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# Responses of terrestrial ecosystem phosphorus cycling to nitrogen addition: A meta-analysis

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Responding to reviewer and editor comments:

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EDITOR-IN-CHIEF'S COMMENTS TO AUTHORS

*We have now completed the review process on your manuscript 'Responses of terrestrial ecosystem phosphorus cycling to nitrogen additions: a meta-analysis' (Ref. GEB-2016-0359.R1). You will find the reports of the referees, and the comments of the handling editor, Mr. Xiaofeng Xu, appended below. As you will see, there are a number of points that require your attention, but these seem to constitute a minor revision. I invite you to prepare a modified version of your manuscript that addresses the referees' and the editor's concerns. In a cover letter, please explain how you have modified the manuscript in response to each of their comments, preferably point by point. On points where you disagree with the reviewers, or you feel that modification of the original text is unwarranted, please explain why. It is unlikely that we will need to refer the revised version of the manuscript to the referees again, provided that you adequately address the concerns that they raise in their reports. In addition, please make sure that your manuscript conforms with journal style and format, as described on our web site http://onlinelibrary.wiley.com/journal/10.1111/(ISSN)1466-8238/.*

**Response:** We thank the Editors-in-Chief for the consideration of our manuscript, and giving us another opportunity to improve the manuscript. In this revised version, we have addressed all reviewer's comments, and issued raised by the handling editor, Dr. Xu. We also double-checked to make sure that the manuscript confirms with journal style and format. We hope that the manuscript could be accepted for publication in Global Ecology and Biogeography.

EDITOR'S COMMENTS TO AUTHORS

Editor: Xu, Xiaofeng

Comments to the Author:

*Both reviewers appraised the work, and both agreed that the paper is publishable. And R2 had some minor comments on writing. I would like to see a little bit advanced discussion on the implication of this study to ongoing phosphors modeling. The current writing with one sentence at the end of the manuscript is too vague; everyone is saying that. I would like to encourage the*

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*authors to take this opportunity to finalize the manuscript, fixing small pitfalls, improving writings, further raising the quality of this paper.*

**Response:** We thank Dr. Xiaofeng Xu for promptly handling our manuscript and for his thoughtful comments. We also appreciate the review comments from two anonymous reviewers. In this version, we expanded our discussion on P-modeling by adding more descriptions of P pools and processes, and linking some of our results to model simulations (Pages 16-17, Lines 438-463). We also fixed all minor errors and improved the writing (see details below). Hope these revisions are adequate. The following is our revised discussion on P-modeling:

"Given the importance of P on plant growth and productivity, inclusion of P cycling in ecosystem models could significantly improve our ability to better forecast ecosystem C sequestration in the future. Recently, P modules have been built into ecosystem models such as CASA-CNP (Wang *et al.*, 2010), JSBACH-CNP (Goll *et al.*, 2012), CLM-CNP (Yang *et al.*, 2014), and N-COM (Zhu *et al.*, 2016) to investigate nutriment limitations on C cycling and C-N-P interactions. In these models, P is usually stored in several pools including plant biomass, litter, plant available P forms in the soils, and unavailable organic P forms in the soils (Smil, 2000; Vitousek *et al.*, 2010). Major P processes include P uptake, mineralization, immobilization, dissolution, precipitation, occlusion, and leaching. P dynamics are often coupled with C and/or N cycling through stoichiometric relationship of C, N and P in plant tissues and soils (Wang *et al.*, 2010; Goll *et al.*, 2012; Yang *et al.*, 2014). The results of enhanced plant P uptake and P mineralization with N additions in this meta-analysis would disproportionably alter P in different pools in the models, and ultimately result in greater P limitation. Our results of stimulated plant biomass and P contents in plant tissues with N additions were also supported by some model simulations. For example, Yang et al. (2014) found that, using the CLM-CNP model, plant production is substantially increased with N addition at the N-limited site, resulting in higher P uptake and P contents in plant biomass, considering that C:P ratios for plant tissues are kept constant in the model. But the model showed no impact with N additions at P-limited site indicating the interaction of N and P could be complicated by field nutrient availability. The influences of N additions on the P pools revealed in this study should help us understand the roles that N and P play in controlling plant growth and internal nutrient accumulation and accurately parameterize these C-N-P models. However, more nutrient addition experiments will benefit model testing and calibration (Reed et al. 2015; Achat *et al.*, 2016a)."

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We hope that this revision adequately addressed Dr/ Xu's concerns with P modeling.

REVIEWER COMMENTS TO AUTHOR

Referee: 1

Comments to the Author

*The authors have satisfactorily addressed the comments from last time.*

**Response:** We thank the reviewer for the positive comments.

Referee: 2

Comments to the Author

*This is my second review of the submitted study.*

*As a whole, authors have modified their manuscript following reviewers' comments. I find this second version much better than the former version, and I think it is now acceptable for publication.*

*I have only one problem to report (which could be fixed easily), a few minor corrections, and some non-mandatory suggestions.*

*My personal congratulations to the authors; I believe they produced a good job.*

**Response:** We thank the reviewer for the very positive comments and constructive suggestions.

** Problem:*

*The caption of Figure 2 contains information on three panels. But only two panels are in the document. This is probably an error.*

**Response:** Thanks for pointing this out. We removed one panel as it has a small sample size. We corrected this in the revised manuscript.

** Minor points:*

*- line 11, page 1: "Meta" and not "Mate".*

*- line 37: replace "8.4%" by "8%".*

*- line 170: put a comma after "NH4F" because there are four categories.*

*- line 191: please limit the number of references (1 or 2).*

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*- line 375: replace "may" by "likely".*

*- line 427: "a major challenge for us, if N deposition continue to increase in the future".*

*- Figure 6: indicate in the caption the pH values defining "alkaline", "neutral", and "acidic".*

*- Appendix S2: You put NH4NO3 with an exponent.*

**Response:** We corrected all the above issues as suggested. Thanks.

** Suggestions:*

*- lines 122-123: you can omit "with no restriction on publication year".*

**Response:** We deleted this part.

*- line 324: I think it would be better to write "Our results demonstrated that external N can significantly alter terrestrial [etc.]".*

**Response:** We revised as suggested.

*- line 438: A review paper has just been published on this topic (Achat et al. Future challenges in coupled C–N–P cycle models for terrestrial ecosystems under global change: a review. Biogeochemistry, Online First).*

**Response:** We thank the reviewer for the reference. We added this reference here and cited it in other places in the manuscript.

*- lines 440-449: I think that this paragraph could be placed between line 427 and line 428. It would enable finishing the manuscript by lines 436-439, which is a good "end message".*

**Response:** We moved this paragraph as suggested.

*- Figures 3 and 5 could be moved to SI in order to give more importance to other figures (which are more interesting for most readers).*

**Response:** We moved these two figures to SI, and also revised the abstract (Page 3, Lines 43-46) accordingly in order to demonstrate the core results for the readers. Thanks.

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# Responses of terrestrial ecosystem phosphorus cycling to nitrogen additions: a meta-analysis

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**Type of paper:** Meta-analysis

**Key words:** Available phosphorus, meta-analysis, nitrogen additions, phosphatase activity, phosphorus limitation, total phosphorus.

**Running title:** Impact of N additions on P cycle

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**Number of words, table and figures:** 295 words in the Summary with 6 key words, 5464 words in the main text (776 words in Introduction, 1718 words in Materials and methods, 863 words in Results, 2053 words in Discussion, and 54 words in Acknowledgments), 64 references, 6 figures in this manuscript, 4 tables and 4 figures in the Supporting Information.

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## ABSTRACT

**Aim** Anthropogenic nitrogen (N) additions are expected to drive terrestrial ecosystems toward greater phosphorus (P) limitation. However, a comprehensive understanding of how ecosystem P cycle responds to external N inputs remains elusive, making model predictions of the anthropogenic P limitation and its impacts largely uncertain.

**Location** Global.

**Methods** We conducted a meta-analysis with 288 independent study sites from 192 articles to evaluate global patterns and controls of 10 variables associated ecosystem P cycling under N additions.

**Results** Overall, N additions increased biomass in plant (+34%) and litter (+15%), and plant P content (+17%), while decreasing plant and litter P concentrations (-8% and -11%). N additions did not change soil labile P and microbial P, but enhanced phosphatase activity (+24%). Effects of N additions on litter P pool and soil total P remained unclear due to significant publication biases. The response of P cycling to N additions in tropical forests was different from those in other ecosystem types. N additions did not change plant biomass or phosphatase activity in tropical forests, but significantly reduced plant P and soil labile P concentrations. Shift in plant P concentration under N additions was negatively correlated with N application rate or total N load. N-induced change in soil labile P was strongly regulated by soil pH value at the control sites, with significant decrease of 14% only in acidic soils (pH<5.5).

**Main conclusions** Our results suggest that, as anthropogenic N enhancement continues in the future, it could induce P limitation in terrestrial ecosystems while accelerating P cycling, particularly in the tropical forests. A quantitative framework generated based on this meta-analysis is useful for our understanding of ecosystem P cycling with N additions, and for incorporating the anthropogenic P limitation into ecosystem models used to analyze effects of future climate change.

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## INTRODUCTION

Globally, nitrogen (N) and phosphorus (P) are the most limited nutrients for plant growth (Elser *et al.*, 2007; Vitousek *et al.*, 2010), and their synergistic interactions are widespread as plants require elements in relatively constant proportions to catalyze metabolic reactions and synthesize essential compounds with specific ratios of N:P (Ågren, 2008; Harpole *et al.*, 2011; Yuan & Chen, 2015a). Terrestrial biogeochemical models have explicitly considered such interactions between the N and P cycles (Zhang *et al.*, 2011; Goll *et al.*, 2012; Zhu *et al.*, 2016), and suggested that elevated inputs of either N or P may have been implicated in massive shifts in nutrient cycle and balance, and in turn influence ecosystem productivity and functioning (Wang *et al.*, 2010; Goll *et al.*, 2012; Peñuelas *et al.*, 2013).

Due to fossil fuel combustion and intensive application of N-based fertilizers, the inputs of reactive N to the Earth's land surface have mostly been doubled during the past century (Gruber & Galloway, 2008; IPCC, 2013). Unlike N, P cycling is almost unidirectional moving from terrestrial ecosystems to rivers and streams with minor input back through dust and fly ash from wildfires and negligible gaseous P (phosphine, $PH_3$) (Smil, 2000; Filippelli, 2002; Mahowald et *al.*, 2008; Peñuelas *et al.*, 2012). The widespread enrichment in N inputs has considerably improved regional and global N availability and enhanced ecosystem productivity (e.g., Aber *et al.*, 1998; Elser *et al.*, 2007; Xia *et al.*, 2008; Lu *et al.*, 2011a). However, the human-induced imbalance of N and P inputs is also expected to drive terrestrial ecosystems toward greater P limitation of plant growth (Vitousek *et al.*, 2010; Peñuelas *et al.*, 2013). This 'anthropogenic P limitation' has been acknowledged recently by a meta-analysis of impacts of P additions, either alone or with N additions, on plant biomass (Li *et al.*, 2016).

However, our understanding of the response of ecosystem P cycling to N additions and the underlying mechanism is very limited. So far, only the impact of N additions on phosphatase activity is synthesized, which suggests that N inputs

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enhance rather than reduce plant P acquisition due to stimulating both plant root and soil phosphatase activity (Marklein & Houlton, 2012). Ecosystem P cycling consists of multiple pools and processes that are interrelated and interdependent, jointly controlling soil P availability and plant P uptake (Filippelli, 2002; Vitousek *et al.*, 2010). The limited synthesis in P process significantly limits our ability in incorporating the impact of anthropogenic P limitation into ecosystem models used to analyze effects of possible future climate change on global ecosystem productivity (Goll *et al.*, 2012; Peñuelas *et al.*, 2013; Zhu *et al.*, 2016). To improve our understanding of P cycling and develop robust ecosystem models with fully coupled C-N–P interactions, we urgently need a comprehensive synthesis of ecosystem P cycling in response to N additions.

Since N and P play important roles in plant growth and productivity, numerous studies have been conducted to examine the plant growth and ecosystem P cycling with N additions. But the conclusions remain controversial (Finzi, 2009; Braun *et al.*, 2010; Tao & Hunter, 2012). For instance, Li *et al.* (2016) suggested that plant P concentration is the best indicator of P limitations based on a meta-analysis of P additions experiments. Yet the field experiments with N additions showed decreases (Tessier & Raynal, 2003), no change (Weand *et al.*, 2010), and even increases (Liu *et al.*, 2013) in plant P concentration. This is not surprising, as multiple factors and processes regulate ecosystem P cycling (Filippelli, 2002; Vitousek *et al.*, 2010). As an example, ecosystem P cycling may respond to N additions differently among different ecosystems, as it is well known that tropical forest is usually more P limited than other ecosystems (Elser *et al.*, 2007; Yang *et al.*, 2014). Therefore, a better understanding of ecosystem P cycling under N additions and the influencing factors is essentially required for enabling ecosystem models to accurately predict “anthropogenic P limitation” and its impacts.

The objective of this study was to quantitatively evaluate N-induced changes in ecosystem P cycling and their potentially influencing factors. We compiled a large dataset of changes in ecosystem P cycling related to 10 variables at 288 independent

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study sites from 192 articles, and conducted a comprehensive meta-analysis. The specific issues addressed here were as follows: 1) what ecosystem P variables were changed under N additions; 2) whether response of ecosystem P cycling to N additions would vary among different ecosystem types; 3) whether the responses were also affected significantly by other factors such as climate (temperature and precipitation), soil properties (soil pH) and N experimental manipulation (N sources, N application rate, experimental duration and total N load).

## MATERIALS AND METHODS

### Dataset assembly

We searched journal articles that reported ecosystem P dynamics in response to N additions using Google Scholar and ISI Web of Science. Searches included combinations of the terms “nitrogen addition”, “nitrogen fertilization” or “nitrogen input”, and “phosphorus” or “phosphatase”. We also screened previous meta-analysis on the similar topic such as Marklein & Houlton (2012) and Li *et al.* (2016). The former focused on phosphatase activity responses only, and the latter mainly assessed the impacts of P additions either alone or with N additions, rather than the direct N additions impacts. We systematically reviewed all results from the searched articles and included those studies that reported at least one of the selected P variables (A list of the data sources is given in Appendix 1 and the relevant information is shown in Appendix S1 in the Supporting Information) at both the N treatment and control sites. To avoid possible confounding factors caused by human disturbances, we only included studies from field manipulative experiments of N additions that were conducted in natural terrestrial ecosystems. For studies that included additional treatments such as elevated $CO_2$, warming and rainfall changes, we only included the unmanipulated controls and the corresponding N treatment sites in order to avoid possible interactive effects. Finally, our searches yielded a total of 192 useful articles (A list of the data sources is given in Appendix 1), and the compiled database included 10 variables related to ecosystems P cycling and other associated parameters

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(Appendix S1 in the Supporting Information). Only 10% and 13% of these articles in this meta-analysis were reviewed in Marklein & Houlton (2012) and Li *et al.* (2016), respectively.

