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# Individual and combined effects of multiple global change drivers on terrestrial phosphorus pools: A meta-analysis

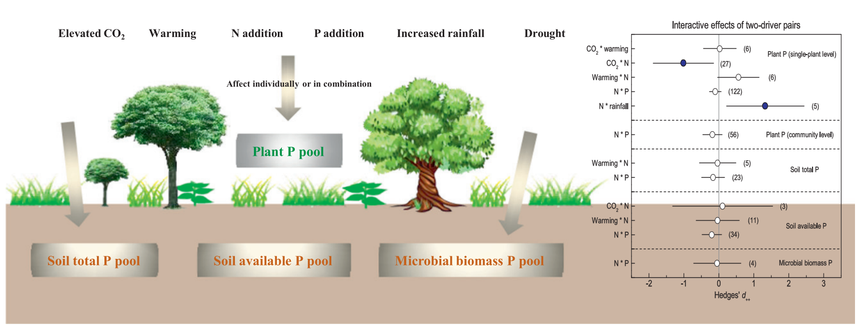
Kai Yue [a], Wanqin Yang [a], Yan Peng [b], Changhui Peng [c,d], Bo Tan [a], Zhenfeng Xu [a], Li Zhang [a], Xiangyin Ni [a], Wei Zhou [e], Fuzhong Wu [a,*]

[a] *Long-term Research Station of Alpine Forest Ecosystems, Provincial Key Laboratory of Ecological Forestry Engineering, Institute of Ecology and Forestry, Sichuan Agricultural University, 211 Huimin Road, Wenjiang District, Chengdu 611130, Sichuan, China*
[b] *Department of Geosciences and Natural Resource Management, University of Copenhagen, Rolighedsvej 23, DK-1958 Frederiksberg C, Denmark*
[c] *Department of Biological Science, Institute of Environment Sciences, University of Quebec at Montreal, Case Postale 8888, succursale Centre-Ville, Montreal, Quebec H3C 3P8, Canada*
[d] *Laboratory for Ecological Forecasting and Global Change, College of Forestry, Northwest A & F University, No. 3 Taicheng Road, Yangling 712100, China*
[e] *College of Resources, Sichuan Agricultural University, 211 Huimin Road, Wenjiang District, Chengdu 611130, Sichuan, China*

## HIGHLIGHTS

- Terrestrial P pools were most sensitive to the individual effects of warming and P addition.
- Terrestrial P pools were consistently stimulated by P addition or N + P addition.
- Individual and combined effects were significantly modulated by environmental and experimental setting factors.
- Interactive effects of multiple drivers on terrestrial P pools were more likely to be additive.

## GRAPHICAL ABSTRACT

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## ABSTRACT

Human activity-induced global change drivers have dramatically changed terrestrial phosphorus (P) dynamics. However, our understanding of the interactive effects of multiple global change drivers on terrestrial P pools remains elusive, limiting their incorporation into ecological and biogeochemical models. We conducted a meta-analysis using 1751 observations extracted from 283 published articles to evaluate the individual, combined, and interactive effects of elevated $CO_2$, warming, N addition, P addition, increased rainfall, and drought on P pools of plant (at both single-plant and plant-community levels), soil and microbial biomass. Our results suggested that (1) terrestrial P pools showed the most sensitive responses to the individual effects of warming and P addition; (2) P pools were consistently stimulated by P addition alone or in combination with simultaneous N addition; (3) environmental and experimental setting factors such as ecosystem type, climate, and latitude could significantly influence both the individual and combined effects; and (4) the interactive effects of two-driver pairs across multiple global change drivers are more likely to be additive rather than synergistic or antagonistic. Our findings highlighting the importance of additive interactive effects among multiple global change drivers on terrestrial P pools would be useful for incorporating P as controls on ecological processes such as photosynthesis and plant growth into ecosystem models used to analyze effects of multiple drivers under future global change.



* Corresponding author.
*E-mail address:* wufzchina@163.com (F. Wu).

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## 1. Introduction

Phosphorus (P) is one of the most limiting nutrients for terrestrial biological productivity that usually plays a crucial role in net carbon (C) uptake in terrestrial ecosystems (Filippelli, 2002). Unlike nitrogen (N), which could be fixed by plants such as legumes, the available P for plants and microorganisms is derived mainly from mechanical rock weathering, atmospheric deposition (Newman, 1995) and, to a lesser extent, from organic matter decomposition (Vitousek, 2004). The flux of P is almost unidirectional, moving from on land ecosystems to streams and rivers with minimal input back via spray (Liu et al., 2008). However, global change drivers and human activities such as a rapidly increasing use of synthetic fertilizers could dramatically change the global cycling of P, which further influences the productivity and functioning of ecosystems (Goll et al., 2012; Peñuelas et al., 2013). Thus it is of great importance to assess the effects of global change drivers on terrestrial P dynamics.

