explained 94% of the variation in Q_{10} (Fig. 6b).

Table 2 Changes in the temperature sensitivity (Q_{10}) of N_{min} in different ecosystems and regions

	Cropland			Grassland			Forest			Total			
Q_{10}	Mean	SE	*N*†	Mean	SE	*N*	Mean	SE	*N*	Mean	SE	*N*	*P* value
North American	1.61	0.15	10	2.54	–	1	3.34	0.70	12	2.55	0.40	23	0.038*
South American	2.20	0.77	2	1.57	–	1	2.40	1.17	2	2.15	0.47	5	0.90
European	2.42	0.42	12	1.86	–	1	2.04	0.19	5	2.28	0.28	19	0.58
Asian	1.85	0.26	20	1.60	0.07	13	1.90	0.21	17	1.80	0.12	50	0.63
Oceanian	2.80	0.76	3	–	–	None	–	–	None	2.80	0.76	3	–
Global	2.02	0.16	47	1.67	0.08	16	2.43	0.27	36	2.21	0.16	100	0.12

†*N* represents the number of study site, – represents none value, the ecosystem type that only has one observation did not involve in the statistical analysis.

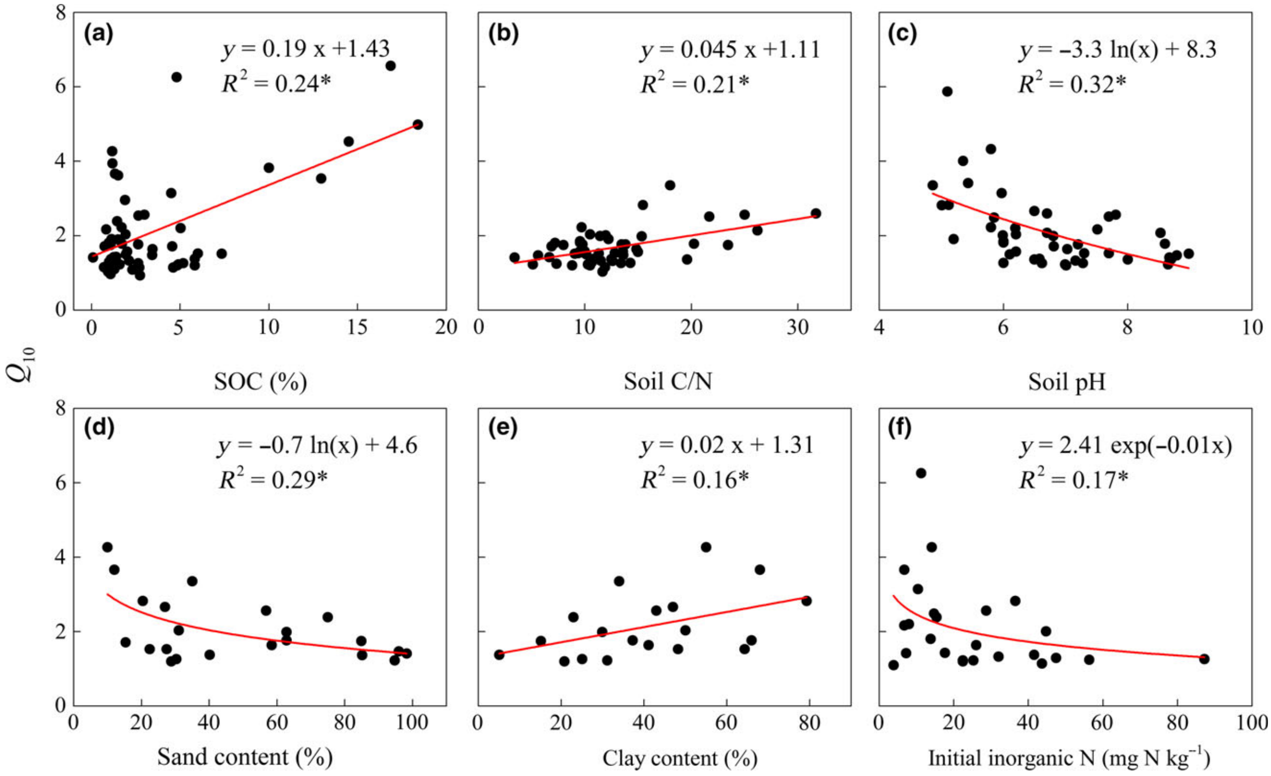

Fig. 5 Relationships between the temperature sensitivity (Q_{10}) of N_{min} and soil properties.

Activation energy (E_a) of N_{min} was significantly negatively correlated with substrate quality index (*A*) among cropland, grassland, and forest ecosystems (Fig. 7), indicating that there was a relationship between E_a and the substrate quality index for most of ecosystems.