Most of the data were either obtained from tables or extracted from figures using the GetData Graph Digitizer (version 2.24, Russian Federation). Only a few plant and litter P contents were calculated using their biomass and P concentrations. For the plant biomass, different estimating methods (e.g. direct harvest for most herbaceous species and use of allometric relationships for some tree species) were accepted, but results from other proxy variables such as plant height, diameter or volume were not included in our biomass analysis. Plant tissues included foliar, above- (e.g., stem, shoot or above-ground), below- (coarse root, fine root or total root) and whole biomass. Phosphatase activity included plant root phosphatase activity and soil phosphatase activity. Soil P variables were used to represent both their concentrations and pool sizes, because very few studies reported soil bulk density at both the control and N treatment sites. It should be noted that N additions may not significantly alter soil bulk density, as showed in a previous meta-analysis (Lu *et al.*, 2011b).

We also collected other site specific information, including source of the data, location (latitude and longitude), ecosystem type, N source applied, N application rate, experimental duration, soil type, organic C, pH value, mean annual temperature (MAT), and mean annual precipitation (MAP) at each study site. Ecosystem types included tropical forest (36), temperate forest (52), boreal forest (12), grassland (88), wetland (87) and tundra (13). N sources were divided into Urea–N, $NH_4NO_3$–N, $NH_4^+$–N and $NO_3^-$–N. Soil pH values below 5.5 and above 7.5 could limit P availability to plants due to binding of phosphate ions with aluminum (Zn), iron (Fe), calcium (Ca) or magnesium (Mg) (Busman *et al.*, 2002; Devau *et al.*, 2009). Thus, we assigned alkaline (pH > 7.5), acidic (pH < 5.5), or neutral (pH 5.5-7.5) based on pH of the control site. We recorded soil depth and P extraction methods that were consistent between the control and treatment sites in all articles. The extraction methods of soil total P were divided into sequential (Hedley procedure), $HNO_3$, $H_2SO_4$, and others

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(e.g., fusion method). The extraction methods of soil labile P were divided into sequential, bicarbonate, $NH_4F$, and others (e.g., *Mehlich* 1 and *Mehlich* 3 methods).

In this study, we focused on the responses of P variables at a community level. To meet the statistical requirement of independence among observations (Koricheva & Gurevitch, 2014), we used one set of data that includes only one paired observations (control and treatment) for each of 10 variables at a given study site (Treseder, 2008). When plants were measured for multiple tissues at a study site, we used the data from the tissue that contains more observations in the corresponding variable. Similarly, when soils were sampled at multiple depths at a study site, we used the data from the top soil layer. For multiple measurements over time or year, or data presented in multiple publications at a study site, we selected the studies including the most P variables, otherwise the data from the latest sampling date were used. At sites when multiple N application rates were used, only the highest application rate was selected. It should be noted that measurements at different geographical locations, ecosystem types (including dominant vegetation), or N sources applied in a study were considered as independent observation. Finally, a total of 288 independent study sites were used in this meta-analysis. However, we included all data when the specific factor was the interest of the study, for example, all soil depths data at each independent study site were included when the effect of soil depth was examined.

## Statistical analysis

We quantified the effects of N additions on the ecosystems P cycling by calculating the natural log of the response ratio (*RR*), a metric commonly used in meta-analyses (Hedges & Olkin 1985; Luo *et al.*, 2006):

$$RR = \ln\left(\frac{\overline{X_t}}{\overline{X_c}}\right) = \ln\left(\overline{X_t}\right) - \ln\left(\overline{X_c}\right) \qquad \text{Eqn 1}$$

where *RR* is the ratio of the mean value of the chosen variable in the N treatment group ($\overline{X_t}$) to that in the control group ($\overline{X_c}$), an index of the effect of the experimental

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treatment on the target variable. To determine if N additions had a significant effect, we applied a random-effects model, and considered study site as the random effect factor (Hedges & Vevea, 1998; Borenstein *et al.*, 2010). Unlike the fixed-effect model with an assumption that all studies share a common *RR*, the random-effects model allows the studies to differ in their *RR*s (Borenstein *et al.*, 2010). Thus, there are two sources of variance in the analysis, including within-study variance ($v$) and between-studies variance ($\tau^2$) that both were used as the weighting factor ($w = \frac{1}{v + \tau^2}$) to calculate the mean *RR*s and 95% confidence intervals (*CI*s). We firstly computed the mean $v$ and *RR*, similar to the approach used in the fixed-effect model (Luo et al., 2006; Deng et al., 2015), and then used these mean values as an estimate of the $\tau^2$. When $\tau^2$ is equal to zero, both fixed-effect and random-effects models are same. The computational details are given in Borenstein *et al.* (2010). The treatment effect of N additions was considered to be significant if the 95% *CI* of mean *RR*s did not overlap with zero (Luo *et al.*, 2006; Deng *et al.*, 2015). The mean *RR*s and 95% *CI*s were then transformed back (i.e. exponentially transformed) and converted to a percentage change.

We further evaluated if the mean *RR*s was affected by the potentially influencing factors that include categorical factors (ecosystem type, N sources applied, and soil pH value for each of the selected P variables, plant tissue for plant P variables, P extraction method and maximum soil depth for soil P variables) and continuous factors (experimental duration, N application rate, total N load, MAT, and MAP for each of the selected P variables). As data sets were not complete for all factors, the statistical significance of each factor was tested independently from the others. For the categorical factor, a separate mean *RR* and 95% *CI* for each category group were calculated based on the random-effects model described above. These mean *RR*s were then compared across groups for each categorical factor using an approach analogous to one-way weighted ANOVA, where total variability ($Q_{\text{total}}$) was partitioned into within and between-group variability ($Q_W$ and $Q_B$, respectively) (Paul *et al*, 2005; Borenstein *et al.*, 2010). The statistical significances of the categorical factors were

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evaluated based on a chi-square test of the between-group sum of squares and the degree of freedom (df). Accordingly, if the 95% *CI* of one group is not overlapped with another one within a categorical factor, there is a significant difference between these two groups (Luo *et al.*, 2006; Deng *et al.*, 2015). To avoid unreliable results, some subgroups without a sufficiently large dataset (n<5) were excluded in the categorical analysis. For the continuous factors (n>20 only), we used a weighed regression-type model to fit the *RR*s to each continuous factor. The weight-*w* was used as the regression weight in the analysis. The regression parameters (slope and intercept) were estimated using the method of moments, and their statistical significances were tested based on an F-test (Lipsey & Wilson, 2001; Paul *et al*, 2005; SAS Institute Inc., 2015).

The publication bias was tested by the funnel plot method (Egger *et al.*, 1997). The funnel plot offers a visual sense of the relationship between effect size (*RR*) and precision (the reverse of standard error of the *RR*). The symmetrical funnel shape of the plot around the mean *RR* indicates the publication bias in the dataset is insignificant (Egger *et al.*, 1997). However, the interpretation of the funnel plot is largely subjective (Borenstein, 2005). Given a small dataset such as n<5, it is difficult or almost impossible to determine if the funnel plot is symmetrical. Thus, in the case of which the mean *RR* had significant difference from zero, we further calculated the fail-safe number by a weighted method to estimate whether our conclusion is affected by the non-published data (Rosenberg, 2005). If the fail-safe number was over 5n+10 (n is the number of cases in the analysis), we made conclusion that our result was strong against publication bias. Otherwise, significant publication bias for the analysis was suggested. In addition, we assessed the sensitivity of our meta-analysis to the individual study site. We removed one study site from the database each time, and estimated the mean *RR* (Philibert *et al.*, 2012; Deng *et al.*, 2015).

All data were analyzed using SAS software (SAS Institute Inc., Cary, NC, USA), and the statistical results were considered to be significant at α= 0.05 level. The graphs were drawn with SigmaPlot software (SigmaPlot 12.5 for windows; Systat

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Software Inc., San Jose, CA, USA).

## RESULTS

Both plant and litter biomass were significantly increased under N additions (Fig. 1a, b). On average, plant biomass was increased by 34% (95% *CI*: +27%, +41%) across the study sites (Fig. 1a), with greater increases in above-ground (+40%; 95% *CI*: +31%, +48%) than below-ground (+11%; 95% *CI*: +0.6%, +24%) biomass (Fig. 2a). Litter biomass was increased by 15% (95% *CI*: +8%, +23%) across the study sites (Fig. 1b).

Plant and litter P contents were also significantly increased under N additions (Fig. 1a, b), but significant publication bias for the result of litter P content was suggested by both funnel plot and Rosenthal's fail-safe number (Appendix S2 and Fig. S1 in the Supporting Information). Plant P content was increased by 17% (95% *CI*: +11%, +23%) across study sites (Fig. 1a), with similar increases in different plant tissues (Appendix S3 in the Supporting Information).

For the plant and litter P concentrations, both were significantly decreased under N additions (Fig. 1a, b). Plant P concentration was decreased by 8% (95% *CI*: -10%, -6.6%) across study sites (Fig. 1a). N additions significantly decreased P concentration by 6.3% (95% *CI*: -8.4%, -4.1%) in foliar and by 9.0% (95% *CI*: -12%, -6.1%) in above-ground tissue (Fig. 2b), but not in below-ground tissue (-1.8%; 95% *CI*: -4.8%, +1.3%) (Fig 2c). For leaf/shoot litter, N addition significantly decreased its P concentration by an average of 8.9% (95% *CI*: -13%, -4.0%) across study sites (Fig. 1b).

Phosphatase activity was significantly increased by 24 % (95% *CI*: +13%, +35%) under N additions (Fig. 1c), with greater increase in plant roots (+62%; 95% *CI*: +37%, +91%) than in the soil (+16%; 95% *CI*: +5.4%, +37%) (Fig. S3). Total soil P was slightly decreased under N additions by an average of only 5.1% (95% *CI*: -10%, -0.5%) across study sites, while both funnel plot and Rosenthal's fail-safe number

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suggested a significant publication bias for this result (Appendix S2 and Fig. S1 in the Supporting Information). There was no significant change in soil labile P (-3.0%; 95% *CI*: -11%, +5.5%) and soil microbial P (+0.4%; 95% *CI*: -1.6%, +2.5%) under N additions (Fig. 1c).

N-induced changes in plant biomass and P concentration varied significantly among different ecosystem types (Appendix S3 in the Supporting Information). Under N additions, plant biomass was increased by an average of 69% (95% *CI*: +45%, +98%) in temperate forest, by 33% (95% *CI*: +24%, +44%) in grassland and by 37% (95% *CI*: +28%, +48%) in wetland (Fig. 3a). For tropical forest, no significant change in plant biomass was estimated under N additions (Fig. 3a). Plant P concentration was decreased by 3.9% (95% *CI*: -4.7%, -1.2%) in tropical forest, by 11% (95% *CI*: -15%, -5.9%) in temperate forest, by 11% (95% CI: -14%, -8.4%) in grassland and by 8.5% (95% *CI*: -12%, -5.4%) in wetland (Fig. 3b). In tundra or boreal forest, plant P concentration did not significantly change under N additions (Fig. 3b). The response of phosphatase activity and soil labile P to N additions also significantly varied among the ecosystem types (Appendix S3 in the Supporting Information). Under N additions, phosphatase activity was increased by 22.3% (95% *CI*: +3.9%, +44%) in temperate forest, by 40% (95% *CI*: +24%, +57%) in grassland, and by 43% (95% *CI*: +8.7%, +88%) in wetland (Fig. 3c). Among the ecosystem types, only in tropical forest soil labile P was significantly reduced by 24% (95% *CI*: -33%, -13%) under N additions (Fig. 3d).

Different N sources had significant effects on P concentrations for both plant and litter in responses to N additions (Appendix S3 in the Supporting Information). N application with mono sources ($NH_4^+$–N and $NO_3^-$–N) generally caused greater decreases in plant and litter P concentrations compared with N application with mixed sources (Urea–N and $NH_4NO_3$–N) (Fig. S4). The response of soil labile P to N additions was likely regulated by soil pH value at the control site, with significant decrease of 14% (95% *CI*: -30%, -9.4%) only in acidic soils (Fig. 4a). Different P extraction methods had minor effect on soil total P in response to N addition (Table S3

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in the Supporting Information), while the response of soil labile P significantly varied with P extraction methods (Appendix S3 in the Supporting Information). Among P extraction methods, only with the $NH_4F$ method soil labile P was significantly reduced by 18% under N additions (Fig. 4b). Soil P variables did not significantly change with soil depth probably due to very few studies that sampled soil in multiple depths (Appendix S4 in the Supporting Information).

As the annual rate of N additions or total N load increased, the log response ratio of P concentration in plant and litter decreased across all plant tissues and ecosystems (Appendix S4 in the Supporting Information; Fig. 5a-d). However, the latter (N load) relationships might be partly caused by the fact that N application rate and N load were highly correlated to each other, as experiment duration had no effects on plant and litter P concentrations (Appendix S4 in the Supporting Information). For all variables, no significant effect was found in soil type, soil organic C, and climatic factors (MAT and MAP) (Appendix S4 in the Supporting Information).

## DISCUSSION

Our results demonstrated that external N inputs can significantly alter terrestrial ecosystem P cycling across multiple ecosystems. Overall, N additions stimulated P sequestration in both plant and litter biomass (Fig. 1). The net P accumulation in plants and litter may be primarily attributed to the increased biomass production, as more P is required to maintain faster plant growth under N additions (Ågren, 2008; Harpole *et al.*, 2011; Yuan & Chen, 2015a). Consistent with previous meta-analysis studies (e.g. Aber et al., 1998; Xia & Wan, 2008; Liu & Greaver, 2010), N additions increased more biomass in the above-ground than below-ground tissues (Fig. 2a), while they stimulated P sequestration equally (Appendix S3 in in the Supporting Information). It appears that N additions did not alter P allocation pattern in plant tissues.

