Soil acidity governs cropland phosphorus availability under future climate

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Understanding the response of agricultural phosphorus (P) cycling to climate change is fundamental for ensuring global food security and protecting planetary boundaries[1–2]. Recently, Wang et al.[3] reported a drastic reduction in soil P bioavailability (32–34%) under long-term elevated carbon dioxide (eCO_2) and warming in rice paddies, attributing it to enhanced geochemical sequestration *via* iron–organic carbon (Fe–OC) complexes. While we laud their decade-scale free-air CO_2 enrichment experiment for providing compelling insights into Fe–OC-mediated P immobilization, we argue that the extent to which this mechanism can be generalized across broader croplands is limited. By synthesizing global observations encompassing both paddy and non-paddy fields, we demonstrate that this climate-driven P risk is highly context-dependent and gated by environmental acidity, rather than an inevitable consequence of future climate change—with only about one-eighth of croplands worldwide vulnerable to such severe exposure.

Using a comprehensive dataset of 49 climate-change experiments across diverse climatic and edaphic contexts, we evaluated the broader sensitivity of the soil–plant–microbial P cascade to eCO_2 and warming (Fig. 1a and Supplementary Figs. 1–2). Across all studies, eCO_2 and warming systematically stimulate aboveground biomass (~13%–31%) and P uptake (~5%–9%), while leaving soil total P stocks unchanged, implying a sufficient P supply and redistribution within soil fractions *via* accelerated turnover. In contrast to the pronounced decline reported by Wang et al.[3], we found that available P also exhibits no significant change globally (Fig. 1a). Instead, its responses vary strongly among geographic sites and are primarily mediated by initial soil pH. Multiple independent analyses, including Bayesian meta-regression, model selection, and MetaForest, consistently rank soil pH as the paramount predictor of available P alterations, second only to duration, exceeding the explanatory power of climate factors (temperature and precipitation) and baseline Fe-associated OC pools (Fig. 1b–d).

The statistical dominance of initial soil pH highlights a geochemical boundary condition that complements the localized findings of Wang et al.[3]. By isolating the posterior distributions of available P changes, we found that the severe P depletion reported by Wang et al.[3] operates within a constrained context (slightly acidic soils with pH of ~6.7, as shown in their Supplementary Fig. 1). Our results show that significant reductions in available P occur predominantly in acidic soils (−16.5%, 90% credible intervals: [−27.9%, −3.9%]) and partially in neutral soils (−10.9%, [−22.6%, 2.0%]) subjected to prolonged climate forcing (Fig. 2a). In alkaline environments, however, the risk of P depletion is effectively counteracted and even trends toward a highly positive release under short-term exposure (+26.3%), although the long-term estimate warrants cautious interpretation due to a scarcity of observations (Fig. 2a). These divergent trajectories are largely rooted in the variations of Fe-associated OC pools across soil pH gradients[4]. Acidic soils naturally harbor a vastly superior and more active pool of Fe-bound OC complexes, whereas their concentration decreases progressively as soil acidity transitions to alkalinity ($P < 0.001$; Fig. 2b).

The underlying geochemical controls align with established pH-dependent sorption theory[4,5]. In acidic soils, the protonation of surface hydroxyl groups on variable-charge Fe and aluminum (Al) oxyhydroxides can enhance organo–mineral associations *via* inner-sphere complexation and ligand exchange[4]. Under climate-driven forcing, accelerated plant-derived organic inputs quickly satisfy this high binding potential, expanding the volatile Fe/Al–OC complexes that promotes orthophosphate occlusion[5]. Conversely, alkaline systems are less dominated by Fe surface chemistry. As the net positive surface charge on Fe oxides dissipates or reverses, carbonate equilibria, mineral dissolution and clay-associated processes jointly exert stronger controls on P dynamics[5]. Such differences likely weaken the persistence of Fe-mediated P occlusion outside acidic agroecosystems, e.g., promoting calcium-phosphate (Ca-P) dissolution *via* rhizosphere acidification and thus decoupling crop nutrient supply from Fe–OC burial observed in heavily weathered soils[6] (Supplementary Fig. 3).

