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**Global response patterns of plant functional traits to nitrogen and phosphorus addition are governed by additive interactions, climatic demand, and species acquisition strategy**

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**Abstract**

The availability of nutrients such as nitrogen and phosphorus plays a central role in shaping plant ecophysiological responses to global change. While nitrogen availability has been asserted as a key driver of plant responses to global change, the role of phosphorus – both individually and in combination with nitrogen – remains less understood due to a lack of data syntheses that precludes the development of a mechanistic framework. To address this knowledge gap, we compiled data from full-factorial nitrogen and phosphorus addition experiments across the globe and conducted a meta-analysis of leaf and whole-plant traits. We quantified the individual and interactive effects of nitrogen and phosphorus addition on leaf nutrient content, leaf photosynthetic traits, and biomass partitioning and assessed how climate and species acquisition strategy mediate these responses. Nutrient addition played no role in shaping leaf-level photosynthetic parameters, despite nitrogen and phosphorus addition increasing foliar nutrient concentrations and increasing aboveground biomass. Most trait responses to combined nitrogen and phosphorus addition were driven by additive interactions, except for aboveground biomass, which demonstrated a stronger response to combined nitrogen and phosphorus addition than the sum of the individual effects of nitrogen and phosphorus. Some responses were mediated by climate, with leaf nitrogen content responses to nitrogen addition and leaf phosphorus content responses to phosphorus addition each being strongest in colder and drier regions. Additionally, some trait responses to nutrient addition were mediated by acquisition strategy, with nitrogen-fixing species or species that associate with mycorrhizal fungi that adopt mining strategies often demonstrating dampened responses to nutrient addition than non-fixing species or species that associate with mycorrhizal fungi that adopt scavenging strategies. These findings clarify the role of phosphorus availability in shaping plant ecophysiological trait variation, highlight possible mechanisms governing trait responses across climatic gradients and acquisition strategies, and provide a foundation for improving the representation of C-N-P interactions in terrestrial biosphere models.

**Introduction**

Terrestrial ecosystems are regulated by complex carbon, nitrogen, and phosphorus cycles. Recent terrestrial biosphere model development has focused on incorporating fully coupled nitrogen and phosphorus cycles, following from evidence that nutrient availability constrains primary productivity under present and future climates (Hungate *et al.*, 2003; LeBauer & Treseder, 2008; Wieder *et al.*, 2015; Fay *et al.*, 2015). Models with fully coupled nutrient cycles generally reduce the magnitude of the land carbon sink (Goll *et al.*, 2012; Wieder *et al.*, 2015; Braghiere *et al.*, 2022), and ensemble analyses often show stronger agreement with observations compared to carbon-only models (Kou-Giesbrecht *et al.*, 2023; Stocker *et al.*, 2025). However, land carbon sink trends still diverge substantially across models, with some studies showing a stronger divergence in simulated carbon sink trends between nutrient-coupled models than carbon-only models (Davies-Barnard *et al.*, 2020; Kou-Giesbrecht *et al.*, 2023; Stocker *et al.*, 2025). This disparity is likely due to an incomplete understanding of how nutrient availability influences plant traits that drive ecosystem carbon and nutrient fluxes, highlighting the need for global data syntheses to resolve broad-scale patterns of nutrient effects on plant traits.

Nitrogen availability has long been recognized as an important driver of plant ecophysiological trait variation. Soil nitrogen availability is often positively correlated with leaf nitrogen content, while leaf nitrogen content is often positively correlated with indices of photosynthetic capacity (Field & Mooney, 1986; Evans, 1989; Walker *et al.*, 2014; Firn *et al.*, 2019; Liang *et al.*, 2020). These relationships arise because large amounts of nitrogen are required to build and maintain photosynthetic enzymes (Evans & Seemann, 1989; Waring *et al.*, 2023) and therefore represent a key determinant of carbon and nutrient fluxes in terrestrial biosphere models (Rogers *et al.*, 2017). Leaf nutrient and photosynthetic responses to nitrogen availability often manifest at the whole-plant level as an increase in biomass, typically through stronger increases in aboveground biomass than belowground biomass (Liang *et al.*, 2020; Stocker *et al.*, 2025). Plant responses to nitrogen availability may depend on climate and species acquisition strategy, with stronger responses expected under climatic conditions that heighten photosynthetic demand for soil resources and in species with nutrient acquisition strategies that rely on soil nitrogen availability (Cheaib *et al.*, 2025b; Perkowski *et al.*, 2025).