The greater uptake of P and consequently sequestration in biomass and litter

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under N additions (Fig. 1a, b) may result in a significant decrease in soil P, as P inputs are generally very low in natural ecosystems (Smil, 2000; Ilg *et al.*, 2009; Vitousek *et al.*, 2010). In our meta-analysis, N additions only slightly decreased soil total P and this result suffered from significant publication bias (Fig. 1c, Appendix S2 and Fig. S1 in in the Supporting Information). This is probably due to the dearth of long-term experiments (≤11 years) for soil total P in our dataset (Appendix S1 in in the Supporting Information). Given a much large P pool in soil than that in vegetation, it is difficult to detect a significant depletion in soil total P in a short-term (Vitousek *et al.*, 2010). Soil labile P fraction should be more sensitive to depletion than total P due to faster P uptake. However, our meta-analysis shows no change in soil labile P under N additions (Fig. 1c). This suggests that N additions likely promotes P mobilization, which is supported by the increase in phosphatase activity our and a previous meta-analysis showed (Fig. 1c; Marklein & Houlton, 2012). To meet greater P demands, trees may invest more C and other resources in root exudates and microbial symbioses that degrade clay minerals or organic P compounds (Chen *et al.*, 2008). In addition, the accumulation and recycling of P in litter may also account for the no change in soil labile P under N additions (Fig. 1b). P may be rapidly recycled internally through reabsorption and litter decomposition (Yuan & Chen, 2015b).

The decreased plant P concentration under N additions may not be simply related to decreasing P availability, since N additions increased phosphatase activity and did not change soil labile P in our meta-analysis (Fig. 1c). Alternatively, it may be due to the massive imbalance in soil availability of N and P with more N inputs, which stimulate plant to uptake more N but limit P uptake. We know that leaf photosynthesis rate is often positively correlated with foliar N and P concentrations (e.g., Reich *et al.*, 2010). Thus, the decrease in foliar P concentration observed in this study (Fig. 2b) suggests that N additions might actually induce P limitation that would have negative feedback on plant growth in response to the increased foliar N concentration under N additions. Li *et al.* (2016) also demonstrated that N enrichment aggravated P limitation on biomass production, and suggested that plant P concentration is the best

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indicator of these P limitations. P concentration in below-ground tissue was not changed under N additions, indicating that roots may be less affected by the reduced P availability compared to other plant tissues (Fig. 2b). However, the relatively smaller biomass gained in below-ground components may also contribute to this unchanged P concentration (Fig. 2a).

Although the very few study sites in certain ecosystems such as tundra or boreal forest limited us to fully evaluate the effect of ecosystem types on the response of P cycling to N additions (Appendix S3 in the Supporting Information), our meta-analysis clearly demonstrated that the responses in some P variables may be quite different between the tropical forest and other ecosystem types (Fig. 3). This suggests that the magnitudes of anthropogenic P limitation as well as the underlying mechanisms likely vary among these ecosystems. For example, we found that N additions significantly decreased plant P concentration and also soil labile P in the tropical forests (Fig. 3b, d). The combined decreases in plant P concentration and soil labile P indicates that N additions may induce greater P limitation to the tropical forests than other terrestrial ecosystems. In addition, plant growth in the tropical forests is less limited by N, due to that litter decomposition is fast and N availability is high (Cusack *et al.*, 2010). The greater P limitation likely offsets the slightly positive effect of N additions on plant growth in the tropical forests. As a result, our meta-analysis shows no significant response of plant biomass to N additions in the tropical forests (Fig. 3a).

Two processes may help explain the greater magnitudes of anthropogenic P limitation in the tropical forests. First, N additions can exacerbate soil acidification in the tropical forest (Tian & Niu, 2015). This exacerbated acidification may directly decrease soil P availability in the tropical forest by binding of phosphate ions with Al and Fe (Busman *et al.*, 2002; Devau *et al.*, 2009), as the tropical soils are often highly acidic (Vitousek *et al.*, 2010; Lu *et al.*, 2014). This was supported by that N additions significantly decreased soil labile P only in acidic soils (Fig. 5a). Second, the exacerbated acidification in the tropical forests may also restrain microbial activity

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and hence phosphatase activity. In fact, we found that N additions did not stimulate phosphatase activity in the tropical forests (Fig. 3c).

Our analysis suggests a significant effect of P extraction methods on the response of soil labile P to N additions (Fig. 4b; Appendix S3 in the Supporting Information). The use of different P extraction methods usually depends on the soil types sampled. For example, bicarbonate extractions are commonly used in soils with higher pH, while $NH_4F$ extractions are primarily used in acidic soils where soil labile P tends to decrease under N additions. There may also be a covariance with geography, as $NH_4F$ method is mainly used in North America and Oceania, but much less used in Europe or South America. Thus, the significant effect of the extraction method is likely due to a combination of methodological artifacts and covariance with physically significant soil properties.

There was a significant effect of N sources on the response of plant P concentration (Appendix S3 in the Supporting Information). Moreover, N additions with mono sources ($NH_4^+$–N and $NO_3^-$–N) generally caused greater decreases in plant P concentration compared with mixed sources (Urea–N and $NH_4NO_3$–N) (Fig. S4a). This suggests that other elements contained in $NH_4^+$–N or $NO_3^-$–N fertilizer regulate P availability or plant P uptake. For example, calcium nitrate additions may release calcium ion to bind with phosphate ions, in turn decreasing P availability in the soils (Devau *et al.*, 2009; Vitousek *et al.*, 2010). Thus, identity of any associated ions in N deposition in future studies is much important for accurate assessment of the impact of P limitation.

It is well understood that N application rate and total N load would have significant effects on the response of ecosystem P cycling as more N inputs would cause greater imbalance of N:P ratio. However, the quantification of their relationships remains challenging due to different background levels of soil N status and N deposition across study sites. For example, the tropic area generally experiences high N deposition in the past several decades, which may have

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contributed to a high N loading in the tropical forests (Huang *et al.*, 2012a). In these tropical forests, P cycling is very sensitive to N additions and even small N inputs may cause massive alterations in P cycling (Vitousek *et al.*, 1993; Huang *et al.*, 2012b). Despite such confounding factors, we did detect negative relationships of the change in plant P concentration with both N application rate and total N load (Fig. 5a, c). These findings indicate that the P limitation in terrestrial ecosystems could become a major challenge for us, if N deposition continues to increase in the future.

As with any meta-analysis, our results reflect uncertainty and assumptions in these case studies. For example, other soil properties such as soil texture, organic C, Al-Fe oxides and clay minerals may influence the dynamics of P availability (Yang & Post, 2011; Augusto *et al.*, 2013; Achat *et al.*, 2016b; Gerard, 2016). However, due to the limitation of data availability, we could not derive some clear relationships between them here (Appendix S3 and S4 in the Supporting Information). In addition, the dearth of long-term N manipulative experiments (90% studies of experimental duration are within 10 years) may limit us to obtain clearer trends of ecosystem P cycling in response to N additions. Thus, more long-term experiments are needed to observe P limitation with external N inputs.

Given the importance of P on plant growth and productivity, inclusion of P cycling in ecosystem models could significantly improve our ability to better forecast ecosystem C sequestration in the future. Recently, P modules have been built into ecosystem models such as CASA-CNP (Wang et al., 2010), JSBACH-CNP (Goll et al., 2012), CLM-CNP (Yang et al., 2014), and N-COM (Zhu et al., 2016) to investigate nutriment limitations on C cycling and C-N-P interactions. In these models, P is usually stored in several pools including plant biomass, litter, plant available P forms in the soils, and unavailable organic P forms in the soils (Smil, 2000; Vitousek *et al.*, 2010). Major P processes include P uptake, mineralization, immobilization, dissolution, precipitation, occlusion, and leaching. P dynamics are often coupled with C and/or N cycling through stoichiometric relationship of C, N and P in plant tissues and soils (Wang *et al.*, 2010; Goll *et al.*, 2012; Yang *et al.*, 2014). The results of

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enhanced plant P uptake and P mineralization with N additions in this meta-analysis would disproportionably alter P in different pools in the models, and ultimately result in greater P limitation. Our results of stimulated plant biomass and P contents in plant tissues with N additions were also supported by some model simulations. For example, Yang et al. (2014) found that, using the CLM-CNP model, plant production is substantially increased with N addition at the N-limited site, resulting in higher P uptake and P contents in plant biomass, considering that C:P ratios for plant tissues are kept constant in the model. But the model showed no impact with N additions at P-limited site, indicating the interaction of N and P could be complicated by field nutrient availability. The influences of N additions on the P pools and processes revealed in this study could help us understand the roles that N and P play in controlling plant growth and internal nutrient accumulation and accurately parameterize these C-N-P models. However, more nutrient addition experiments will benefit model testing and calibration (Reed et al. 2015; Achat *et al.*, 2016a).

To concluded, this study, to the best of our knowledge, is the first comprehensive evaluation of global response of the ecosystem P cycling to the external N inputs (Fig. 6). Previous synthesis has indicated that N inputs can accelerate terrestrial ecosystem P cycling due to stimulating phosphatase activity (Marklein & Houlton, 2012). Our results demonstrate that N additions accelerated P cycling but still decreased plant P concentration, and might eventually lead to P limitation in terrestrial ecosystems, particularly in tropical forests where both plant P concentration and soil labile P were reduced. In addition to the effect of faster plant growth and greater P demand, alterations in soil environment such as soil acidification and chemical reaction between phosphate ions and other associated ions in N fertilizers could also be a major cause of shift toward P limitation under N additions. Moreover, the P limitation could become more profound as total N load increases. The effects of continuous anthropogenic N enrichment on ecosystem structure and function will likely be constrained by the P availability in the future. To improve the prediction of the potential impacts of anthropogenic P limitation in ecosystem modeling, ecosystem

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type, soil properties, previous and future N loads, as well as other associated ions in N deposition must be considered (Fig. 6).

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## APPENDIX 1: DATA SOURCES

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## SUPPORTING INFORMATION

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

**Appendix S1.** Studies included in the meta-analysis.

**Appendix S2.** Rosenthal's fail-safe number used to test the publication bias.

**Appendix S3.** Statistical significances of effects of categorical factors.

**Appendix S4.** Statistical significances of relationships between the response ratio and continuous factors.

**Fig. S1.** Funnel plots of the effect size plotted against the precision for each P variable.

**Fig. S2.** Sensitivity analysis for each P variable.

**Fig. S3.** Percentage change (×100) of phosphatase activity in plant root and soil under N additions.

**Fig. S4.** Percentage change (×100) of plant P concentration (a) and litter P concentration (b) to N additions with different N sources.

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## FIGURE LEGENDS

**Fig 1.** Percentage change (×100) of ecosystem P cycling to N additions. Error bars represent 95% bootstrap confidence intervals. The sample size for each variable is shown next to the error bar. *: significant publication bias for the analysis suggested by both funnel plot and Rosenthal's fail-safe number.

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**Fig. 2.** Percentage change (×100) of plant biomass (a) and plant P concentration (b) in different plant tissues. Error bars represent 95% confidence intervals. The sample size for each variable is shown next to the error bar. Statistical significances of effects of plant tissue were evaluated based on a chi-square test (also see Appendix S3 in the Supporting Information).

**Fig. 3.** Percentage change (×100) of plant biomass (a), plant P concentration (b), phosphatase activity (c), and soil labile P (d) to N additions in different ecosystem types. Error bars represent 95% confidence intervals. The sample size for each variable is shown next to the error bar. Statistical significances of effects of ecosystem type were evaluated based on a chi-square test (also see Appendix S3 in the Supporting Information).

**Fig. 4.** Percentage change (×100) of soil labile P with different soil pH value (a) and with different P extraction methods (b). Error bars represent 95% confidence intervals. The sample size for each variable is shown next to the error bar. Alkaline: pH > 7.5; acidic: pH < 5.5; and neutral: pH = 5.5-7.5. Statistical significances of effects of P extraction method were evaluated based on a chi-square test (also see Appendix S3 in the Supporting Information).

**Fig. 5.** Log response ratios of plant P concentration (a, c) and litter P concentration (b, d) as a function of N application rate and total N load, and Log response ratios of soil labile P as a function of control soil pH value. Statistical significances of relationships were evaluated based on an F-test (also see Appendix S4 in the

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Supporting Information).

**Fig. 6.** A quantitative framework for the responses of ecosystem P cycling to N additions. +: positive; -: negative; n.s.: non-significant; $^{\#}$: data for soil microbe and pH from Treseder (2008) and Tian & Niu (2015), respectively. *: significant publication bias for the analysis suggested by both funnel plot and Rosenthal's fail-safe number.

