Soil acidification drives the negative effects of nitrogen enrichment on soil microbial biomass at the global scale

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Soil acidification drives the negative effects of nitrogen enrichment on soil microbial biomass at the global scale

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Abstract

Background and aims Nitrogen (N) deposition is a global driver of change that affects microbial biomass and ecosystem processes. However, it remains unclear whether N enrichment impacts microbial biomass in soil across ecosystems.

Methods In this study, we synthesized 1,385 paired observations from 125 studies worldwide to evaluate the effects of N addition on soil microbial biomass.

Results We found that N enrichment substantially suppresses total microbial biomass, including bacterial, fungal, and arbuscular mycorrhizal fungi biomass. Importantly, we found strong negative effects on microbial biomass globally caused by N-enrichment-induced soil acidification. Moreover, N enrichment mainly shapes the acidification of soil through the increased concentration of ammonium and by changing exchangeable cations in soil, including...
Conclusions Overall, our findings demonstrate that N-enrichment-induced soil acidification is a crucial factor to consider for preserving microbial communities and ecosystem function under future trends of increasing N enrichment.

Keywords Nitrogen enrichment, microbial biomass, soil acidification, meta-analysis

Introduction Anthropogenic nitrogen (N) enrichment, mainly caused by fossil-fuel combustion and chemical-fertilizer application, increased almost five-fold by the end of the 20th century (IPCC 2013). The increased N supply affects microbial growth and community composition, as well as many essential ecosystem processes (Treseder 2008; Zhang et al. 2018). Soil microorganisms constitute an important part of the genetic diversity on Earth, and N enrichment can lead to changes in soil microorganisms; this in turn can significantly impact plant diversity and ecosystem functionality in the biosphere (Karhu et al. 2014; Bennett et al. 2017; Teste et al. 2017). Although the effects of N enrichment on soil microbes have been widely studied, how N enrichment affects soil microbial biomass and communities remains largely unclear and controversial, especially for specific groups such as arbuscular mycorrhizal fungi (AMF), actinomycetes (ACT), gram-positive bacteria (G+), and gram-negative bacteria (G−). Thus, a better understanding of the responses of soil microbes to N enrichment is critical to explain these mechanisms and predict the development of global terrestrial ecosystem functions under further atmospheric N enrichment (Wang et al. 2018).

In theory, increased N addition can strongly alter soil N availability, which could promote plant productivity, litter biomass, and thus soil microbial biomass (Lebauer and Treseder 2008). However, research has found that increased N enrichment does not always lead to a net increase in soil microbial biomass. Negative and neutral effects of N enrichment on soil microbial
biomass have also been reported (Wei et al. 2018; Ma et al. 2021). A key reason for such inconsistencies and conflicts among studies could be N enrichment, which can subsequently cause soil acidification and inhibit microbial growth (Chen et al. 2016).

At the global scale, it is common for soil pH to decrease linearly following N enrichment (Mao et al. 2017; Midolo et al. 2019). However, it remains unclear whether N-induced soil acidification leads to negative effects on soil microbes on a global scale. N enrichment can enhance nitrification and is accompanied by leaching of alkaline cations and nitrate ions (NO$_3^-$), as well as plant uptake of ammonium (NH$_4^+$), which also releases hydrogen ions (H$^+$) (Guo et al. 2008). Both of these processes induce soil acidification. In addition, increased losses of base cations (e.g., manganese ions [Mn$^{2+}$], calcium ions [Ca$^{2+}$], and magnesium ions [Mg$^{2+}$]) and enhanced solubility of iron (Fe) and aluminum (Al) phases, which co-occur with acidification, may play important roles in altering soil substrates associated with soil microbes, resulting in a decrease in pH (Chen et al. 2015). Multiple studies have found that substituting acidic Al$^{3+}$ in the soil structure for Fe via ion exchange can lower Al$^{3+}$ concentrations and alleviate the effects of soil acidification (Tao et al. 2019). However, there is limited research conducted on the effects of increased N-induced soil acidification on soil microbes and the underlying mechanisms across ecosystems on large scales.