Phosphorus availability is also an important determinant of plant ecophysiological trait variation, yet its effects have historically garnered less attention. Soil phosphorus availability is positively correlated with leaf phosphorus content (Firn *et al.*, 2019), and leaf phosphorus content is often correlated with indices of photosynthetic capacity (Walker *et al.*, 2014; Ellsworth *et al.*, 2022). These relationships arise because phosphorus is required to build and maintain energy transfer compounds (i.e., ATP, NADPH) that play a central role in driving the Calvin-Benson cycle. Similar to nitrogen, increasing phosphorus availability often leads to an increase in biomass that stems from a stronger increase in aboveground biomass than belowground biomass (cite). These patterns indicate that phosphorus constraints on leaf nutrient-photosynthesis relationships and downstream effects on biomass production may just be as important for predicting carbon and nutrient fluxes in terrestrial biosphere models as nitrogen. However, unlike nitrogen, the extent to which plant responses to phosphorus availability vary with climate and acquisition strategy remains less understood. Additionally, the absence of broad-scale syntheses that assess phosphorus effects on leaf and whole-plant traits, both individually and interactively with nitrogen, precludes the development for mechanistic frameworks for predicting carbon and nutrient fluxes in phosphorus-coupled models.

Nitrogen and phosphorus commonly colimit plant growth, making their interactive effects important for resolving divergent land carbon sink trends across nutrient-coupled models. At the leaf level, nitrogen supports the construction and maintenance of photosynthetic enzymes, while phosphorus supplies the energy transfer compounds needed to drive the Calvin-Benson cycle. This complementarity suggests that combined enrichment of nitrogen and phosphorus could jointly enhance leaf nutrient content, photosynthesis, and biomass production (Niinemets & Kull, 2005; Walker *et al.*, 2014; Fay *et al.*, 2015). Some studies suggest that plants respond to combined nitrogen and phosphorus addition by increasing aboveground biomass more strongly than predicted through individual effects of nitrogen and phosphorus addition, highlighting the likelihood that some plant responses to nitrogen and phosphorus availability may be synergistic (Fay *et al.*, 2015; Fang *et al.*, 2024). Such synergistic interactions may be particularly apparent in ecosystems where nitrogen and phosphorus strongly co-limit growth, such as the tropics (Vitousek *et al.*, 2010; Du *et al.*, 2020). Yet, existing syntheses have only quantified nitrogen and phosphorus interactions for a subset of traits (Fang *et al.*, 2024; Ding *et al.*, 2025), limiting our ability to predict when plant trait responses to nitrogen and phosphorus availability will be additive, synergistic, or antagonistic.

Here, we conducted a global meta-analysis using experiments that manipulated nitrogen and phosphorus in full-factorial designs to address three primary objectives. First, we sought to quantify the effects of nitrogen, phosphorus, and nitrogen+phosphorus addition on leaf nutrient content, net photosynthesis, photosynthetic capacity, leaf nitrogen and phosphorus use efficiency, biomass production, and biomass partitioning. Second, we quantified the interaction effect size of each trait to understand whether the effects of nitrogen+phosphorus addition were the product of additive, synergistic, or antagonistic individual effects of nitrogen and phosphorus addition. Finally, we evaluated how climate and species identity traits (e.g., photosynthetic pathway, ability to associate with nitrogen-fixing bacteria, mycorrhizal nutrient acquisition strategy) moderate leaf and whole-plant responses to nutrient addition. We used this meta-analysis and study objectives to test the following hypotheses:

1. Nitrogen and phosphorus addition will increase leaf nitrogen content and leaf phosphorus content, respectively. The effects of nitrogen and phosphorus addition on leaf nitrogen and phosphorus content will be amplified in regions where demand for building and maintaining photosynthetic enzymes is increased (e.g., high aridity, low temperature, high light availability), or in species that use nutrient acquisition strategies that rely on soil-derived nutrients (e.g., species that do not form associations with nitrogen-fixing bacteria, species that form associations with scavenging mycorrhizal species).
2. Nitrogen and phosphorus addition will not influence photosynthetic parameters unless resource availability is insufficient to satisfy demand to build and maintain photosynthetic enzymes. In nitrogen-limited systems, nitrogen addition is expected to increase the maximum rate of Rubisco carboxylation. In phosphorus-limited systems, phosphorus addition is expected to increase the maximum rate of electron transport for RuBP regeneration.
3. Nitrogen and phosphorus addition will increase total biomass through stronger increases in aboveground biomass than belowground biomass, which will decrease the root-to-shoot ratio and root mass fraction.
4. The combined effects of nitrogen and phosphorus addition on leaf and whole-plant traits will be no different than the sum of the corresponding individual effects of nitrogen and phosphorus addition, as nitrogen and phosphorus play distinct roles in driving leaf and whole-plant processes.