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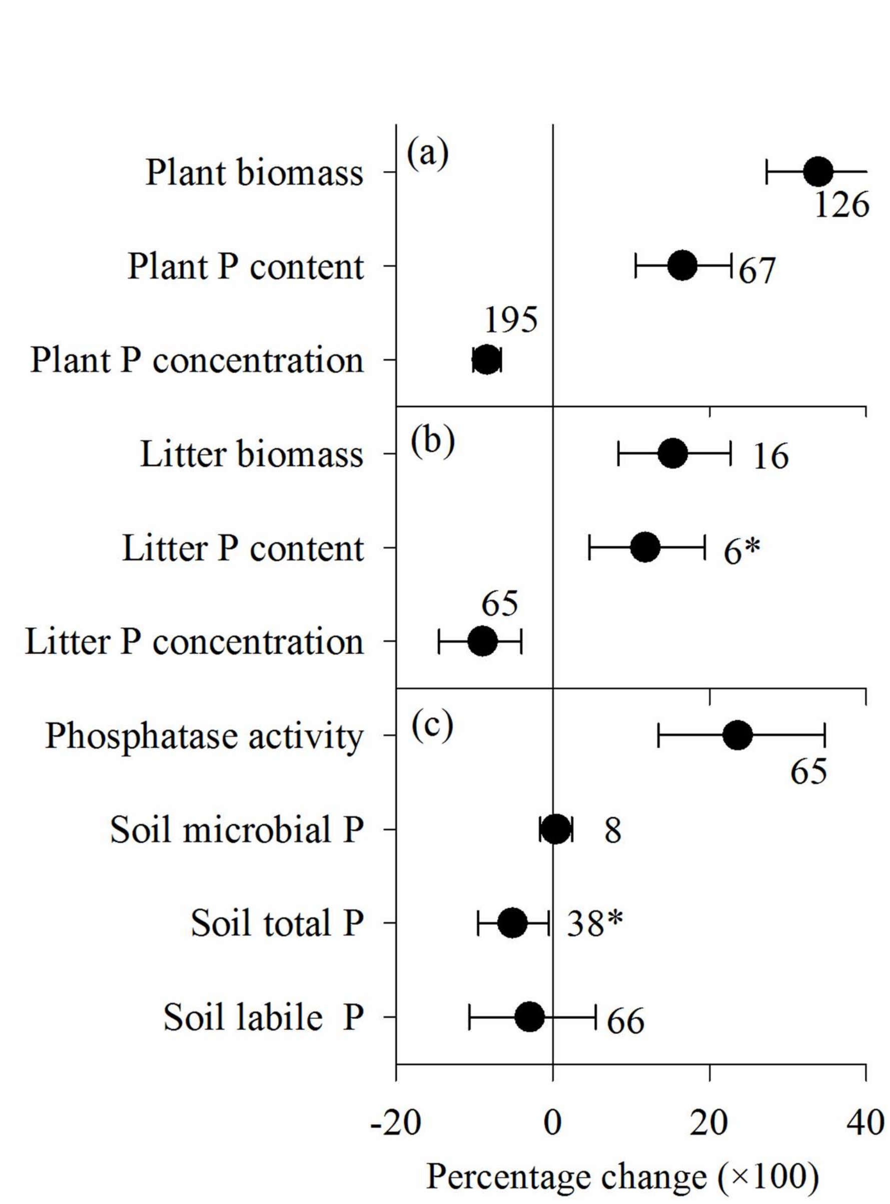

Fig 1. Percentage change (×100) of ecosystem P cycling to N additions. Error bars represent 95% bootstrap confidence intervals. The sample size for each variable is shown next to the error bar. *: significant publication bias for the analysis suggested by both funnel plot and Rosenthal's fail-safe number.
Fig. 1
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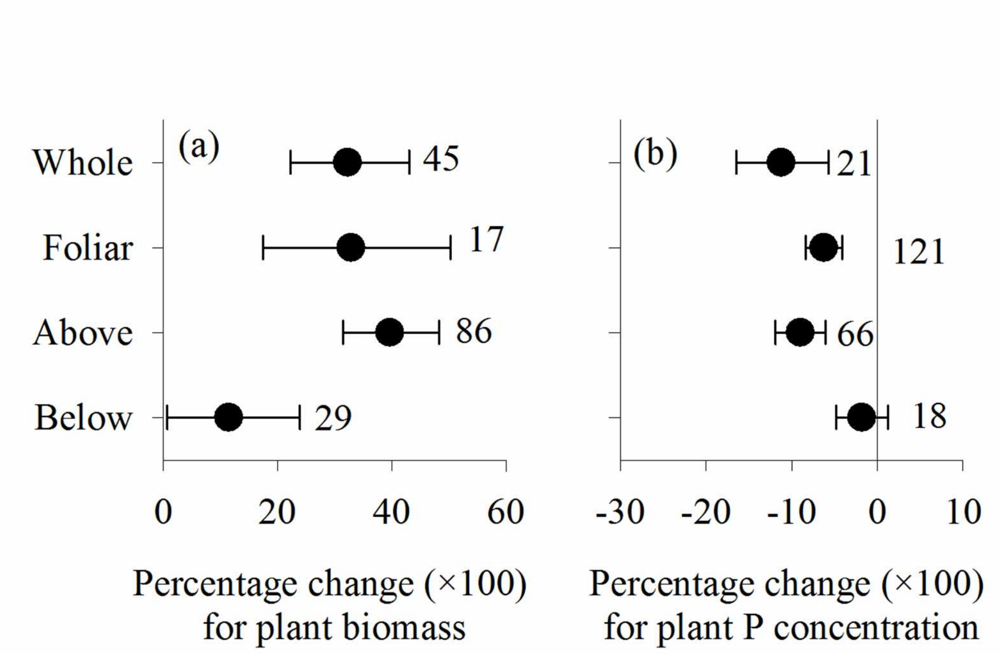

Fig. 2. Percentage change (×100) of plant biomass (a) and plant P concentration (b) in different plant tissues. Error bars represent 95% confidence intervals. The sample size for each variable is shown next to the error bar. Statistical significances of effects of plant tissue were evaluated based on a chi-square test (also see Appendix S3 in the Supporting Information).
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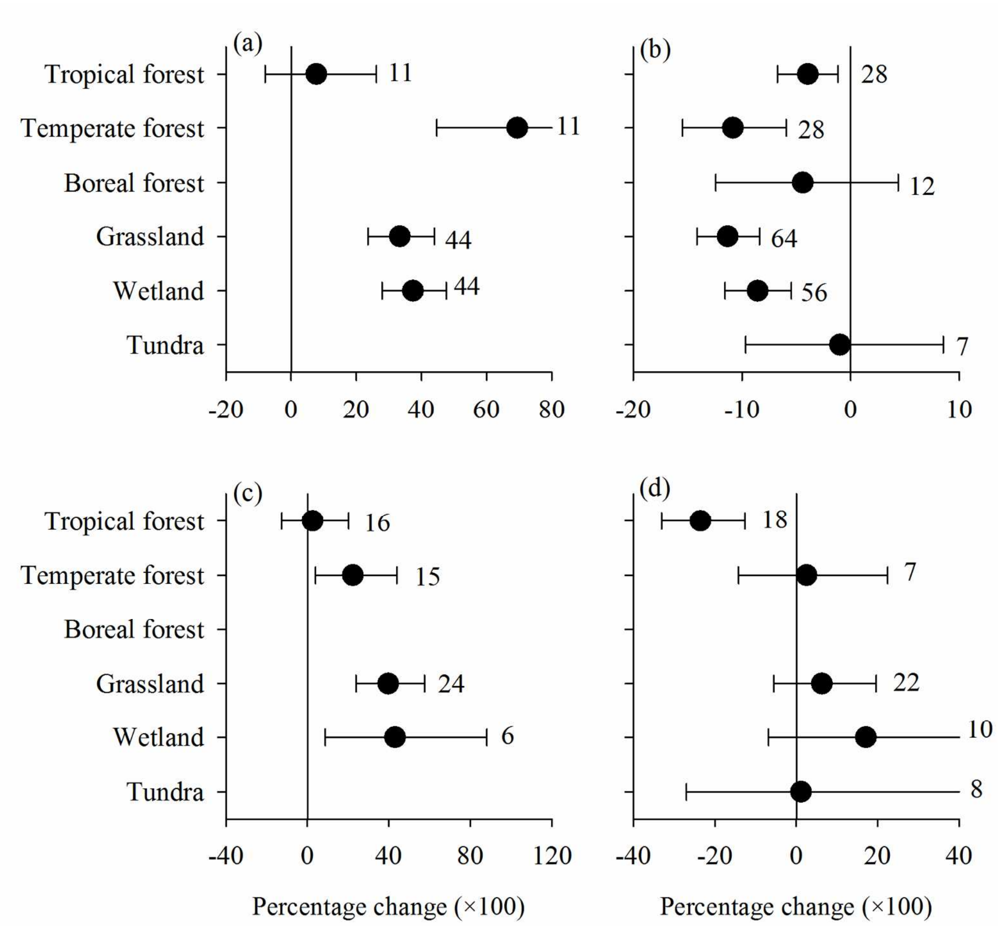

Fig. 3. Percentage change (×100) of plant biomass (a), plant P concentration (b), phosphatase activity (c), and soil labile P (d) to N additions in different ecosystem types. Error bars represent 95% confidence intervals. The sample size for each variable is shown next to the error bar. Statistical significances of effects of ecosystem type were evaluated based on a chi-square test (also see Appendix S3 in the Supporting Information).

Fig. 3

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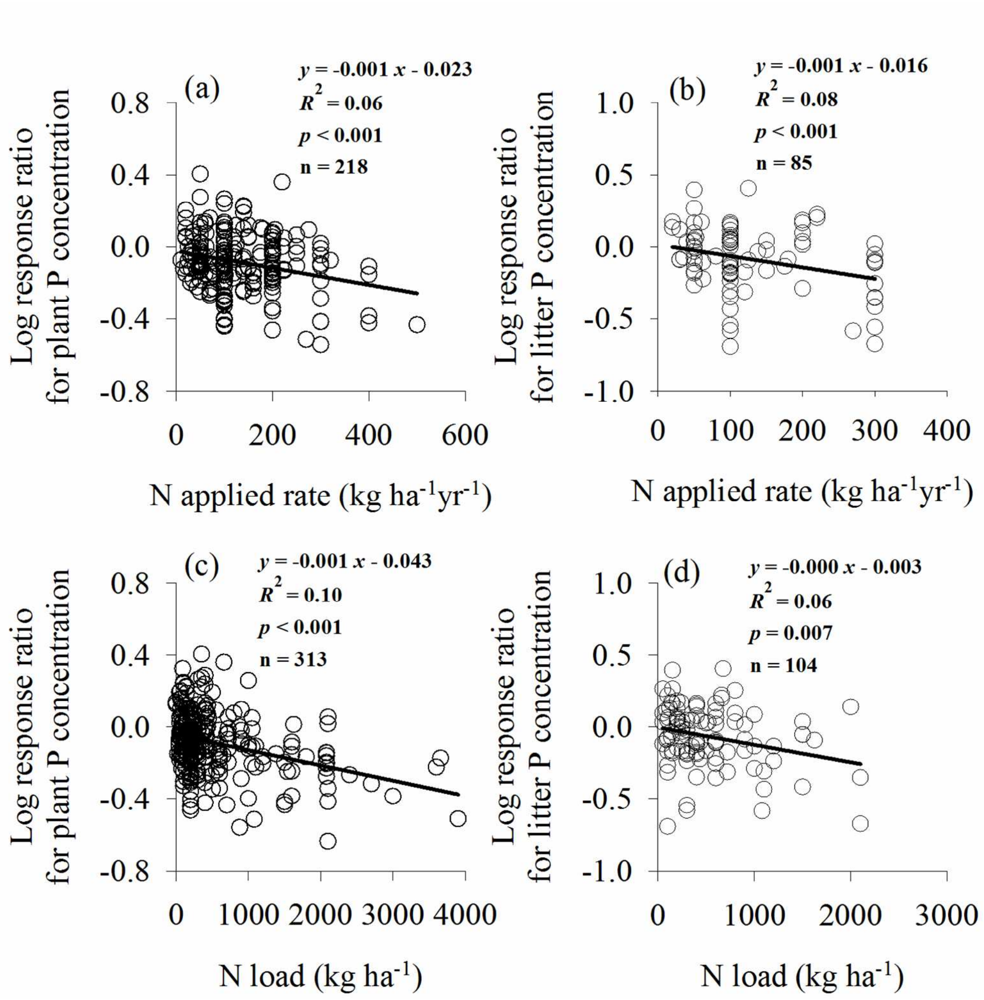

Fig. 4. Percentage change (×100) of soil labile P with different soil pH value (a) and with different P extraction methods (b). Error bars represent 95% confidence intervals. The sample size for each variable is shown next to the error bar. Alkaline: pH > 7.5; acidic: pH < 5.5; and neutral: pH = 5.5-7.5. Statistical significances of effects of P extraction method were evaluated based on a chi-square test (also see Appendix S3 in the Supporting Information).

Fig. 4

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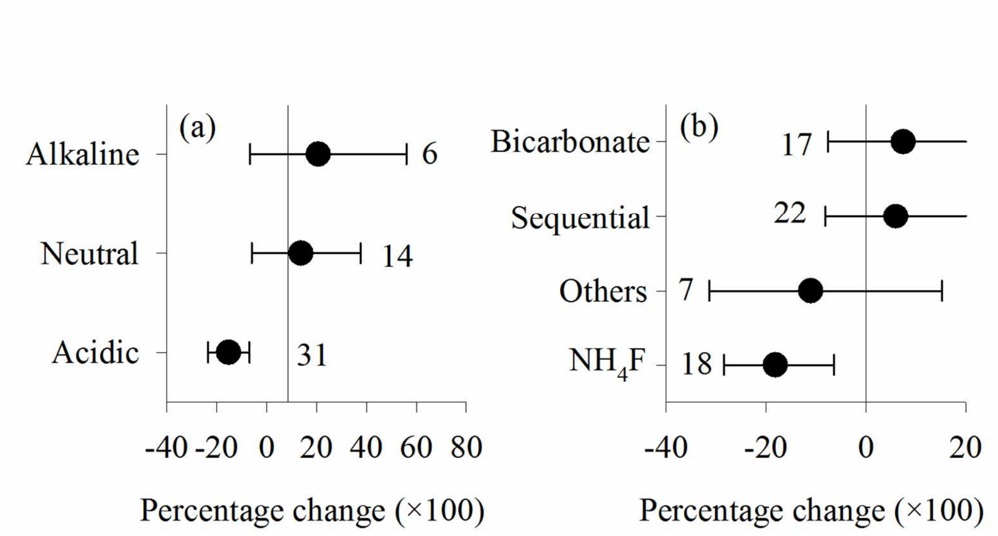

Fig. 5. Log response ratios of plant P concentration (a, c) and litter P concentration (b, d) as a function of N application rate and total N load, and Log response ratios of soil labile P as a function of control soil pH value. Statistical significances of relationships were evaluated based on an F-test (also see Appendix S4 in the Supporting Information).
Fig. 5
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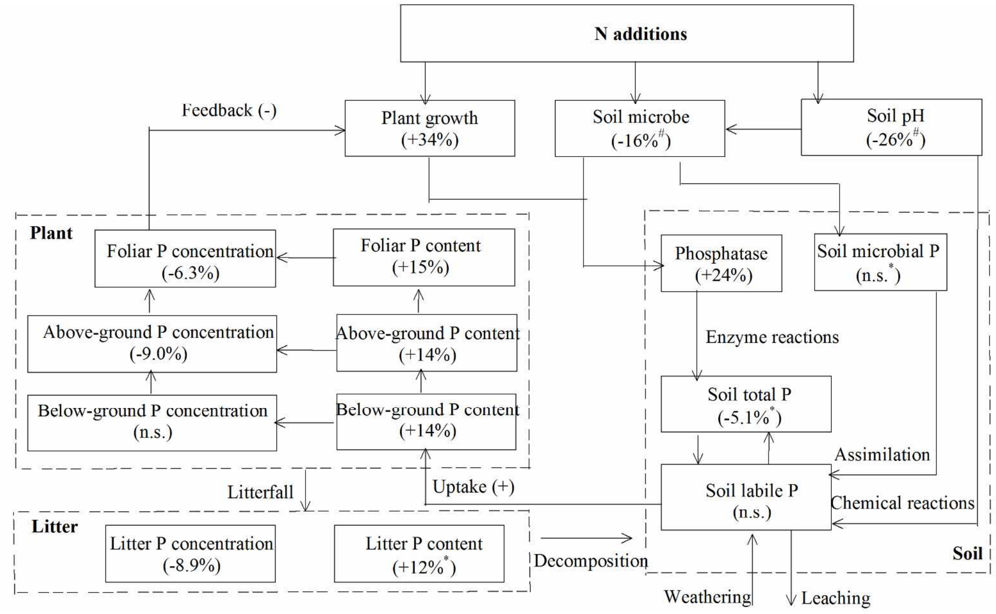

Fig. 6. A quantitative framework for the responses of ecosystem P cycling to N additions. +: positive; -: negative; n.s.: non-significant; #: data for soil microbe and pH from Treseder (2008) and Tian & Niu (2015), respectively. *: significant publication bias for the analysis suggested by both funnel plot and Rosenthal's fail-safe number.
Fig. 6
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# Responses of terrestrial ecosystem phosphorus cycling to nitrogen additions: a meta-analysis

Qi Deng, Dafeng Hui, Sam Dennis, & K. Chandra Reddy

## Supporting Information

**Appendix S1.** Studies included in the meta-analysis.

**Appendix S2.** Rosenthal's fail-safe number used to test the publication bias.

**Appendix S3.** Statistical significances of effects of categorical factors on the response ratios were evaluated based on a chi-square test.