The effect of N enrichment on microbial biomass in soil remains unclear, as studies have reported different results, which might have been attributable to differences in N application rate, experimental duration, background precipitation, soil depth, and ecosystem types. Due to nutrient limitations for microorganisms, an increase in N enrichment can reduce investment in fine roots and increase the fraction of recalcitrant compounds of lignin and melanins, leading to less available carbon for soil microbes (Fierer et al. 2009; Liu et al. 2016; Peng et al. 2017). Moreover, an insufficient amount of carbon available to bind N can lead to increased N leaching over time, resulting in progressive microbial inhibition (Zhang et al. 2018). Although
soil microbes are relatively inactive and unable to use N resources in arid regions, increased N leaching caused by increased rainfall can also decrease microbial activity (Cregger et al. 2014). Furthermore, the decline in available N with soil depth may alter the effect of N enrichment (Fierer, 2003). The effects of N enrichment on microbial biomass in soil should be studied while considering the complexity of the global terrestrial system, including human reclamation and extreme environments, as these parameters have considerable consequences on the responses of microbial biomass to N enrichment (Xu et al. 2022).

In this comprehensive study, we compiled a global dataset consisting of 1,385 paired observations from 125 studies to assess the response of soil microbial biomass to N enrichment (Fig. 1, Supplement Fig. S1, and Supplementary Data S1). Our two objectives were to assess the impact of long-term reactive N enrichment on soil microbial biomass and to study the role of N-induced soil acidification in modulating soil microbial biomass under different ecosystem types and environmental conditions.

**Materials and methods**

Data collection

We conducted a meta-analysis of peer-reviewed articles by searching for (nitrogen enrichment OR nitrogen deposition OR elevated nitrogen OR nitrogen) AND (microbial abundance OR microbial community OR microbial biomass OR soil respiration OR microbial respiration OR microbial activity) within the Web of Science, Google Scholar, and the China National Knowledge Infrastructure databases (Fig. 1 and Supplement Fig. S1). Our criteria for inclusion were as follows: N fertilizers were added directly to experimental plots with control and treatment groups; the control and treatment groups were established under the same conditions at the same time; at least one soil microbial metric was reported; and the mean, standard deviation, and sample sizes could be extracted or calculated. We used Engauge Digitizer v4.1 (https://engauge-digitizer.software.informer.com/4.1/) to obtain numerical data from graphs.
We also collected environmental variables, including mean annual temperature (range, −4.1°C to −28°C), mean annual precipitation (range, 80–5,461 mm), ecosystem type (cropland, forest, grassland, or tundra), soil pH, latitude, longitude, N-addition rate (kg N ha\(^{-1}\) year\(^{-1}\)), N-addition duration (1–153 years), and concentrations of NH\(_4^+\), NO\(_3^-\), Mg\(^{2+}\), Ca\(^{2+}\), Na\(^+\), and Al\(^{3+}\), either directly from investigated papers or from cited papers. The extracted data enabled us to evaluate whether the change in soil pH induced by N enrichment dominated the negative effects on microbial biomass. We further tested the effects of the change in soil cations to determine the effect by which N enrichment induces soil acidification.

To compare differences in microbial biomass response to N enrichment, we partitioned the data according to different groups, including N-addition rate (≤ 60, 60–120, and > 120 kg ha\(^{-1}\)), precipitation (≤ 300, 300–600, 600–900, and > 900 mm), duration (≤ 5 and > 5 years), and ecosystem type (cropland, forest, grassland, or tundra).

Meta-analysis

The natural logarithm response ratio (lnRR) was used to quantify the magnitude of N enrichment effects. The analysis is performed using metaWin ver. 2.1 (Hedges et al. 1999). The calculations for the variance (v) (equation 2), weighted factor (W\(_{ij}\)) (equation 3), weighted mean response ratio (RR++; equation 4), and 95% confidence interval (CI) (equation 6) are as follows:

\[
\text{lnRR} = \ln \left( \frac{X_t}{X_c} \right) \quad \text{(Equation 1)}
\]

\[
v = \left( \frac{s_t^2}{n_t x_t^2} \right) + \left( \frac{s_c^2}{n_c x_c^2} \right) \quad \text{(Equation 2)}
\]

where \(S_t\) and \(S_c\) represent the standard deviations and \(n_t\) and \(n_c\) represent the numbers of replicates for a given variable in the N-enrichment and control group, respectively.