Notably, given the inherent link between Wang et al.'s findings[3] and redox oscillations unique to flooded settings, a critical validation is to test the independent influence of environmental acidity from water regimes. We therefore conducted sensitivity analyses by partitioning our dataset into distinct cropland types and irrigation methods. Our subgroup analyses show that the comparison between cropland types does not explain the variations in available P; only after accounting for specific irrigation practices, the significant P reduction in paddies emerges, but the magnitude remains less severe than that reported by Wang et al.[3] (Supplementary Fig. 4). However, irrigated non-paddy systems exhibit significantly positive P responses, in stark contrast to the intense P depletion under rainfed conditions (Supplementary Fig. 4b). More importantly, the dominant role of soil pH is remarkably robust and consistent even while incorporating or controlling the variable water-regime effects (Supplementary Fig. 5). These findings demonstrate that while redox-driven Fe fluctuations provide a necessary geochemical substrate, the climate-driven P response across broader contexts is modulated by initial soil pH, which dictates whether water inputs stimulate Ca-P dissolution or accelerate orthophosphate occlusion[7].

Biological feedbacks are also amplified by these contrasting responses across pH gradients[8]. In strongly acidic soils, CO_2 fertilization and warming will stimulate microbial proliferation, but severe orthophosphate constraints force microbial communities to prioritize energy toward synthesizing acid phosphatase and inorganic P-solubilization genes (e.g., *pqqC*) to claw back mineral-bound pools[7–9]. Due to the narrow C:P ratio in their biomass, microbes rapidly sequester this newly mobilized labile P into biomass P, triggering an aggressive immobilization that competes with crop roots, intensifying the agricultural P deficit[3]. Nevertheless, in alkaline systems, climate change generally supports higher phosphatase efficiency and fosters arbuscular mycorrhizal fungi (AMF) symbioses (Fig. 1a). This enhanced biological partnership will expand the hyphal network that facilitates the acquisition and uptake of insoluble P by crops[10], implying that the P crisis is probably restricted to acidic soils, while non-acidic croplands maintain a cooperative, AMF-mediated nutrient loop.

To upscale these findings and quantify the actual global vulnerability of agriculture to this P crisis, we performed a spatial overlay analysis by intersecting the global cropland pH distribution with crop P use efficiency (PUE) maps[11] (Fig. 2c). We defined "P crisis hotspots" as agricultural zones intrinsically characterized by acidic soils and low crop PUE. Our spatial analysis reveals that this P crisis is geographically restricted, covering only 12.9% of global croplands (Fig. 2c). These hotspots are heavily clustered in the intensely weathered, highly acidic Oxisols and Ultisols of the humid tropics (e.g., Southeast Asia and Sub-Saharan Africa) and specific subtropical croplands like the study site of Wang et al.[3]. Such vulnerable boundary is expected to contract even further after accounting for the global pattern of microbial PUE, which depicts a pervasively similar capacity of soil microbes to immobilize P due to stoichiometric homeostasis[12] (Supplementary Fig. 6). Only when the dual PUE deficit emerges under resource-limited conditions, an intense plant–microbial P competition will occur[7,11,12]. Thus, the overwhelming majority of global agroecosystems possess sufficient P resilience to withstand eCO_2 and warming, but policy and mitigation efforts are still required for those most vulnerable and food-insecure regions on the planet.

In conclusion, the P crisis under future climate is not a universal consequence, but a context-specific risk dictated by soil geochemical background. While the Fe-mediated locking mechanism proposed by Wang et al.[3] represents an important breakthrough for understanding P cycling in acidic paddy systems, initial soil pH could act as the general gatekeeper of the global agricultural P budget. Future assessments of nutrient limitations and Earth system models should move beyond uniform feedback assumptions and explicitly integrate pH-dependent sorption dynamics[5,10]. Acknowledging this geochemical heterogeneity is imperative to prioritizing nature-based solutions against both soil acidification and nutrient imbalance, such as enhanced rock weathering[13] and precision residue management[14], to safeguard global food security and trade policies in a changing world[1,15].

Data availability

All data used in this study have been deposited in GitHub (https://github.com/TianyiQiu13/Clim-agroP). Other baseline data can be found in Supplementary Information.

Code availability

The code supporting the findings of this study has been deposited and freely available in GitHub (https://github.com/TianyiQiu13/Clim-agroP).

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Author contributions

T.Q. and L.F. designed the study. T.Q. collected and analyzed the data, and wrote the first draft of the paper. S.P., D.S.G., J.R.L., C.T., and X.H. contributed to shaping the overall framework and provided conceptual inputs to improve the manuscript. Y.C. and J.L. offered expert inputs and supported data analysis regarding PUE datasets. Q.C., S.Z., L.C., Q.Y., R.B., and P.S. advised on the interpretation of the results. All authors edited the manuscript and approved the final version.

Competing interests

The authors declare no competing interests.