**Appendix S4.** Statistical significances of relationships between the response ratio and continuous factors were evaluated based on a F-test.

**Fig. S1.** Funnel plots of the effect size (log response ratio) plotted against the precision (the reverse of standard error of the response ratio) for each P variable (a, plant biomass; b, plant P content; c, plant P concentration; d, litter biomass; e, litter P content; f, litter P concentration; g, phosphatase activity; h, soil microbial P; i, soil total P; j, soil labile P). The blue line represents the mean log response ratio (*RR*)of N additions on ecosystem P cycling.

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**Fig. S2.** Sensitivity analysis for each P variable (a, plant biomass; b, plant P content; c, plant P concentration; d, litter biomass; e, litter P content; f, litter P concentration; g, phosphatase activity; h, soil microbial P; i, soil total P; j, soil labile P). The blue line represents the mean log response ratio (*RR*) of N additions on ecosystem P cycling using the dataset from all study site. Circles show estimates of mean *RR* when one study site is removed.

**Fig. S3.** Percentage change (×100) of phosphatase activity in plant root and soil under N additions. Error bars represent 95% confidence intervals. The sample size for each variable is shown next to the error bar. Statistical significances of response ratios between plant root phosphatase activity and soil phosphatase activity were evaluated based on a *t*-test.

**Fig. 4.** Percentage change (×100) of plant P concentration (a) and litter P concentration (b) to N additions with different N sources. Error bars represent 95% confidence intervals. The sample size for each variable is shown next to the error bar. Statistical significances of effects of N source applied were evaluated based on a chi-square test (also see Appendix S3 in the Supporting Information).

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**Appendix S1** Experimental sites included in meta-analysis. The selected 10 variables including plant biomass, P content and P concentration, litter biomass, P content and P concentration, phosphatase activity, soil microbial P, soil total P and labile P.

| Number | Reference | Ecosystem | N source | N applied rate (kg N ha$^{-1}$ yr$^{-1}$) | Duration (yr) | Total N load (kg N ha$^{-1}$) | P variable |
|---|---|---|---|---|---|---|---|
| 1 | Adamek, 2009 | Tropical Forest | Urea | 125 | 1.4 | 250 | Plant biomass, P content and P concentration, litter biomass and soil total P. |
| 2 | Adegbidi et al., 2003 | Temperate Forest | Urea | 300 | 3.4 | 900 | Plant biomass and soil total P. |
| 3 | Aerts & Berendse, 1988 | Temperate Forest | $NH_4NO_3$ | 200 | 2.4 | 600 | Plant biomass, P content and P concentration. |
| 4 | Aerts et al., 2001 | Wetland | $NH_4NO_3$ | 100 | 3.4 | 400 | Plant biomass, P content and P concentration. |
| 5 | Aerts et al., 2003a | Grassland | $NH_4NO_3$ | 100 | 11 | 1100 | Plant biomass, P content and P concentration, soil total and labile P. |
| 6 | Aerts et al., 2003b | Grassland | $NH_4NO_3$ | 100 | 11 | 1100 | Litter P concentration. |
| 7 | Aerts et al., 2006 | Wetland | $NH_4^+$ | 100 | 4 | 400 | Litter P concentration. |
| 8 | Aerts, 2009 | Wetland | $NH_4^+$ | 50 | 4 | 200 | Litter P concentration. |
| 9 | Akinola et al., 2010 | Grassland | Urea | 23 | 1.5 | 46 | Plant biomass, P content and P concentration. |
| 10 | Allen et al., 2010 | Temperate Forest | $NH_4NO_3$ | 100 | 7 | 700 | Plant P concentration and soil labile P. |
| 11 | An et al., 2011 | Grassland | Urea | 138 | 0.3 | 138 | Plant P concentration and litter P concentration |
| 12 | Andersen et al., 2010 | Tropical Forest | Urea | 125 | 1.4 | 250 | Plant biomass, P content and P concentration, and soil labile P. |
| 13 | Arroniz-Crespo et al., 2008 | Grassland | $NH_4NO_3$ | 140 | 11.2 | 1400 | Plant P concentration and phosphatase activity. |
| 14 | Barger et al., | Grassland | Urea | 200 | 0.4 | 200 | Plant biomass and P concentration, and soil |

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|---|---|---|---|---|---|---|---|
| | 2002 | | | | | | labile P. |
| | Barger et al., 2003 | Grassland | Urea | 200 | 0.4 | 200 | Plant biomass and P concentration, and soil labile P. |
| | Bassin et al., 2012 | Grassland | $NH_4NO_3$ | 50 | 2 | 100 | Plant biomass and P concentration. |
| | Bennett & Adams, 2001 | Grassland | Urea | 50 | 2 | 100 | Plant biomass, P content and P concentration, litter biomass, P content and P concentration. |
| | Birk &Vitousek, 1986 | Temperate Forest | $NH_4NO_3$ | 450 | 0.5 | 450 | Plant biomass and soil labile P. |
| | Blanke et al., 2011 | Grassland | $NH_4NO_3$ | 85 | 4 | 340 | Plant biomass, P content and P concentration, and soil labile P. |
| | Blanke et al., 2012 | Grassland | $NH_4NO_3$ | 50 | 2 | 100 | Plant biomass, P content and P concentration. |
| | Bobbink et al., 1991 | Grassland | $NH_4NO_3$ | 100 | 2 | 200 | Plant biomass, P content and P concentration |
| | Bowman et al., 1993 | Tundra | Urea | 250 | 1.3 | 500 | Plant biomass and P concentration, and soil labile P. |
| | Bowman, 1994 | Tundra | Urea | 250 | 1.3 | 500 | Plant biomass, P content and P concentration. |
| | Braun et al., 2010 | Temperate Forest | $NH_4NO_3$ | 160 | 14 | 2240 | Plant P concentration and phosphatase activity. |
| | Britton et al., 2008 | Grassland | $NH_4NO_3$ | 50 | 3 | 150 | Plant P concentration. |
| | Bubier et al., 2011 | Wetland | $NH_4NO_3$ | 200 | 8 | 1600 | Plant P concentration. |
| | Bucci et al., 2006 | Grassland | $NH_4NO_3$ | 100 | 1.7 | 200 | Plant P concentration. |
| | Campo & Dirzo, 2003 | Tropical Forest | Urea | 220 | 3.9 | 880 | Plant P concentration. |
| | Campo et al., 2007 | Tropical Forest | Urea | 220 | 3.9 | 880 | Litter biomass, P content and P concentration. |

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| Chiang et al., 2000 | Wetland | $NH_4^+$ | 140 | 4 | 640 | Plant biomass and P concentration. |
| Clarholm, 1993 | Boreal Forest | $NH_4NO_3$ | 60 | 21 | 1260 | Plant P concentration, phosphatase activity and soil microbial P |
| Corbin et al., 2003 | Temperate Forest | $NH_4NO_3$ | 97 | 3 | 291 | Plant biomass, P content and P concentration, and soil labile P. |
| Craft et al., 1995 | Wetland | $NH_4^+$ | 224 | 2 | 448 | Plant biomass, P content and P concentration, soil total and labile P. |
| Craine et al., 2008 | Grassland | $NH_4NO_3$ | 100 | 1.6 | 200 | Plant biomass, P content and P concentration. |
| Cuevas-Reyes et al., 2011 | Grassland | $NH_4NO_3$ | 100 | 1.7 | 200 | Plant P concentration. |
| Cui et al., 2010 | Grassland | $NH_4NO_3$ | 205 | 2 | 410 | Plant P concentration and soil labile P. |
| Cusack et al., 2010 | Tropical Forest | $NH_4NO_3$ | 50 | 5.7 | 300 | Phosphatase activity. |
| D'Antonio & Mack, 2006 | Grassland | Urea | 100 | 0.4 | 100 | Plant and litter P concentration |
| Davidson et al., 2004 | Tropical Forest | Urea | 100 | 0.5 | 100 | Plant biomass and P concentration, litter P concentration, soil total and labile P. |
| Davison et al., 1997 | Grassland | Urea | 300 | 7 | 2100 | Plant and litter P concentration, soil total and labile P. |
| DeForest et al., 2004 | Temperate Forest | $NH_4NO_3$ | 30 | 1 | 30 | Phosphatase activity. |
| Drenovsky & Richards, 2004 | Temperate Forest | $NH_4NO_3$ | 210§ | 2 | 420§ | Plant P concentration. |
| Drenovsky & Richards, 2005 | Temperate Forest | $NH_4NO_3$ | 233.6§ | 1 | 233.6§ | Plant P concentration. |
| Du & Fang, 2014 | Boreal Forest | $NH_4NO_3$ | 100 | 2 | 200 | Plant biomass and P concentration. |

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| Elvir et al., 2006 | Temperate Forest | $NH_4^+$ | 25.2 | 14 | 352.8 | Plant biomass and P concentration. |
| Falk et al., 2010 | Grassland | $NH_4NO_3$ | 50 | 2 | 100 | Plant biomass, P content and P concentration, and soil labile P. |
| Fang et al., 2012 | Grassland | Urea | 320 | 7 | 2240 | Plant biomass, P content and P concentration, soil total and labile P. |
| Feller et al., 1999 | Wetland | Urea | 150§ | 5 | 750§ | Plant biomass, P content and P concentration. |
| Feller et al., 2003a | Wetland | Urea | 150§ | 2 | 300§ | Plant and litter P concentration. |
| Feller et al., 2003b | Wetland | Urea | 150§ | 2 | 300§ | Plant and litter P concentration. |
| Feller et al., 2007 | Wetland | Urea | 150§ | 4 | 600§ | Plant and litter P concentration, and soil labile P. |
| Feller et al., 2009 | Wetland | Urea | 150§ | 4 | 600§ | Litter P concentration. |
| Feller, 1995 | Wetland | Urea | 150§ | 2 | 300§ | Plant P concentration and soil labile P. |
| Ferdie & Fourqurean, 2004 | Wetland | Urea | 77 | 1.2 | 77 | Plant biomass and P concentration. |
| Fetcher et al., 1996 | Tropical Forest | Urea | 102 | 0.7 | 102 | Plant biomass and P concentration. |
| Frost et al., 2009 | Wetland | $NH_4^+$ | 500 | 2.4 | 1000 | Plant biomass and P concentration. |
| Gerdol et al., 2007 | Wetland | $NH_4NO_3$ | 30 | 3 | 90 | Plant biomass, P content and P concentration. |
| Gordon et al., 2001 | Tundra | $NH_4NO_3$ | 50 | 7 | 350 | Plant P concentration. |
| Grogan & Chapin III, 2000 | Grassland | $NH_4NO_3$ | 20 | 1 | 20 | Plant biomass, P content and P concentration. |
| Gundersen, 1998 | Boreal Forest | $NH_4NO_3$ | 35 | 4 | 140 | Plant P concentration, litter biomass, P content and P concentration. |
| Güsewell et al., 2002 | Wetland | $NH_4NO_3$ | 200 | 2 | 400 | Plant biomass, P content and P concentration, and soil labile P. |

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| Güsewell et al., 2003 | Wetland | $NH_4NO_3$ | 200 | 2 | 400 | Plant biomass, P content and P concentration. |
| Gutknecht et al., 2010 | Grassland | $NO_3^-$ | 70 | 6 | 420 | Phosphatase activity. |
| Haines et al., 2015 | Grassland | $NH_4NO_3$ | 135 | 2.6 | 405 | Plant biomass, P content and P concentration, and soil labile P. |
| Han et al., 2014 | Grassland | $NH_4NO_3$ | 100 | 3.8 | 400 | Plant biomass, P content and P concentration. |
| Heijmans et al., 2001 | Wetland | $NH_4NO_3$ | 50 | 2.3 | 150 | Plant biomass, P content and P concentration. |
| Heijmans et al., 2002a | Wetland | $NH_4NO_3$ | 50 | 1.4 | 100 | Plant biomass, P content and P concentration. |
| Heijmans et al., 2002b | Wetland | $NH_4NO_3$ | 50 | 1.4 | 100 | Plant biomass and P concentration, litter biomass, P content and P concentration. |
| Henry et al., 2006 | Grassland | $NO_3^-$ | 70 | 6.5 | 490 | Plant biomass, P content and P concentration. |
| Herbert, 1995 | Tropical Forest | $NH_4NO_3$ | 100 | 1.6 | 200 | Plant biomass and P concentration, and litter biomass. |
| Herbert & Fownes, 1995 | Tropical Forest | $NH_4NO_3$ | 100 | 1.6 | 200 | Plant biomass and P concentration, and litter biomass. |
| Herbert et al., 1999 | Tropical Forest | $NH_4NO_3$ | 100 | 1.6 | 200 | Plant biomass and P concentration, and litter biomass. |
| Hobbie et al., 2000 | Tropical forest | $NH_4NO_3$ | 300 | 13 | 3900 | Litter P concentration. |
| Hogan et al., 2010 | Wetland | $NO_3^-$;<br>$NH_4^+$;<br>$NH_4NO_3$ | 56 | 3.6 | 224 | Phosphatase activity. |
| Högberg et al., 2006 | Boreal Forest | $NH_4NO_3$ | 118 | 30 | 3540 | Plant P concentration. |
| Holub & Tůma, 2010 | Wetland | $NH_4NO_3$ | 50 | 2 | 100 | Plant biomass, P content and P concentration. |