\[
W_{ij} = \frac{1}{v} \quad \text{(Equation 3)}
\]
\[ RR_{++} = \frac{\sum_{i=1}^{m} \sum_{j=1}^{k} W_{ij} RR_{ij}}{\sum_{i=1}^{m} \sum_{j=1}^{k} W_{ij}} \]  
(Equation 4)

\[ (RR_{++}) = \frac{1}{\sqrt{\sum_{i=1}^{m} \sum_{j=1}^{k} W_{ij}}} \]  
(Equation 5)

where \( m \) represents the number of subgroups and \( k \) represents the number of \( RR \) in the \( i \)th subgroup \((i = 1, 2, 3..., m; j = 1, 2, 3..., k)\).

\[ 95\% CI = RR_{++} \pm 1.96S(RR_{++}) \]  
(Equation 6)

The actual percentual change was calculated using the equation \( (e^{\ln RR} - 1) \times 100\% \) for the variables under N enrichment. The effects were considered significant with 95% CI of the actual percentage change overlapping zero.

To analyze the importance of predictor variables for a given response variable, we used Akaike information criterion (AIC) values, which were calculated using the R package gmulti (Calcagno and de Mazancourt 2010). A higher AIC weight in the models for a predictor indicates a higher importance value which can be regarded as the overall support for each predictor across all models. We considered predictors with a relative importance value \( \geq 0.8 \) to be important predictors. We performed linear regression analysis using OriginPro 2022.

**Results**

Effects of N enrichment on microbial biomass in soil

In our study, N enrichment significantly decreased soil microbial biomass at the global scale (Fig. 2). Specifically, it decreased total microbial biomass (TMB) \((-14.0\%)\), bacterial biomass \((-16.0\%)\), fungal biomass \((-18.0\%)\), AMF biomass \((-29.5\%)\), and the ratio of fungal to bacterial biomass (F/B ratio) \(-7.4\%). The microbial biomass of the functional groups of ACT, \( G^+ \), and \( G^- \) were also decreased, but the effect was not significant (Fig. 2). Moreover, the negative effect on microbial biomass was amplified with increasing N rates (Fig. 3a).
Compared with the control treatment, N enrichment significantly reduced the TMB (−16.9%), bacterial biomass (−23.0%), fungal biomass (−25.5%), AMF biomass (−41.3%), ACT biomass (−15.9%), and F/B ratio (−5.6%) under high N levels (> 120 kg ha$^{-1}$). At medium N levels (60–120 kg ha$^{-1}$), N enrichment significantly decreased the TMB (−16.9%), bacterial biomass (−17.9%), fungal biomass (−22.2%), ACT biomass (−5.1%), and the F/B ratio (−10.1%). However, at low N levels (≤ 60 kg ha$^{-1}$), N enrichment significantly decreased only the TMB (−7.7%) (Fig. 3a). Among the different levels of precipitation (> 900 mm, 600–900 mm, and 300–600 mm), N enrichment significantly decreased the TMB (−11.6%, −23.8%, and −16.3%), bacterial biomass (−11.5%, −26.8%, and −18.1%), and fungal biomass (−15.0%, −28%, and −18.3%), respectively (Fig. 3b). Additionally, it decreased the microbial biomass across different treatment durations and ecosystem, with long-term (> 5 years) and forest and grassland of N enrichment having the largest effects (Fig. 3c, d).

Effects of N enrichment on soil pH, available nitrogen, and cations

Among all important predictors, the model-averaged importance indicated that soil pH was the most significant predictor for microbial biomass (Fig. 4). N enrichment significantly decreased soil pH, with the highest N rate (> 120 kg ha$^{-1}$) having the greatest effect (Fig. 5a). Regarding available soil N and cations, N enrichment significantly increased the concentrations of NO$_3^-$ (92.1%), NH$_4^+$ (53.6%), Mn$^{2+}$ (43.2%), and Al$^{3+}$ (16.6%) while decreasing the concentrations of Na$^+$ (−12.5%), Mg$^{2+}$ (−13.0%), and Ca$^{2+}$ (−18.5%) (Fig. 5b).

Influence of environmental and management factors

The negative response of soil pH to N enrichment increased with an increasing N rate (Fig. 5a). In addition, there were significant negative correlations between soil pH and microbial biomass, microbial respiration, and soil respiration (Fig. 6 and Supplement Fig. S4). There was also a positive correlation between soil pH and the response ratios of Ca$^{2+}$ and Mg$^{2+}$, and significant negative correlations with the response ratios of Mn$^{2+}$, Al$^{3+}$, and NH$_4^+$ (Fig. 7). Regarding
environmental factors, only MAT was correlated with the biomass values of ACT, $G^+$, and $G^-$ (SupplementTable S1).