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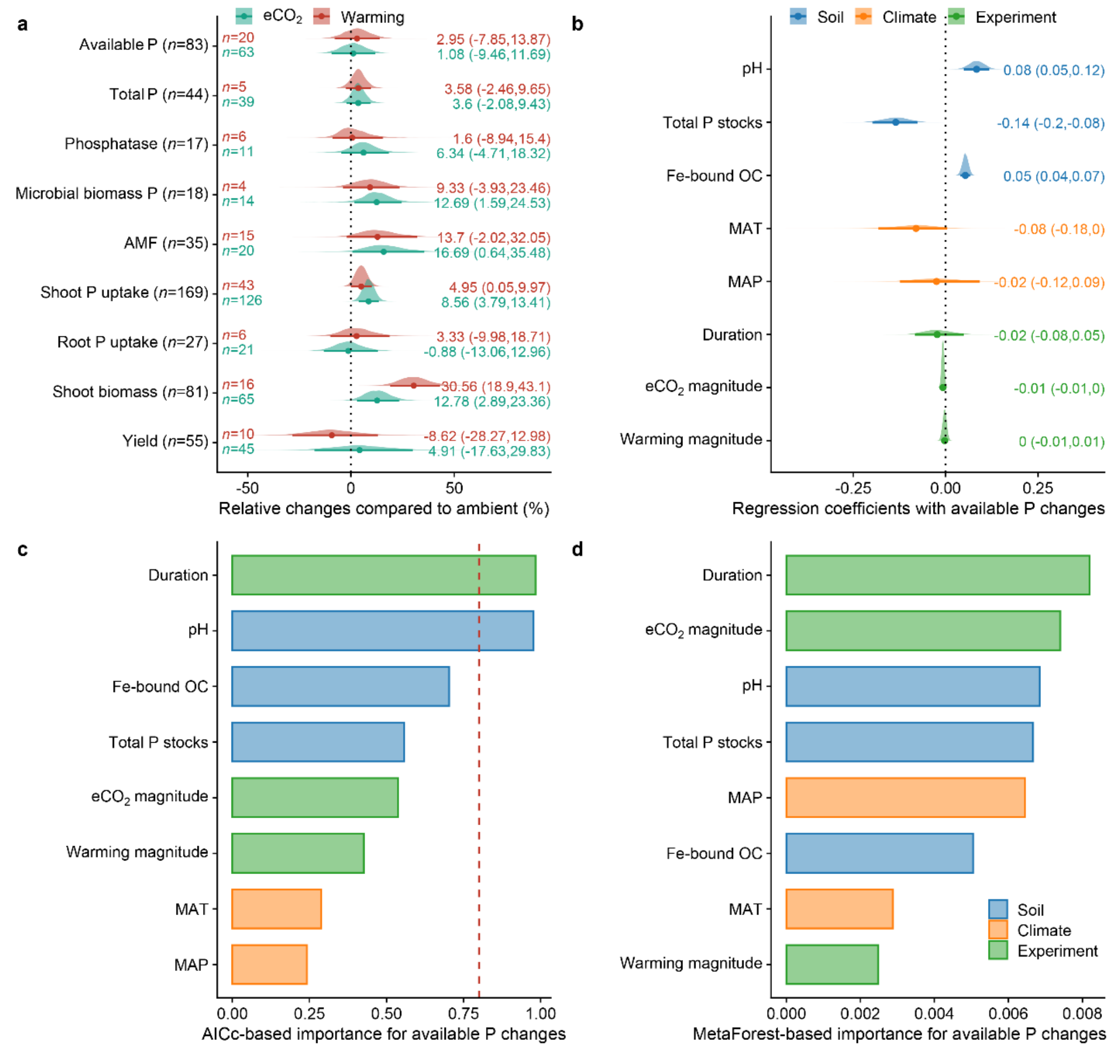

Fig. 1 Global responses of cropland phosphorus (P) availability to climate change and the key drivers. a, Sensitivity of the soil–plant–microbial P cascade to elevated CO_2 (eCO_2) and warming scenarios across 48 field experiments. Effect sizes are presented as percentage changes (%) and their 90% credible intervals derived from the Bayesian meta-analysis (Supplementary Text 2). Numbers in parentheses or on the right indicate the sample sizes (*n*) for each variable or each treatment, respectively. **b–d**, Relative importance of biotic and abiotic predictors governing the climate-driven alterations in available P (n = 83), determined *via* three independent statistical analyses: Bayesian meta-regression **(b)**, corrected Akaike's Information Criterion (AICc)-based model selection **(c)**, and MetaForest **(d)**. Predictors include initial soil properties (pH, total P stocks, and iron-associated organic carbon [Fe-bound OC]), climate factors (mean annual temperature [MAT], mean annual precipitation [MAP]), and experimental setup (eCO_2 magnitude, warming magnitude, and duration). The red line in (**c**) denotes the cutoff (0.8) to identify the most important factors.