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| Holub & Záhora, 2008 | Grassland | $NH_4NO_3$ | 50 | 2 | 100 | Plant biomass, P content and P concentration, and litter P concentration. |
| Holub et al., 2010 | Grassland | $NH_4NO_3$ | 50 | 2 | 100 | Plant biomass, P content and P concentration, and litter P concentration. |
| Hoosbeek et al., 2002 | Wetland | $NH_4NO_3$ | 30 | 3 | 90 | Litter P concentration. |
| Hu et al., 2010 | Boreal Forest | $NH_4NO_3$ | 100 | 6.3 | 700 | Phosphatase activity and soil total P. |
| Huang et al., 2012a | Tropical forest | $NH_4NO_3$ | 100 | 4.5 | 500 | Plant P concentration. |
| Huang et al., 2012b | Tropical forest | $NH_4NO_3$ | 100 | 6 | 600 | Phosphatase activity and soil total P. |
| Huang et al., 2015 | Tropical forest | $NH_4NO_3$ | 100 | 4.5 | 500 | Plant biomass, P content and P concentration. |
| Huber et al., 2004 | Temperate Forest | $NH_4^+$; $NH_4NO_3$ | 62 | 7 | 434 | Plant and litter P concentration. |
| Huenneke et al., 1990 | Grassland | $NH_4NO_3$ | 100 | 2 | 200 | Plant biomass and soil labile P. |
| Jacobson & Pettersson, 2001 | Boreal Forest | $NH_4NO_3$ | 150 | 7 | 1050 | Plant P concentration. |
| Joergensen & Scheu, 1999 | Boreal Forest | $NH_4NO_3$ | 1080 | 1.3 | 1320 | Soil microbial P. |
| Johnson et al., 1997 | Temperate Forest | $NH_4^+$ | 200 | 3.5 | 800 | Plant biomass, P content and P concentration, soil total and labile P. |
| Johnson et al., 1998 | Grassland | $NH_4NO_3$ | 120 | 7 | 840 | Phosphatase activity. |
| Johnson et al., 1999 | Grassland | $NH_4NO_3$ | 140 | 6 | 840 | Plant P concentration and phosphatase activity. |
| Judd et al., 1996 Temperate Urea 400 4 1600 Plan | | | | | | t biomass and P concentration. |

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| | | Forest | | | | | |
| | Keeler et al., 2009 | Grassland; Temperate Forest | $NH_4NO_3$ | 100 | 6 | 600 | Phosphatase activity. |
| | Ket et al., 2011 | Wetland | $NH_4^+$ | 50 | 4 | 200 | Plant biomass and P concentration. |
| | Kishchuk et al., 2002 | Boreal Forest | $NH_4NO_3$ | 150 | 14 | 2100 | Plant P concentration. |
| | Koehler et al., 2009 | Tropical forest | Urea | 125 | 8 | 1000 | Soil total P. |
| Kozovits et al., 2007 | | Grassland | $NH_4NO_3$ | 100 | 1.7 | 200 | Plant and litter P concentration. |
| Li et al., 2010 Grassland NH | | | $_4NO_3$ | 200 | 5 | 1000 | Plant biomass and P concentration. |
| Li et al., 2012 Grassland NH | | | $_4NO_3$ | 200 | 5 | 1000 | Litter P concentration, soil total and labile P. |
| Li J et al., 2015 Tropical | | forest | $NH_4NO_3$ | 100 | 3.1 | 100 | Soil labile P. |
| 0 Li X et al., 2015 Grassland NH | | | $_4NO_3$ | 100 | 3.3 | 400 | Plant and litter P concentration. |
| 1 Limpens et al., 2004 | | Wetland | $NH_4NO_3$ | 40 | 3 | 120 | Soil labile P. |
| 2 Liu et al., 2010 Grassland Urea 640 2 1280 Litt | | | | | | | er P concentration. |
| 3 | Liu et al., 2012 | Tropical forest | $NH_4NO_3$ | 100 | 4.5 | 500 | Plant P concentration. |
| 4 | Liu et al., 2013 | Tropical forest | $NH_4NO_3$ | 100 | 4.5 | 500 | Plant P concentration. |
| 5 | Liu et al., 2015 | Tropical forest | $NH_4NO_3$ | 100 | 4.5 | 500 | Litter P concentration. |
| 6 | Lovelock et al., 2004 | Wetland | Urea | $300^{\S}$ | 2.5 | $900^{\S}$ | Plant P concentration. |
| 7 | Lovelock et al., 2007 | Wetland | Urea | $300^{\S}$ | 4 | $1200^{\S}$ | Litter P concentration. |

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| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 8 | Lu et al., 2012 | Tropical forest | $NH_4NO_3$ | 100 | 6 | 600 | Soil labile P. |
| 9 | Ludwig et al., 2001 | Grassland | $NO_3^-$ | 200 | 2.5 | 600 | Plant biomass and P concentration. |
| 0 | Lv et al., 2011 | Grassland | $NH_4NO_3$ | 175 | 2.8 | 525 | Plant P concentration. |
| 1 | Lv et al., 2012 | Grassland | $NH_4NO_3$ | 175 | 2.8 | 525 | Plant and litter P concentration, and soil labile P. |
| 2 | Mao et al., 2013 | Wetland | $NH_4^+$ | 120 | 6.5 | 840 | Plant biomass and P concentration, litter biomass, P content and P concentration. |
| 3 | Mao et al., 2014 | Wetland | $NH_4NO_3$ | 120 | 6 | 720 | Plant biomass and P concentration. |
| 4 | May et al., 2005 | Temperate Forest | $NH_4^+$ | 35 | 12 | 420 | Plant P concentration. |
| 5 | Mayor et al., 2014a | Tropical forest | Urea | 125 | 12.7 | 1625 | Soil labile P. |
| 6 | Mayor et al., 2014b | Tropical forest | Urea | 125 | 12.7 | 1625 | Plant and litter P concentration. |
| 7 | McDowell & Koopmans, 2006 | Grassland | Urea | 400 | 9 | 3600 | Phosphatase activity, soil total and labile P. |
| 8 | McKenzie & Jacobs, 2002 | Grassland | Urea | 60 | 1 | 60 | Plant P concentration. |
| 9 | Menge, 2003 | Grassland | $NO_3^-$ | 270 | 4 | 1080 | Plant and litter P concentration, and phosphatase activity. |
| 0 | Mirmanto et al., 1999 | Tropical forest | Urea | 225 | 3.2 | 675 | Litter biomass, P content and P concentration. |
| 1 | Mo et al., 2008 | Tropical forest | $NH_4NO_3$ | 300 | 1.1 | 300 | Plant biomass and P concentration, and soil labile P. |
| 2 | Morecroft et al., 1994 | Grassland | $NH_4NO_3$ | 140 | 3 | 420 | Plant P concentration. |
| 3 | Morse et al., 2004 | Wetland | Urea | 225 | 1 | 225 | Plant biomass and soil total P. |
| 4 | Niinemets & | Grassland | $NH_4NO_3$ | 40 | 1 | 40 | Plant biomass, P content and P concentration. |

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| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | Kull, 2005 | | | | | | |
| 5 | Ochoa-Hueso & Stevens, 2013a | Temperate Forest | $NH_4NO_3$ | 50 | 3 | 150 | Soil total and labile P. |
| 6 | Ochoa-Hueso & Stevens, 2013b | Temperate Forest | $NH_4NO_3$ | 50 | 3 | 150 | Phosphatase activity. |
| 7 | Ochoa-Hueso & Stevens, 2015 | Temperate Forest | $NH_4NO_3$ | 50 | 3 | 150 | Plant biomass and soil labile P. |
| 8 | Øien, 2004 | Wetland | Urea | 120 | 2 | 240 | Plant biomass, P content and P concentration. |
| 9 | Ostertag, 2010 | Tropical forest | $NH_4NO_3$ | 300 | 13 | 3900 | Plant P concentration. |
| 0 | Otto et al., 2007 | Temperate Forest | $NH_4NO_3$ | 80 | 3 | 240 | Plant P concentration. |
| 1 | Pakeman & Lee, 1991 | Grassland | $NH_4NO_3$ | 175 | 0.5 | 175 | Plant biomass and P concentration. |
| 2 | Pasquini & Santiago, 2011 | Tropical forest | $NH_4NO_3$ | 150 | 7.5 | 1200 | Plant P concentration. |
| 3 | Persson & Ahlstrom, 2002 | Boreal Forest | $NH_4NO_3$ | 200 | 4 | 800 | Plant biomass, P content and P concentration. |
| 4 | Pilkington et al., 2005 | Wetland | $NH_4NO_3$ | 50 | 1.2 | 50 | Phosphatase activity. |
| 5 | Plassmann et al., 2009 | Grassland | $NO_3^-$ | 50 | 2.1 | 100 | Plant biomass, P content and P concentration. |
| 6 | Raich et al., 1996 | Tropical Forest | $NH_4NO_3$ | 100 | 2 | 200 | Plant biomass and P concentration. |
| 7 | Rainey et al., 1999 | Temperate Forest | $NH_4NO_3$ | 150 | 7.5 | 1200 | Plant biomass, P content and P concentration. |
| 8 | Rejmánková & Snyder, 2008 | Wetland | $NH_4NO_3$ | 200 | 4 | 800 | Plant and litter P concentration, and phosphatase activity. |
| 9 | Robinson et al., | Tundra | $NH_4NO_3$ | 50 | 1.2 | 50 | Soil total and labile P. |

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| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | 2004 | | | | | | |
| 0 | Robroek et al., 2009 | Grassland | $NH_4NO_3$ | 20 | 2.1 | 40 | Plant biomass, P content and P concentration, phosphatase activity, soil total and labile P. |
| 1 | Roem et al., 2002 | Grassland | $NH_4NO_3$ | 100 | 5 | 500 | Plant biomass and P concentration. |
| 2 | Rueth et al., 2003 | Boreal Forest | $NH_4NO_3$ | 25 | 3 | 75 | Plant P concentration. |
| 3 | Sarmiento et al., 2006 | Grassland | Urea | 100 | 0.5 | 100 | Plant P concentration. |
| 4 | Schaberg et al., 1997 | Temperate Forest | $NH_4^+$ | 31.4 | 7.2 | 219.8 | Plant P concentration. |
| 5 | Schils & Snijders, 2004 | Grassland | $NO_3^-$ | 400 | 4 | 1600 | Plant P pool and soil total P. |
| 6 | Simms, 1987 | Temperate Forest | Urea | 100 | 1 | 100 | Plant P concentration. |
| 7 | Sinsabaugh et al., 2005 | Temperate Forest | Urea | 80 | 2 | 160 | Phosphatase activity. |
| 8 | Son, 2002 | Temperate Forest | $NH_4^+$ | 400 | 0.5 | 400 | Plant P concentration. |
| 9 | Soudzilovskaia et al., 2005 | Tundra | Urea | 90 | 3.3 | 360 | Plant biomass, P content and P concentration. |
| 0 | Soudzilovskaia et al., 2007 | Tundra | Urea | 90 | 3.3 | 360 | Litter biomass, P content and P concentration. |
| 1 | Sparrius et al., 2013 | Grassland | $NH_4NO_3$ | 42.9 | 3.5 | 171.6 | Plant biomass, P content and P concentration. |
| 2 | Stursova et al., 2006 | Grassland | $NH_4NO_3$ | 100 | 4 | 400 | Phosphatase activity. |
| 3 | Suding et al., 2008 | Tundra | Urea | 160 | 5 | 900 | Plant biomass and phosphatase activity. |
| 4 | Sundqvist et al., | Tundra | $NH_4NO_3$ | 100 | 2 | 200 | Soil labile P. |

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| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | 2014 | | | | | | |
| 5 | Tanner et al., 1990 | Tropical forest | Urea | 100 | 3 | 300 | Plant P concentration. |
| 6 | Tanner et al., 1992 | Tropical forest | Urea | 150 | 3 | 450 | Litter P concentration. |
| 7 | Thayer et al., 2008 | Grassland | $NO_3^-$ | 70 | 7 | 490 | Plant biomass and P concentration. |
| 8 | Tomassen et al., 2004 | Wetland | $NH_4NO_3$ | 80 | 3 | 240 | Plant biomass, P content and P concentration, and soil labile P. |
| 9 | Treseder & Vitousek, 2001 | Tropical forest | $NH_4NO_3$ | 300 | 13 | 3900 | Plant and litter P concentration. |
| 0 | Tu et al., 2014 | Temperate forest | $NH_4NO_3$ | 300 | 2 | 600 | Phosphatase activity and soil labile P. |
| 1 | Turner et al., 2013 | Tropical forest | Urea | 125 | 9 | 1125 | Phosphatase activity. |
| 2 | Turner & Wright, 2013 | Tropical forest | Urea | 125 | 9 | 1125 | Phosphatase activity. |
| 3 | Tyler et al., 1992 | Boreal Forest | $NH_4NO_3$ | 180 | 5 | 900 | Plant and litter P concentration. |
| 4 | van der Hoek et al., 2004 | Grassland | $NH_4NO_3$ | 200 | 3 | 600 | Plant biomass, P content and P concentration. |
| 5 | van der Waal et al., 2011 | Grassland | $NH_4NO_3$ | 785$^{\S}$ | 2 | 1570$^{\S}$ | Plant P concentration. |
| 6 | van Dijk et al., 2012 | Wetland | $NH_4NO_3$ | 29.5 | 3 | 88.8 | Plant P concentration and phosphatase activity. |
| 7 | van Duren et al., 1997 | Wetland | Urea | 200 | 1 | 200 | Plant biomass, P content and P concentration. |
| 8 | van Heerwaarden et al., 2003 | Wetland | $NH_4^+$ | 100 | 3 | 300 | Plant and litter P concentration. |