Discussion

Based on 1,385 observations of N enrichment experiments (Data S1), we found the negative effect of N enrichment on soil microbial biomass was altered by N application rate, precipitation, experimental duration and ecosystem type. More importantly, our study provides the first comprehensive evidence on a global scale of a negative effect of N enrichment on soil microbial biomass by N-induced soil acidification. Changes in the concentrations of $\text{NH}_4^+$, $\text{Mn}^{2+}$, $\text{Al}^{3+}$, $\text{Mg}^{2+}$, and $\text{Ca}^{2+}$ were the main factors contributing to soil acidification. Our research findings mechanistically explain and support the new perspective that ongoing N enrichment, leading to soil acidification, has critical negative global effects on microbial biomass in soil and related functions.

Our meta-analysis highlights the crucial contribution of precipitation, duration, and ecosystem type to soil microbial biomass changes in response to N enrichment (Fig. 3). The negative effect of N enrichment increases over time (Pregitzer et al. 2008; Lu et al. 2011). Some argue that combining precipitation and N enrichment significantly increases microbial biomass (Liu et al. 2018); this differs from our findings that N enrichment decreased microbial biomass, but mainly in moist habitats (Fig. 3b). This can be explained by the crucial role of moisture availability in regulating microbial activity and nutrient dynamics (Cregger et al. 2014). In moist habitats, the negative effects of N enrichment on microbial biomass can be attributed to various factors. One primary factor is the alteration of nutrient availability ratios. N enrichment can shift the C:N ratio, which is an essential factor for microbial growth and nutrient cycling (Cross et al. 2007). Elevated N availability can lead to an imbalance in C:N ratios, favoring the growth of fast-growing microbial communities that have a high N demand such as copiotrophs (Gul and Whalen 2022). This shift in microbial community composition
results in a decline in overall microbial biomass. In contrast, drier habitats may exhibit more resistance to the negative effects of N enrichment on microbial biomass. These habitats typically have lower moisture availability and microbial activity, which can provide some level of protection against the adverse impacts of N enrichment (Cregger et al. 2014). This implies that N enrichment has a negative effect on microbes in moist zones. Additionally, as N enrichment persists, the excessive availability of N can lead to imbalances in nutrient ratios, particularly the carbon-to-nitrogen (C:N) ratio (Cross et al. 2007). In such conditions, slower growing nutrient-conserving microorganisms, known as oligotrophs, may be outcompeted. A shift in microbial community composition toward copiotrophs can lead to a decline in overall bacterial and fungal biomass (Gul and Whalen 2022). Furthermore, the duration of N enrichment was found to interact with this negative effect on bacterial and fungal biomass ($p < 0.05$) (Fig. 3c). Studies have shown that longer periods of N enrichment have a more negative impact on microbial communities (Zhang et al. 2018). This suggests that microbial communities may initially have some resilience to N enrichment, but prolonged exposure can lead to cumulative effects that further suppress their biomass. These results reflect the limitations of short-term experiments involving N enrichment; in future work, N needs to be added for long enough to reveal its effects on microbial biomass in soil. Finally, declines in microbial biomass occurred in all ecosystems except cropland and tundra (Fig. 3d). This is because cropland and tundra ecosystems usually have different characteristics and nutrient dynamics that can influence microbial responses to N enrichment. Cropland ecosystems typically receive regular applications of N-based fertilizers to meet the nutrient demands of crops (Liu et al. 2019). In such cases, additional N enrichment may not have a significant effect on soil microbial biomass since the system is already nutrient-rich. Moreover, other aspects of cropland management, such as tillage and pesticide use, can impact soil microbial communities and their response to N enrichment (Liu et al. 2019). Tundra ecosystems, conversely, are characterized by low temperatures, short growing seasons, and limited nutrient availability. In
cold environments, the decomposition and nutrient uptake rates of microbes are generally low. Consequently, the addition of N may not have a significant effect on soil microbial biomass in tundra ecosystems due to the overall low microbial activity and limited nutrient availability (Sistla et al. 2013).