Discussion

Global patterns of soil N_{min}

N_{min} varied significantly among different ecosystems. The highest value was observed in soils of wetland ecosystems (average 7.1 mg soil kg^{-1} day^{-1}), and the lowest occurred in soils of shrubland ecosystems (average 0.4 mg kg^{-1} day^{-1}). Differences in litter composition and microbial composition were expected to cause differences in N_{min} among various ecosystems (Chapin *et al.*, 2011). The lowest N_{min} in shrubland ecosystems may be caused by the lower microbial biomass observed in shrubland ecosystems than in other ecosystems (Colman & Schimel, 2013). The *in situ* decomposition of SOM in wetlands was slow due to waterlogging anoxic/acidic conditions, resulting in accumulation of SOM (Bai *et al.*, 2012). When incubated under optimal conditions (optimal temperature and soil

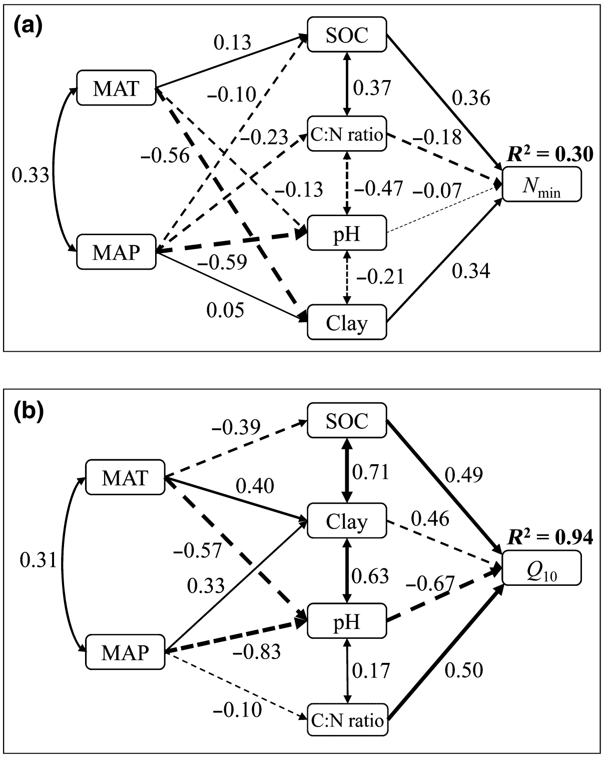

Fig. 6 Path analysis of the effects of climatic variables and soil properties on the latitude variations of soil net nitrogen mineralization (N_{min}) and temperature sensitivity (Q_{10}). Solid and dashed arrows represented the positive and negative effects in a fitted structural equation model, respectively. Line thickness indicates the strength of the effects of variables on each other. Models satisfactorily fitted to our data, as suggested by the χ^2 and RMSEA values [$\chi^2 = 11.1$ ($P = 0.435$), RMSEA = 0.021, df = 11 in N_{min}; and $\chi^2 = 6.24$ ($P = 0.795$), RMSEA = 0, df = 10 in Q_{10}).

moisture), without excessive limitation for microbial activity, the N_{min} is expected to be higher than that in other ecosystems due to the richer SOM. At the global scale, N_{min} decreased with both latitude and altitude, consistent with a previous study conducted in China (Liu *et al.*, 2016).

Spatial heterogeneity in climate conditions can lead to dramatic variations in soil properties at the global scale, such as changes in the concentrations of C, N, and P and in soil microbial biomass (Xu *et al.*, 2013). In this study, soil physical and chemical properties as well as microbial biomass exhibited latitudinal patterns (Figs S3 and S4). Moreover, both SOC and soil TN contents have been shown to be higher in soils with a higher clay content (Spain, 1990). Additionally, loam and clay soils always have higher bacteria biomasses than sandy soils (Hassinld *et al.*, 1993). Therefore, the decreased clay content with increasing latitude may reduce microbial biomass, indirectly affecting N_{min} (Sollins *et al.*, 1996; Santruckova *et al.*, 2003). Additionally, soil microbial biomass is a pivotal indicator of global nutrient cycling (Li *et al.*, 2014). Generally, N_{min} is positively correlated with MBC and MBN (Hu *et al.*, 2008). Many studies have demonstrated that higher N_{min} always correspond to higher soil microbial biomass (Hatch *et al.*, 2000). Furthermore, soil microbial biomass itself is an important pool of readily mineralized organic N in soils (Bonde *et al.*, 1988). In this study, MBC and MBN significantly decreased with both latitude and altitude, mainly due to the low temperatures at higher latitudes and altitudes (Rustad *et al.*, 2001), resulting in a decreased N_{min} values with increasing latitude and altitude. Additionally, substrate quality also regulates N_{min}. Higher quality compounds always correspond to lower soil C:N ratios and thus are more easily decomposed by microbes (Bengtsson *et al.*, 2003). The C:N ratio of SOM increased significantly with increasing latitude, indirectly explaining the lower N_{min} at higher latitudes and altitudes observed in this study.