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| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 9 | Venterink et al., 2001 | Grassland | $NH_4NO_3$ | 200 | 0.2 | 200 | Plant biomass, P content and P concentration. |
| 0 | Verhoeven & Schmitz, 1991 | Wetland | $NH_4NO_3$ | 100 | 0.4 | 100 | Plant biomass, P content and P concentration. |
| 1 | Verhoeven et al., 2011 | Wetland | $NO_3^-$;<br>$NH_4^+$ | 70 | 4 | 280 | Plant biomass, P content and P concentration. |
| 2 | Vitousek & Farrington, 1997 | Tropical Forest | $NH_4NO_3$ | 100 | 2 | 200 | Plant P concentration. |
| 3 | Vitousek & Hobbie, 2000 | Tropical Forest | $NH_4NO_3$ | 100 | 2 | 200 | Litter P concentration. |
| 4 | Vitousek et al., 1993 | Tropical Forest | $NH_4NO_3$ | 100 | 2 | 200 | Plant P concentration and soil labile P. |
| 5 | Vitousek, 1998 | Tropical Forest | $NH_4NO_3$ | 100 | 10 | 1000 | Plant and litter P concentration. |
| 6 | von Oheimb et al., 2010 | Grassland | $NH_4NO_3$ | 50 | 4 | 200 | Plant P concentration and soil labile P. |
| 7 | Wang et al., 2008 | Temperate Forest | Urea | 100 | 0.4 | 100 | Soil microbial P, phosphatase activity, soil total and labile P. |
| 8 | Wang et al., 2010 | Grassland | Urea | 200 | 3 | 600 | Plant biomass and phosphatase activity. |
| 9 | Wang et al., 2015 | Grassland | Urea | 150 | 8 | 1200 | Phosphatase activity. |
| 0 | Wang FM et al., 2014 | Tropical forest | $NH_4NO_3$ | 100 | 3.1 | 300 | Soil labile P. |
| 1 | Wang JS et al., 2014 | Grassland | Urea | 100 | 2 | 200 | Soil labile P. |
| 2 | Wang XG et al., 2014 | Grassland | $NH_4NO_3$ | 52.5 | 2 | 105 | Litter P concentration. |
| 3 | Warren et al., 2005 | Temperate Forest | Urea | 275 | 2 | 550 | Plant P concentration. |
| 4 | Weand et al., | Tropical | $NH_4NO_3$ | 50 | 5 | 250 | Plant P concentration, soil microbial P, |

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| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | 2010 | Forest | | | | | phosphatase activity, soil total and labile P. |
| 185 | Willems et al., 1993 | Grassland | $NH_4NO_3$ | 10 | 4 | 40 | Plant biomass, P content and P concentration. |
| 186 | Zeglin et al., 2007 | Grassland | $NH_4NO_3$ | 142 | 55 | 7810 | Phosphatase activity and soil total P. |
| 187 | Zhang et al., 2011 | Tropical Forest | $NH_4NO_3$ | 150 | 2 | 300 | Soil total and labile P. |
| 188 | Zhang et al., 2014 | Grassland | Urea | 100 | 3 | 300 | Soil total and labile P. |
| 189 | Zhang GN et al., 2013 | Grassland | Urea | 560 | 2 | 1120 | Phosphatase activity, soil total and labile P. |
| 190 | Zhang NY et al., 2013 | Grassland | $NH_4NO_3$ | 100 | 4 | 400 | Soil total and labile P. |
| 191 | Zheng et al., 2015 | Tropical Forest | $NH_4NO_3$ | 150 | 5 | 750 | Phosphatase activity, soil total and labile P. |
| 192 | Zhu et al., 2013 | Tropical Forest | $NH_4NO_3$ | 150 | 5 | 750 | Plant biomass, P content and P concentration, phosphatase activity and soil labile P. |

[§] The unit of N applied rate and total N load are g N tree$^{-1}$ yr$^{-1}$ and g N tree$^{-1}$, respectively.

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**Appendix S2.** Rosenthal's fail-safe number used to test the publication bias. Fonts in bold indicate that the mean response ratio (*RR*) had significant difference from zero. Asterisk indicates a significant publication bias for the analysis by the Rosenthal's fail-safe number.

| Treatment | Plant biomass | | | | Plant P content | | | | Plant P concentration | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Mean *RR* | 95% CI | n | Fail-safe number | Mean *RR* | 95% CI | n | Fail-safe number | Mean *RR* | 95% CI | n | Fail-safe number |
| Overall | **0.29** | **0.24~0.34** | **126** | **65236** | **0.15** | **0.10~0.21** | **67** | **6976** | **-0.08** | **-0.11~-0.06** | **195** | **17560** |
| Tropical forest | 0.07 | -0.08~0.23 | 11 | | 0.24 | -0.15~0.64 | 1 | | **-0.04** | **-0.07~-0.01** | **28** | **175** |
| Temperate forest | **0.53** | **0.37~0.68** | **11** | **807** | 0.23 | -0.1~0.47 | 3 | | **-0.11** | **-0.17~-0.06** | **28** | **372** |
| Boreal forest | 0.17 | -0.22~0.57 | 2 | | 0.04 | -0.29~0.38 | 2 | | -0.04 | -0.13~0.04 | 12 | |
| Grassland | **0.29** | **0.21~0.36** | **44** | **7944** | **0.13** | **0.06~0.20** | **36** | **1235** | **-0.12** | **-0.15~-0.09** | **64** | **3352** |
| Wetland | **0.32** | **0.25~0.39** | **44** | **12674** | **0.20** | **0.11~0.28** | **22** | **1231** | **-0.09** | **-0.12~-0.06** | **56** | **1348** |
| Tundra | 0.03 | -0.21~0.27 | 4 | | 0.05 | -0.21~0.31 | 3 | | -0.01 | -0.10~0.08 | 7 | |
| $NO_3^-$-N | 0.20 | -0.08~0.49 | 5 | | **0.43** | **0.14~0.71** | **3** | **50** | **-0.20** | **-0.31~-0.11** | **6** | **44** |
| $NH_4^+$-N | **0.34** | **0.15~0.53** | **11** | **139** | **0.26** | **0.06~0.45** | **4** | **26**$^*$ | **-0.12** | **-0.17~-0.07** | **25** | **438** |
| $NH_4NO_3$ | **0.30** | **0.24~0.36** | **84** | **34360** | **0.13** | **0.08~0.18** | **51** | **3147** | **-0.08** | **-0.11~-0.06** | **119** | **6236** |
| Urea | **0.27** | **0.16~0.38** | **24** | **2079** | 0.07 | -0.08~0.22 | 7 | | **-0.06** | **-0.10~-0.03** | **43** | **527** |

Note: If the fail-safe number was over 5n+10 (n is the number of cases in the analysis), we make conclusion that our result was strong against publication bias. Otherwise, a significant publication bias for the analysis was suggested by the Rosenthal's fail-safe number.

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| Treatment | Litter biomass | | | | Litter P content | | | | Litter P concentration | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Mean *RR* | 95% CI | n | Fail-safe number | Mean *RR* | 95% CI | n | Fail-safe number | Mean *RR* | 95% CI | n | Fail-safe number |
| Overall | **0.14** | **0.08~0.20** | **16** | **140** | **0.11** | **0.05~0.18** | **6** | **30**$^*$ | **-0.09** | **-0.17~-0.04** | **65** | **828** |
| Tropical forest | 0.10 | -0.06~0.24 | 8 | | 0.08 | -0.03~0.18 | 1 | | -0.00 | -0.08~0.08 | 20 | |
| Temperate forest | | | 0 | | | | 0 | | -0.17 | -0.44~0.09 | 2 | |
| Boreal forest | 0.05 | -0.19~0.28 | 1 | | -0.09 | -0.31~0.11 | 1 | | -0.08 | -0.32~0.16 | 2 | |
| Grassland | 0.17 | -0.05~0.38 | 1 | | **0.19** | **0.03~0.33** | **1** | **2**$^*$ | **-0.23** | **-0.33~-0.13** | **14** | **293** |
| Wetland | **0.16** | **0.06~0.26** | **5** | **3**$^*$ | **0.10** | **0.02~0.18** | **3** | **3**$^*$ | **-0.13** | **-0.21~-0.05** | **27** | **146** |
| Tundra | 0.06 | -0.17~0.29 | 1 | | | | 0 | | | | 0 | |
| $NO_3^-$-N | | | 0 | | | | 0 | | **-0.25** | **-0.38~-0.08** | **18** | **2721** |
| $NH_4^+$-N | **0.28** | **0.13~0.42** | **8** | **10**$^*$ | | | 0 | | **-0.11** | **-0.17~-0.05** | **34** | **972** |
| $NH_4NO_3$ | **0.20** | **0.07~0.30** | **6** | **9**$^*$ | 0.12 | -0.04~0.27 | 5 | | **-0.04** | **-0.07~-0.01** | **10** | **50**$^*$ |
| Urea | **0.10** | **0.03~0.16** | **2** | **3**$^*$ | **0.12** | **0.07~0.17** | **1** | **2**$^*$ | -0.04 | -0.09~0.00 | 1 | |

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| Treatment | Phosphatase activity | | | | Soil microbial P | | | |
|---|---|---|---|---|---|---|---|---|
| | Mean *RR* | 95% CI | n | Fail-safe number | Mean *RR* | 95% CI | n | Fail-safe number |
| Overall | **0.21** | **0.13~0.30** | **65** | **9487** | 0.01 | -0.02~0.02 | 8 | |
| Tropical forest | 0.02 | -0.14~0.18 | 16 | | -0.00 | -0.02~0.02 | 5 | |
| Temperate forest | **0.20** | **0.04~0.36** | **15** | **806** | -0.18 | -0.48~0.12 | 1 | |
| Boreal forest | 0.13 | -0.26~0.52 | 3 | | 0.04 | -0.01~0.10 | 2 | |
| Grassland | **0.33** | **0.21~0.45** | **24** | **1895** | | | | |
| Wetland | **0.36** | **0.08~0.63** | **6** | **47** | | | | |
| Tundra | -0.14 | -0.82~0.54 | 1 | | | | | |
| $NO_3^-$-N | 0.10 | -0.23~0.43 | 1 | | | | | |
| $NH_4^+$-N | 0.44 | -0.27~1.15 | 4 | | | | | |
| $NH_4NO_3$ | **0.20** | **0.11~0.30** | **49** | **4932** | 0.00 | -0.02~0.03 | 7 | |
| Urea | **0.27** | **0.06~0.48** | **11** | **152** | -0.18 | -0.48~0.12 | 1 | |

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| Treatment | Soil total P | | | | Soil labile P | | | |
|---|---|---|---|---|---|---|---|---|
| | Mean *RR* | 95% CI | n | Fail-safe number | Mean *RR* | 95% CI | n | Fail-safe number |
| Overall | **-0.05** | **-0.10~-0.01** | **38** | **150**$^{*}$ | -0.03 | -0.11~0.05 | 66 | |
| Tropical forest | 0.00 | -0.09~0.09 | 12 | | **-0.27** | **-0.40~-0.13** | **18** | **483** |
| Temperate forest | **-0.18** | **-0.30~-0.06** | **4** | **13**$^{*}$ | 0.03 | -0.15~0.20 | 7 | |
| Boreal forest | -0.09 | -0.26~0.07 | 2 | | 0.03 | -0.58~0.63 | 1 | |
| Grassland | -0.02 | -0.09~0.05 | 14 | | 0.06 | -0.06~0.18 | 22 | |
| Wetland | -0.11 | -0.25~0.02 | 5 | | 0.16 | -0.07~0.39 | 10 | |
| Tundra | -0.02 | -0.30~0.26 | 1 | | 0.01 | -0.31~0.34 | 8 | |
| $NO_3^-$-N | -0.04 | -0.21~0.12 | 12 | | -0.04 | -0.91~0.82 | 15 | |
| $NH_4^+$-N | **-0.20** | **-0.34~-0.05** | **20** | **139** | -0.10 | -0.52~0.33 | 46 | |
| $NH_4NO_3$ | -0.03 | -0.09~0.03 | 4 | | -0.09 | -0.21~0.01 | 4 | |
| Urea | -0.05 | -0.12~0.03 | 2 | | 0.13 | -0.08~0.31 | 1 | |

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**Appendix S3.** Statistical significances of effects of categorical factors on the response ratios were evaluated based on a chi-square test. Significant factors are indicated in bold. In order to avoid gaining unreliable conclusions, some subgroups without a sufficiently large dataset (n<5) were excluded in the analysis. '-" indicates that there was no at least two subgroups with sufficiently large dataset (n>5).

| Variable | Plant tissue | | | Ecosystem | | | N source | | |
|---|---|---|---|---|---|---|---|---|---|
| | $\chi^2$ | df | *P* | $\chi^2$ | df | *P* | $\chi^2$ | df | *P* |
| Plant biomass | **13.14** | **3** | **0.004** | **15.35** | **3** | **0.002** | 0.90 | 3 | 0.825 |
| Plant P content | 2.27 | 3 | 0.518 | 1.28 | 1 | 0.258 | 0.90 | 1 | 0.343 |
| Plant P concentration | **27.51** | **3** | **<0.001** | **15.43** | **5** | **0.009** | **8.20** | **3** | **0.042** |
| Litter biomass | | | | 0.05 | 1 | 0.831 | 0.00 | 1 | 0.998 |
| Litter P content | | | | - | - | - | - | - | - |
| Litter P concentration | | | | **12.41** | **2** | **0.002** | **10.85** | **2** | **0.014** |
| Phosphatase activity | | | | **8.85** | **3** | **0.031** | 0.24 | 1 | 0.622 |
| Soil microbial P | | | | - | - | - | - | - | - |
| Soil total P | | | | 2.18 | 3 | 0.337 | 0.17 | 1 | 0.676 |
| Soil labile P | | | | **17.32** | **4** | **0.002** | 0.06 | 1 | 0.840 |

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| Variable | P extraction method | | | Soil pH | | | Soil type | | |
|---|---|---|---|---|---|---|---|---|---|
| | $\chi^2$ | df | *P* | $\chi^2$ | df | *P* | $\chi^2$ | df | *P* |
| Plant biomass | | | | 0.22 | 2 | 0.894 | 0.79 | 2 | 0.674 |
| Plant P content | | | | 4.46 | 1 | 0.108 | - | - | - |
| Plant P concentration | | | | 3.16 | 2 | 0.175 | 0.23 | 2 | 0.890 |
| Litter biomass | | | | 2.47 | 1 | 0.291 | - | - | - |
| Litter P content | | | | - | - | - | - | - | - |
| Litter P concentration | | | | 2.71 | 2 | 0.272 | - | - | - |
| Phosphatase activity | | | | 1.79 | 1 | 0.408 | 0.30 | 1 | 0.581 |
| Soil microbial P | | | | - | - | - | - | - | - |
| Soil total P | 2.58 | 3 | 0.461 | 0.76 | 1 | 0.685 | 0.33 | 2 | 0.850 |
| Soil labile P | **9.79** | **3** | **0.021** | **8.74** | **2** | **0.013** | 1.23 | 1 | 0.267 |