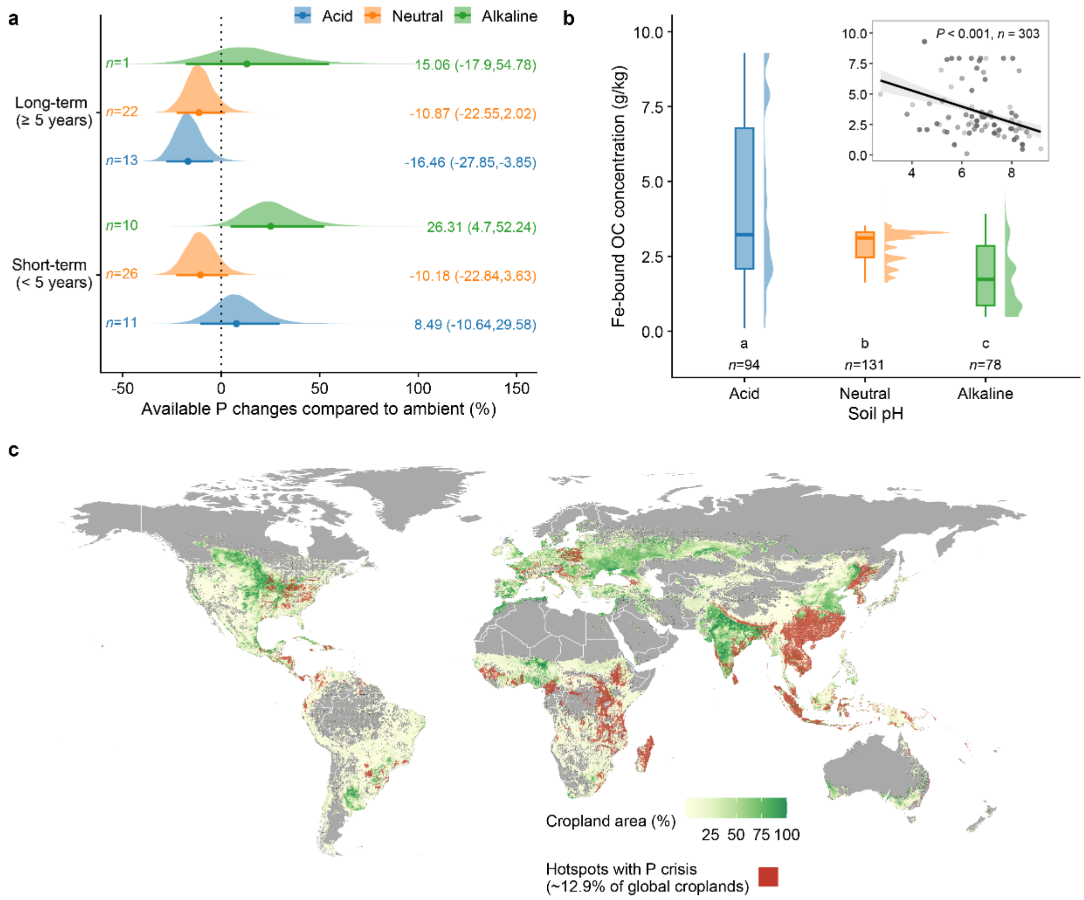

Fig. 2 Acidity-dependent phosphorus (P) responses, geochemical mechanisms, and hotspots across the globe. a, Available P changes in response to climate change (%) under short-term (< 5 years) versus long-term (≥ 5 years) forcing, stratified by background soil acidity categories, including acid (pH < 6.5), neutral (pH = 6.5–7.5), and alkaline (pH > 7.5). Shaded distributions represent the posterior density derived from the Bayesian meta-analysis, with central points and thick horizontal lines denoting medians and their 90% credible intervals, respectively. Sample sizes (*n*) for each category are shown on the left of the distributions. **b**, Variations in baseline soil iron-associated organic carbon (Fe-bound OC) concentrations across soil pH gradients. Boxplots and half-eye distribution curves illustrate the differences among the three acidity categories, with different lowercase letters denoting the statistical significance (Tukey's HSD test). Numbers below the letters indicate the corresponding number of observations. **c**, Global pattern of P crisis hotspots. Hotspots are defined as the cropland grids simultaneously characterized by acidic soils (pH < 6.5) and the bottom quartile (< 25%) of baseline crop P use efficiency (PUE, here represented by maize). Cell-area distortions are corrected *via* ellipsoidal grid-cell integration, yielding a restricted proportion of 12.9% of global croplands (see more details in Supplementary Text 5).