The prevailing viewpoint is that N enrichment leads to a decrease in microbial biomass in soil globally (Zhang et al. 2018), and we have further revealed, based on the evaluation of multiple factors, that soil acidification caused by N is the main factor leading to the reduction of microbial biomass globally (Fig. 4). This is supported by the positive correlation between the relative reduction of microbial biomass and pH (Fig. 6). Some researchers have argued that when an appropriate amount of N is added to soil, it can be absorbed and used by microbial organisms, leading to an increase in microbial biomass (Li et al. 2016). However, excess N can contribute to soil acidification, resulting in a decrease in soil pH, in turn leading to a decrease in microbial biomass (Fig. 5a). Acidic conditions can limit microbial growth and reproduction because many soil enzymes are pH dependent, and acidic conditions can impair their activity (Ajwa et al. 1999). This can affect the breakdown of organic matter and nutrient availability, which in turn impacts microbial biomass (Stark et al. 2014). Moreover, acidic conditions favor acid-tolerant microbial species and inhibit the survival of acid-sensitive species (Çakmakcl et al. 2010). This shift in microbial community composition can influence the overall microbial biomass. Interestingly, taking the initial soil pH into account, we observed that N enrichment had a positive effect on microbial biomass when the initial soil pH was less than 6 (Supplement Fig. S3). This may be due to the significant increase in soil nutrient availability upon N enrichment (Stark et al. 2014). N is a key nutrient for microbial growth; its enrichment in the form of fertilizers can stimulate microbial activity and increase biomass (Chen et al. 2014). In soils with low initial pH, N enrichment is an additional nutrient source that supports microbial growth (Khaled and Fawy 2011). Moreover, some forms of N fertilizers, such as NH₄⁺-based
fertilizers, have pH-buffering effects and can temporarily increase soil pH to levels more favorable for microbial growth. Such pH-buffering effects can enhance microbial biomass in soils with initially low pH (Wang et al. 2020). Therefore, our findings imply that changes in soil pH predominantly explain the global negative effects of N enrichment on microbial biomass.

We further studied the mechanisms underlying soil acidification induced by N fertilizer enrichment (Fig. 7). Our results imply that the change in soil pH during N enrichment may be attributable to two factors. First, NH$_4^+$ is an acidic cation, meaning it has a positive charge and can release H$^+$ when it undergoes nitrification processes in soil. Nitrification involves the microbial oxidation of NH$_4^+$ into NO$_3^−$. During this process, nitrifying bacteria convert NH$_4^+$ into nitrite (NO$_2^−$) and then NO$_3^−$ (Van Kessel et al. 2015). The release of H$^+$ during nitrification leads to soil acidification, lowering the soil pH (Hinsinger et al. 2003). We observed that soil NH$_4^+$ increased with increasing N and had a significant negative correlation with soil pH (Fig. 5). These results collectively imply that reactive N enrichment, particularly NH$_4^+$, can stimulate the release of H$^+$ into the soil (Kunhikrishnan et al. 2016). Second, N enrichment decreased soil pH, likely due to a decrease in base cations (Mg$^{2+}$ and Ca$^{2+}$) and increase in Al$^{3+}$ and Mn$^{2+}$ (Fig. 5b and Fig. 7). A decrease in base cations can lead to soil acidification, as these cations act as pH buffers in the soil (Lu et al. 2014). They neutralize excess acidity and help maintain soil pH in the optimal range for nutrient availability (Guo et al. 2008; Lucas et al. 2011). However, excessive N inputs can increase the leaching of base cations from the soil. When N is added in excess, it can cause imbalances in nutrient availability and uptake by plants (Niu et al. 2022). Such imbalances can result in decreased uptake of base cations, leading to their leaching out of the soil profile with percolating water (Sverdrup and Rosen 1998). Moreover, the acidifying effect of NH$_4^+$ on soil pH can indirectly contribute to a decrease in base cations. Acidic soils promote the release of bound forms of base cations, making them more soluble
and susceptible to leaching (Mensah and Frimpong 2018). In addition to the changes in base
cations in soil, the concentrations of Al$^{3+}$ and Mn$^{2+}$ increased with N enrichment and showed
significant negative correlations with soil pH (Fig. 7). The change in soil pH during N
enrichment could be attributed to the increases in Al$^{3+}$ and Mn$^{2+}$ soil concentrations. When N
fertilizers are applied to soil, nitrification occurs, which results in the production of NO$_3^-$ and
an accompanying release of H$^+$. This release of H$^+$ can cause soil acidification (Kunhikrishnan
et al. 2016). Al$^{3+}$ is naturally present in soils and can exist in insoluble forms at near-neutral
pH levels (Batayneh 2012). However, as soil becomes more acidic due to the release of H$^+$, the
solubility of Al increases, leading to the release of Al$^{3+}$ into the soil solution (Etou et al. 2011).
Mn$^{2+}$ can similarly contribute to soil acidification during N enrichment. Mn is naturally present
in soils in both insoluble and soluble forms (Homoncik et al. 2010). As soils acidify, the
solubility and availability of Mn increase, resulting in the release of Mn$^{2+}$ into the soil solution
(Fageria et al. 2011). Increases in both Al$^{3+}$ and Mn$^{2+}$ contribute to further soil acidification,
leading to a decrease in soil pH. Therefore, we emphasize that information on the ions in soils
should be incorporated to enhance understanding of the effects of N enrichment on microbial
biomass in soil.