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**Appendix S4.** Statistical significances of relationships between the response ratio and continuous factors (n>20 only) were evaluated based on an F-test. Significant factors are indicated in bold. '-" indicate insufficiently large dataset (n<20) for the analysis.

| Variable | Experimental duration | | | N applied rate | | | Total N load | | | SOC | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | F | n | *P* | F | n | *P* | F | n | *P* | F | n | *P* |
| Plant biomass | 0.02 | 178 | 0.749 | 0.85 | 182 | 0.235 | 1.80 | 215 | 0.094 | 0.11 | 25 | 0.723 |
| Plant P content | 2.07 | 81 | 0.079 | 1.30 | 85 | 0.215 | 0.28 | 97 | 0.497 | - | - | - |
| Plant P concentration | 0.09 | 193 | 0.661 | **15.62** | **218** | **<0.001** | **26.61** | **313** | **<0.001** | 0.10 | 37 | 0.795 |
| Litter biomass | 2.49 | 21 | 0.114 | - | - | - | - | - | - | - | - | - |
| Litter P content | - | - | - | - | - | - | - | - | - | - | - | - |
| Litter P concentration | 1.99 | 89 | 0.166 | **8.27** | **85** | **<0.001** | **7.71** | **105** | **0.007** | - | - | - |
| Phosphatase activity | 0.68 | 81 | 0.308 | 1.43 | 85 | 0.131 | 1.79 | 98 | 0.108 | 3.01 | 28 | 0.083 |
| Soil microbial P | - | - | - | - | - | - | 1.64 | 8 | 0.201 | - | - | - |
| Soil total P | 0.43 | 60 | 0.312 | 1.29 | 55 | 0.156 | 0.23 | 74 | 0.429 | - | - | - |
| Soil labile P | 1.69 | 99 | 0.143 | 0.57 | 85 | 0.351 | 0.06 | 123 | 0.610 | - | - | - |

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| Variable | Soil pH | | | MAT | | | MAP | | | Soil depth | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | F | n | *P* | F | n | *P* | F | n | *P* | F | n | *P* |
| Plant biomass | 0.33 | 74 | 0.566 | 1.36 | 48 | 0.244 | 2.83 | 67 | 0.093 | | | |
| Plant P content | 0.23 | 36 | 0.629 | 0.39 | 23 | 0.532 | 1.33 | 31 | 0.250 | | | |
| Plant P concentration | 1.45 | 114 | 0.206 | 1.40 | 99 | 0.236 | 1.02 | 126 | 0.205 | | | |
| Litter biomass | - | - | - | - | - | - | - | - | - | | | |
| Litter P content | - | - | - | - | - | - | - | - | - | | | |
| Litter P concentration | 1.01 | 49 | 0.316 | 1.29 | 56 | 0.255 | 2.16 | 57 | 0.141 | | | |
| Phosphatase activity | 0.87 | 45 | 0.351 | 1.04 | 34 | 0.307 | 0.77 | 41 | 0.379 | 0.01 | 53 | 0.990 |
| Soil microbial P | - | - | - | - | - | - | - | - | - | - | - | - |
| Soil total P | 0.84 | 28 | 0.358 | 0.01 | 23 | 0.927 | 1.40 | 26 | 0.237 | 2.81 | 70 | 0.932 |
| Soil labile P | **12.85** | **51** | **<0.001** | 1.53 | 43 | 0.216 | 3.22 | 56 | 0.078 | 0.79 | 128 | 0.376 |

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| Variable | Experimental duration | | | N applied rate | | | Total N load | | |
|---|---|---|---|---|---|---|---|---|---|
| | F | n | *P* | F | n | *P* | F | n | *P* |
| Plant biomass | 0.02 | 178 | 0.749 | 0.85 | 182 | 0.235 | 1.80 | 215 | 0.094 |
| Plant P content | 2.07 | 81 | 0.079 | 1.30 | 85 | 0.215 | 0.28 | 97 | 0.497 |
| Plant P concentration | 0.09 | 193 | 0.661 | **15.62** | **218** | **<0.001** | **26.61** | **313** | **<0.001** |
| Litter biomass | 2.49 | 21 | 0.114 | 1.50 | 17 | 0.220 | 1.07 | 18 | 0.284 |
| Litter P content | - | - | - | - | - | - | - | - | - |
| Litter P concentration | 1.99 | 89 | 0.166 | **8.27** | **85** | **<0.001** | **7.71** | **105** | **0.007** |
| Phosphatase activity | 0.68 | 81 | 0.308 | 1.43 | 85 | 0.131 | 1.79 | 98 | 0.108 |
| Soil microbial P | - | - | - | - | - | - | - | - | - |
| Soil total P | 0.43 | 60 | 0.312 | 1.29 | 55 | 0.156 | 0.23 | 74 | 0.429 |
| Soil labile P | 1.69 | 99 | 0.143 | 0.57 | 85 | 0.351 | 0.06 | 123 | 0.610 |

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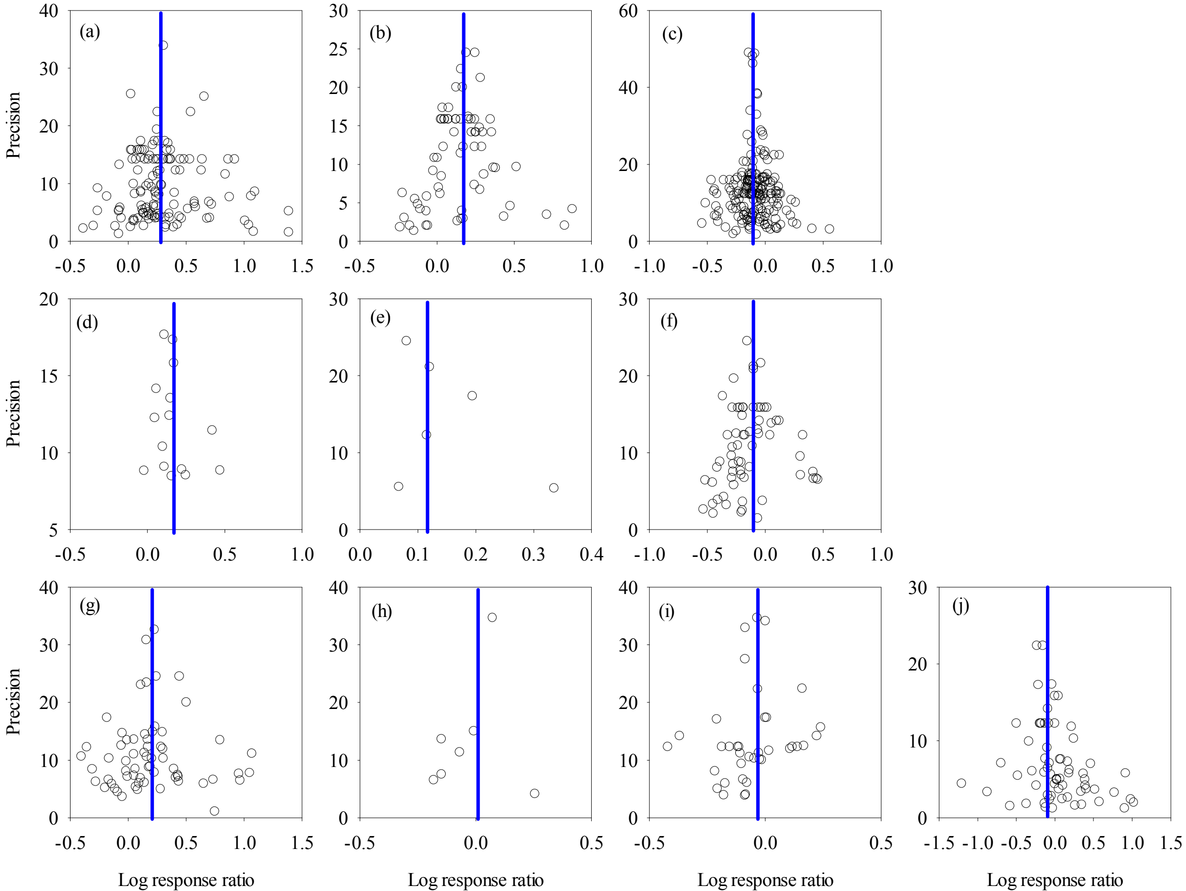

Fig. S1

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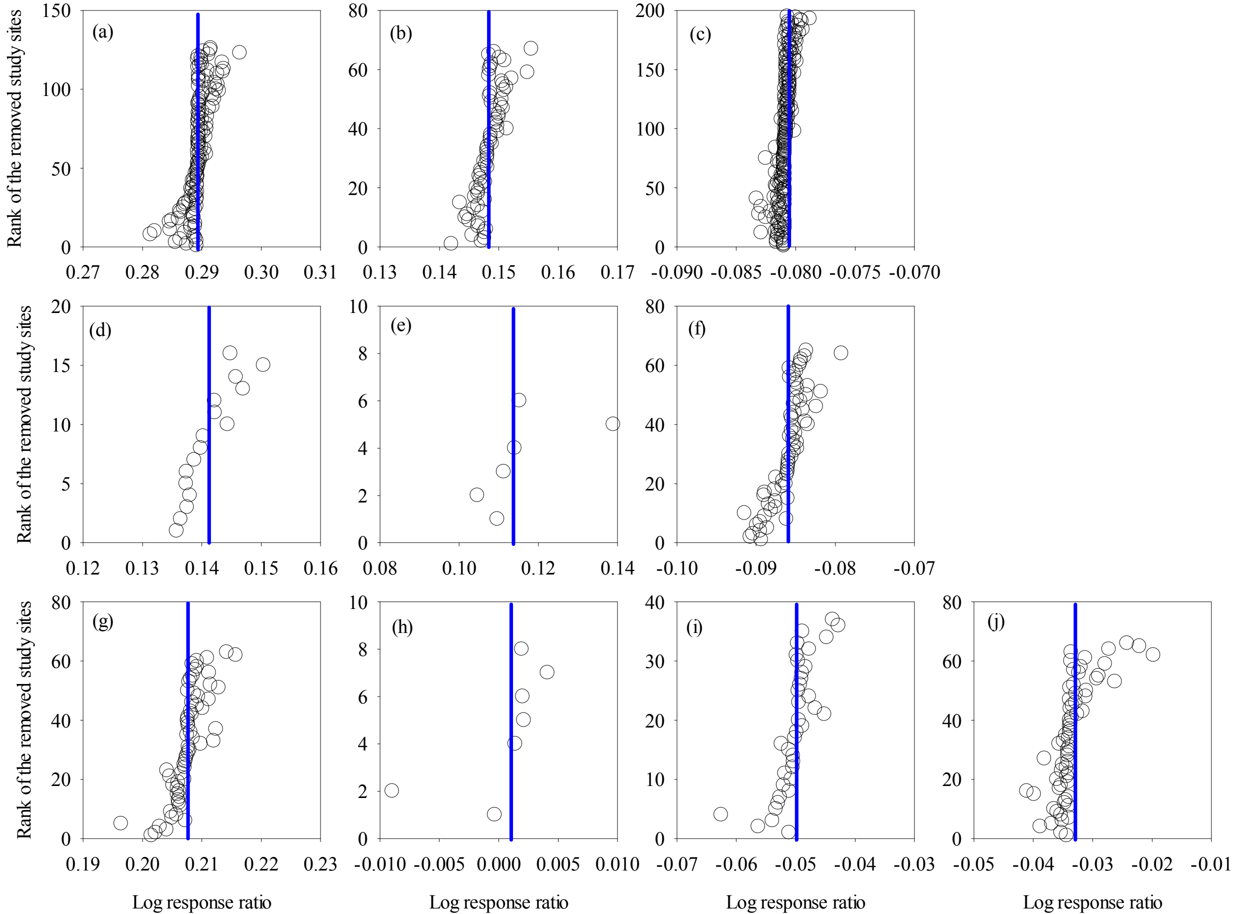
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100
50
0
(a)
0.27
0.28
0.29
0.30
0.31
80
60
40
20
0
(b)
0.13
0.14
0.15
0.16
0.17
200
150
100
50
0
(c)
-0.090
-0.085
-0.080
-0.075
-0.070
Rank of the removed study sites
20
15
10
5
0
(d)
0.12
0.13
0.14
0.15
0.16
10
8
6
4
2
0
(e)
0.08
0.10
0.12
0.14
80
60
40
20
0
(f)
-0.10
-0.09
-0.08
-0.07
Rank of the removed study sites
80
60
40
20
0
(g)
0.19
0.20
0.21
0.22
0.23
Log response ratio
10
8
6
4
2
0
(h)
-0.010
-0.005
0.000
0.005
0.010
Log response ratio
40
30
20
10
0
(i)
-0.07
-0.06
-0.05
-0.04
-0.03
Log response ratio
80
60
40
20
0
(j)
-0.05
-0.04
-0.03
-0.02
-0.01
Log response ratio

Fig. S2

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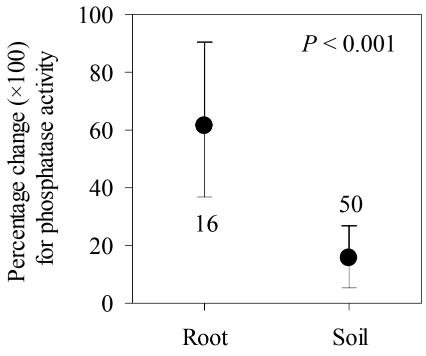

Fig. S3

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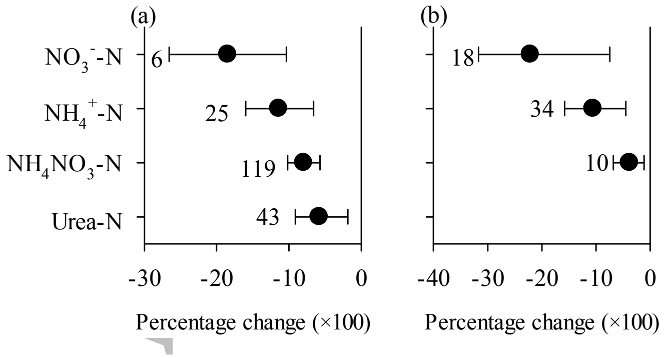

Fig. S4