Terrestrial biogeochemical models and field manipulative studies have examined the individual effects of several global change drivers on terrestrial P concentration. For example, case studies in field experiments have been conducted to examine the effects of N addition on plant P concentration, but negative (Tessier and Raynal, 2003), positive (Liu et al., 2013) and neutral (Weand et al., 2010) effects were all observed. A recent meta-analysis study suggested that N addition decreased plant P concentration by an average of 8% at the global scale (Deng et al., 2017). In contrast, external P addition is more likely to increase the concentrations of P in both plants and soils (Li et al., 2016). A synthesis study showed that drought stress has significant negative effects on plant P concentration, decreasing which by an average of 9.2% (He and Dijkstra, 2014), but have significant positive effects on the concentration of soil available P (SAP) (Delgado-Baquerizo et al., 2013). Moreover, studies also suggested that the individual effects of one driver can be meditated by another one (Huang et al., 2015), indicating that the combined effects of multiple global drivers may be of greater importance than individual effects. However, despite these explicit assessments on the individual effects of multiple global change drivers on terrestrial P concentration, few global syntheses (but see Deng et al., 2017; Li et al., 2016) have been conducted so far to reveal the individual and combined effects of these drivers on terrestrial P pool. The responses of P pool to global change drivers may significantly differ with P concentration. For example, drought has been found to generally reduce plant P concentration (He and Dijkstra, 2014), but plant P concentration can also increase when plant growth decrease more than plant P uptake in response to drought. In such case, however, plant P pool may decrease even more severely. Thus it is important to individually assess the responses of terrestrial P pool to global change drivers. Moreover, even less available studies have noticed if the interaction of the combined effects (interactive effects) of multiple global change drivers might or might not be additive.

Additive interaction occurs when the combined effect of two or more drivers is equal to or not significantly different from the sum of the individual effect. When the combined effect is greater or weaker than the sum of the individual effects, the net effect could be synergistic or antagonistic, respectively (Crain et al., 2008; Yue et al., 2017a). Because N and P are the most limiting nutrients for plant growth (Elser et al., 2007), their interaction was usually reported to be synergistic (Harpole et al., 2011; Li et al., 2016). However, additive interactive effects of N and P on terrestrial C pool was also reported to be more common at a global scale (Yue et al., 2017b). In addition to the observed common additive interaction of N and P, the interactive effects of two-driver pairs of multiple global change drivers such as elevated $CO_2$ ($eCO_2$), warming, increased rainfall and drought on terrestrial C pool (Yue et al., 2017b) and N:P ratio (Yuan and Chen, 2015) were also found to be additive. Despite these interesting findings, both synergistic and antagonistic interactive effects were also observed in previous studies (Dieleman et al., 2012; Mueller et al., 2016; Wu et al., 2011). However, available synthesis studies investigating the interactive effects of global change drivers are mainly focused on N concentration, C pool, or C:N:P ratios (Yue et al., 2017a, 2017b; Yuan and Chen, 2015), no studies have assessed the responses of terrestrial P pools to the interactive effects of multi-drivers. Because the responses of different variables to global change drivers can significantly vary (Zhou et al., 2016), a lack of evaluation on terrestrial P pools will make it difficult to definitively predict whether the interactive effects of multiple global change drivers on terrestrial P pools additive or not, which limits their incorporation into ecological and biogeochemical models under future global change scenarios.

Here, we comprehensively reviewed previously published articles and conducted a meta-analysis to quantitatively evaluate the individual, combined and interactive effects of major global change drivers of $eCO_2$, warming, N addition, P addition, increased rainfall and drought on different types of terrestrial P pools (i.e. plant, soil and microbial biomass) and the potential influencing factors. The main issues addressed in the present study were (1) how the individual and combined effects of the investigated multiple global change drivers affect different types of P pools; (2) which environmental and experimental setting factors (e.g. latitude, climate, ecosystem type and study length) influence the responses of terrestrial P pools to the individual and combined effects of these drivers; and (3) whether the interactive effects of these drivers additive or not. We hypothesized that (1) both the individual and combined effects of multiple global change drivers can significantly affect terrestrial P pools, but the individual effect of P addition or the combined effects of P addition with other drivers are most manifest; (2) additive interactive effects of the investigated multiple global change drivers on terrestrial P pools will be much more common than synergistic and antagonistic ones; and (3) environmental and experimental setting factors can significantly influence both the individual and combined effects.

## 2. Materials and methods

### 2.1. Data collection and extraction

Using *ISI Web of Science*, *PubMed,* and *Google Scholar*, we collected data from peer-reviewed journal articles that reported terrestrial ecosystem P pools in response to key global change drivers of $eCO_2$, warming, N addition, P addition, increased rainfall, drought, and any combination of these six drivers. We searched articles before July 2017 with no restriction on publication year, and focused on field manipulative studies in both agricultural and natural ecosystems. The following criteria were adopted to minimize publication bias for choosing appropriate studies: (i) field manipulative experiments reported at least one of our concerned global change drivers; (ii) full-factorial design was used to assess the combined effects of multiple drivers; (iii) control plots had the same ecosystem type and environmental conditions as all experimental plots at the beginning of the experiment; (iv) the magnitude of the treatment and the study length were clearly recorded, and measurements of the variables in the experimental and control groups were performed at the same spatial and temporal scales; (v) studies were chosen only when the study length was no less than one growing season; and (vi) means, sample sizes, and standard deviations (SD) or standard errors (SE) of the chosen variables were directly provided or could be estimated from the reported data. The treatment magnitude of increased rainfall or drought was expressed as percentage changes in mean annual precipitation. Plant P pools at both single-plant and plant-community levels were either directly reported in the primary studies or calculated as the product of P concentration and the corresponding biomass of whole plant or compartments. Data for soil P and microbial biomass P (MBP) pools were directly extracted from primary studies or determined with soil bulk density, sampling depth, microbial biomass, and corresponding P concentrations. Because SAP is most important for plant growth and