Global patterns of Q_{10} of soil N_{min}

The mean Q_{10} for all ecosystems (2.41) obtained in this study was similar to that estimated for soil C mineralization of global terrestrial ecosystems (Raich & Schlesinger, 1992). Boreal forests have the highest Q_{10}, indicating that boreal forests should respond more dramatically to predicted increases in temperature, which are supposed to have higher N availability at high latitudes (IPCC, 2013, Xu *et al.*, 2015). This observation may be associated with the geographic conditions, climatic conditions, and vegetation composition of boreal forests. Because boreal forests are mainly distributed in the northern region and are comprised of coniferous or needle vegetation, their litter contains more recalcitrant components than those of other forests, which would increase the energy requirement for microbial decomposition and thus enhance the Q_{10} values (Xu *et al.*, 2015).

At the global scale, the values of Q_{10} increased significantly with increasing latitude (increase of 0.0422 per °), indicating that a rise in temperature would dramatically enhance the N_{min} at higher latitudes. As described previously (Vanhala *et al.*, 2008), Q_{10} may be affected by different soil properties, resulting from different climatic conditions and vegetation compositions. Path analysis further showed that Q_{10} was mainly influenced by SOC content, soil clay content, soil pH, and soil C:N ratio. The labile pool of SOC provides important substrates for microbial metabolism. Therefore, the change in SOC content affects soil microbial activities, causing the temperature response of N_{min} to vary among soils with different SOC contents (Zheng *et al.*, 2009). In addition, the composition of the microbial community

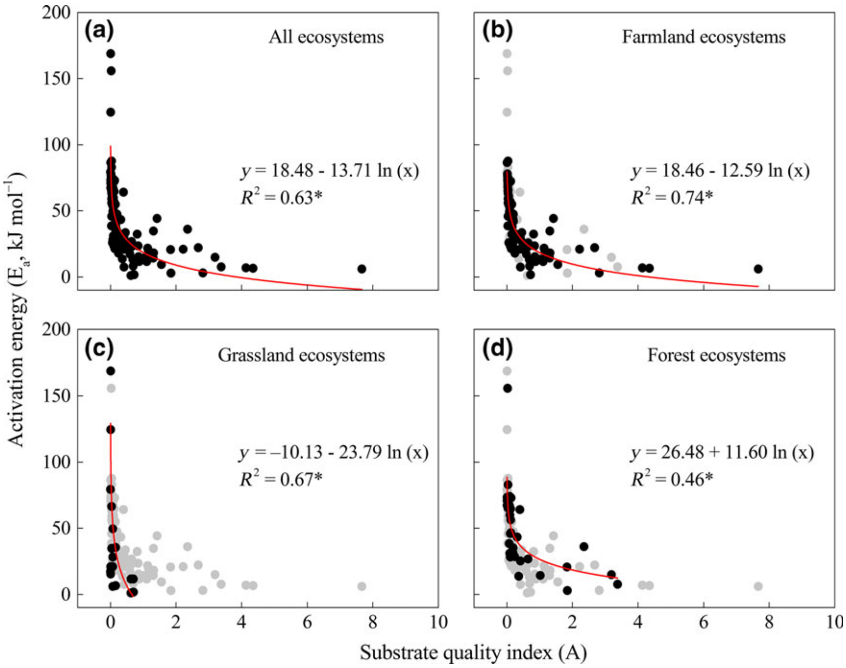

Fig. 7 Relationships between activation energy (E_a) of soil net nitrogen mineralization (N_{min}) and substrate quality index (A) for different ecosystem types.

Table 3 Correlation coefficients between soil net nitrogen mineralization (N_{min}) with climatic variables and soil properties

	Climatic variables		Soil properties					
	MAP	MAT	Sand	Silt	Clay	Soil pH	SOC	Soil C: N ratio
MAT	0.33*							
Sand	−0.13	0.42*						
Silt	0.34*	−0.068	−0.71*					
Clay	−0.13	−0.52*	−0.73*	0.054				
Soil pH	−0.56*	−0.078	0.022	0.044	−0.078			
SOC	−0.051	0.081	−0.083	0.054	0.080	−0.12		
Soil C: N ratio	0.42*	0.023	0.13	−0.071	−0.12	−0.64*	0.34*	
N_{min}	0.0064	0.0078	−0.23	−0.050	0.34*	−0.24*	0.44*	−0.29*

MAT, mean annual air temperature; MAP, mean annual precipitation; SOC, soil organic carbon.
*Significant at $P < 0.05$ level.