Finally, we found a strong negative association between soil acidification and microbial and
soil respiration (Supplement Fig. S4), representing a potential threat to related ecosystem
functions (Kunhikrishnan et al. 2016). Soil respiration, which refers to the release of carbon
dioxide due to soil microbial activity, is also influenced by soil pH. Acidic conditions can
inhibit the activity of soil microorganisms involved in nutrient cycling and organic matter
decomposition, leading to a reduction in soil respiration rates (Janssens et al. 2010). Additionally, in acidic soils, the availability of essential nutrients for microbial activity (e.g.,
N and phosphorus) may become limited (Stark et al. 2014). These findings corroborate that N
enrichment negatively regulates the respiration of soil microbes by acidifying the soil, and
further highlight the interactions between microbes and ecosystem functioning.

Conclusion

Our findings support that N enrichment induces soil acidification and has a negative effect on the soil microbial biomass on a global scale. It causes soil acidification predominantly through an increase in NH$_4^+$ concentrations and by altering exchangeable cations, including Mg$^{2+}$, Ca$^{2+}$, Na$^+$, Mn$^{2+}$, and Al$^{3+}$. Our results also highlight that the strong negative effects of N on soil microbes are amplified under high N enrichment, high precipitation, and long-term N enrichment. This insight into the mechanistic relationship helps to explain the observed negative effect of N enrichment on microbial biomass and highlights the importance of managing N inputs to maintain soil health. These findings provide a theoretical basis to counteract an expected dramatic rise of N enrichment in the future while promoting sustainable ecosystem functions.

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Data Availability The database compiled for this study is available in the Supporting Information.

Conflict of interest The authors declare no competing interests

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**Figures**

**Fig. 1** (a) Site locations of N-enrichment studies included in this study. Dots represent ecosystem types. (b) Kernel density estimates for the “in response ratio” of total microbial biomass, bacterial biomass (B), fungal biomass (F), AMF biomass, ACT biomass, G+ biomass, G− biomass, the F/B ratio, and the ratio of G+ and G− biomass under N enrichment.
Fig. 2 Effects of N enrichment on soil microbial biomass. The variables are categorised into N rate, precipitation, duration, ecosystem. Error bars represent ± 95% CIs. See the note in Fig 1.

Fig. 3 Effects of N enrichment on microbe-related variables across all investigated studies. Error bars represent ± 95% CIs. Dots represent significant effects; circles represent nonsignificant effects. See the note in Fig 1.

Fig. 4 Predictors contributing to the response of microbial biomass to edaphic, climatic, and management factors. The model average importance of the predictor is based on the Akaike information criterion (AIC) values for model selection, and it is obtained as the sum of the Akaike weights. Predictors are considered important if the relative importance value is ≥ 0.8. MAP: mean annual precipitation; MAT: mean annual temperature.

Fig. 5 Response ratios (RRs) of pH to N enrichment on microbial biomass (a) and ions (b) in soil. Error bars represent ± 95% CIs. Dots represent significant effects; circles represent nonsignificant effects.

Fig. 6 Correlations between the RR of microbial biomass and RRs of soil pH in response to N enrichment.

Fig. 7 Correlations between the RR of soil pH and the RRs of Ca^{2+}, Mg^{2+}, Na^{+}, Mn^{2+}, Al^{3+}, NO_{3}^{-}, and NH_{4}^{+} in response to N enrichment.
Fig 1
Fig 5

Fig 6
Fig 7
Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- DataS1.xls
- supplementaryinformation.doc