Table 4 Correlation coefficients between the temperature sensitivity (Q_{10}) with climatic variables and soil properties

	Climatic variables		Soil property					
	MAP	MAT	Sand	Silt	Clay	Soil pH	SOC	Soil C:N ratio
MAT	0.31*							
Sand	−0.62*	−0.45*						
Silt	−0.26	−0.068	−0.53*					
Clay	0.59*	0.50*	−0.59*	−0.31				
Soil pH	−0.40*	−0.13	0.74*	−0.15	−0.11			
SOC	−0.27	−0.54*	0.74*	−0.75*	0.15	−0.45*		
Soil C: N ratio	−0.19	−0.45*	−0.15	0.019	−0.31	−0.030	0.79*	
Q_{10}	−0.15	0.019	−0.48*	0.46*	−0.25	−0.55*	0.49*	0.53*

MAT, mean annual temperature; MAP, mean annual precipitation; SOC, soil organic carbon.
*Significant at $P < 0.05$ level.

is linked with quality and quantity of SOC; thus, the temperature response of N_{min} decreases with a decrease in SOC (Fierer *et al*., 2005). Generally, the soil C:N ratio is considered to be a good indicator of soil quality (Sollins *et al*., 1996). SOM with a higher C:N ratio, for example, derived from litter of boreal forests, is considered a low-quality or recalcitrant substrate. Earlier studies have demonstrated that the activation energy of SOM decomposition (positively related to Q_{10}) increases with increasing molecular complexity of the substrate (Bosatta & Agren, 1999). Therefore, the significant increase in the soil C:N ratio with increasing latitude could partially explain the higher Q_{10} values at higher latitude (Bengtsson *et al*., 2003). In addition, soil pH significantly affects the Q_{10} through its effect on the composition and enzyme activity of microbial communities and substrate availability (Priha *et al*., 2001). Moreover, pH indirectly controls the N_{min} by influencing the redox equilibriums of the soil (Kader *et al*., 2013). Furthermore, the lower Q_{10} values at lower latitude may result from the long-term adaptation of microorganisms to the increased temperatures in these regions (Santruckova *et al*., 2003; Barcenas-Moreno *et al*., 2009).

Kinetic theory may explain the global patterns of N_{min} and Q_{10}

How SOM decomposition responds to temperature changes may be explained by the kinetic theory of Arrhenius-type reactions (Arrhenius, 1889), wherein the increase in decomposition rate with increasing temperature under substrate availability and enzyme activity is not constrained by the reaction rate. Kinetic theory also suggests that organic compounds with low quality (i.e., those that require a higher E_a) should exhibit a higher proportional increase in reaction rate compared with higher quality organic compounds.

The theoretical explanation for the decrease in Q_{10} with increasing temperature is that as the temperature increases, there is a declining relative increase in the fraction of molecules with sufficient energy to react (Davidson & Janssens, 2006). However, several studies have reported that decomposition rates of low-quality SOM (i.e., recalcitrant substrates) have a higher Q_{10} compared with those of higher quality and rapidly decomposing compounds (i.e., labile substrates) (Fierer *et al*., 2005; Davidson & Janssens, 2006; Craine *et al*., 2010; Erhagen *et al*., 2013). To date, differences in the temperature responses of labile substrates and recalcitrant substrates have not been clearly clarified (Giardina & Ryan, 2000; Fang *et al*., 2005). In our study, the E_a of the N_{min} and substrate quality index were significantly negatively correlated among forests, grasslands, and croplands at the global scale, which verified that the CQT hypothesis was applicable to soil N mineralization. That is, the enzymatic decomposition of biochemically recalcitrant substrates (higher requirement of E_a) should generally be more sensitive to temperature changes than that of more labile substrates (high-quality substrates) (Craine *et al*., 2010). In summary, our study shows that N_{min} decreased significantly with increasing latitude at the global scale and the N_{min} was more sensitive to temperature changes at higher latitudes. Higher Q_{10} values at higher latitudes indicated that those regions may have higher N availability for plant growth through higher N_{min} rates under global warming scenarios, which may alleviate the restriction of N supply for increased primary productivity at higher latitudes.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Table S1. Statistics of basic soil properties for different ecosystems.
Table S2. Correlation coefficients between soil net nitrogen mineralization (N_{min}) with climatic variables and soil properties.
Table S3. Pearson's correlation coefficients between different environment variables and latitude.
Fig. S1. Spatial distribution of temperature sensitivity (Q_{10}).
Fig. S2. Changes in soil properties with increasing latitude in the northern hemisphere.
Fig. S3. Changes in soil properties with increasing latitude in the southern hemisphere.
Fig. S4. Changes in soil net N mineralization (N_{min}) with elevation on the global scale.
Fig. S5. Relationships between soil net N mineralization (N_{min}) and climatic variables and between N_{min} and soil properties.
Appendix S1. Description of climate and soil parameters at the study sites.