**Materials and Methods**

*Data compilation*

Initial data for the meta-analysis were collected using citations listed in the Manipulation Experiments Synthesis Initiative (MESI) database (Van Sundert *et al.*, 2023). Manipulation experiments that added nitrogen and phosphorus in a full-factorial design were only selected in this database to ensure that any comparisons made between nitrogen, phosphorus, and nitrogen+phosphorus addition responses were from the same subset of experiments. All data for manuscripts included in the MESI database that fit these criteria were downloaded or extracted using a plot digitizer to ensure that all relevant traits were included in the meta-analysis and undergo a round of quality control to avoid any data entry issues that may arise when using large ecological datasets (Augustine *et al.*, 2024). To supplement studies included in the MESI database, studies that reported data from Nutrient Network experiments were also included in the meta-analysis, including only measurements collected from control, nitrogen, phosphorus, and nitrogen+phosphorus addition plots. Each site in each paper that reported data from Nutrient Network experiments was treated as an independent experiment, following that the Nutrient Network is a globally distributed experiment where independent sites share the same nutrient addition and experimental design scheme (Borer *et al.*, 2014). Specifically, we added leaf nutrient data from Firn et al. (2019), biomass partitioning data from Cleland et al. (2019), and photosynthetic data from Hersch-Green et al. (2024).

To supplement MESI and Nutrient Network datasets, we added additional manipulation experiments using journal articles published on or before March 2025. We selected manipulation experiments where nitrogen and phosphorus were added in a full-factorial design. From this, we selected experiments that measured traits related to leaf photosynthesis (e.g., net photosynthesis maximum rates of Rubisco carboxylation and electron transport for RuBP regeneration), leaf nutrient content (e.g., mass- or area-based leaf nitrogen content, mass- or area-based leaf phosphorus content), biomass (e.g., above-ground or belowground biomass), or biomass partitioning (e.g., root mass fraction, root:shoot ratio). Finally, we selected experiments that included explicit explanations of treatment replication schemes to accurately calculate summary statistics. We first searched for studies that followed these guidelines using citations included in the MESI and Nutrient Network papers. To supplement these studies, we also created a search query in Web of Science using similar search terms as in (Liang *et al.*, 2020). Specifically, our query mined for the following topics: (nitrogen AND phosphorus) AND (fertiliz\* OR addition) AND (effect\* OR respon\* OR affect\* OR impact\* OR increas\* OR decreas\* OR alter\* OR deposition OR enrich\*) AND (leaf nitrogen\* OR leaf phosphorus\* OR \*use efficiency OR biomass OR mass fraction OR root:shoot OR LMA OR SLA OR chlorophyll OR photosynthesis OR Vcmax OR Jmax) NOT (animal\* OR medic\* OR chemist\*).

*Data extraction*

One mean value ± standard deviation per trait per species per nutrient fertilization treatment per experimental site was considered one observation for experiments that reported results at the species level. Observations for different species from the same study were considered independent, allowing us to determine the effects of species identity traits (e.g., mycorrhizal type, photosynthetic pathway, growth form) in modifying plant responses to nutrient treatments. For experiments that reported results at the treatment level, one mean value ± standard deviation per trait per nutrient fertilization treatment per experimental site was considered one observation.

Observations were integrated into a compiled dataset through multiple pathways. First, summary statistics (mean, standard deviation, replication scheme) were calculated directly from published datasets from studies that adopted open data practices. Where possible, summary statistics were extracted from tables included in the main text or supplemental information if studies did not explicitly publish their data. If studies did not include their data or provide summary statistics in tables, we digitized plots using information about treatment and sample replication information. Plots were digitized in R (version 4.4.2) using the ‘metadigitise’ package (Pick *et al.*, 2019). Studies that did not include clear descriptions about the replication scheme were not included in the dataset. Overall, this data extraction approach rendered 4680 observations (1560 observations each for nitrogen, phosphorus, and nitrogen+phosphorus treatments) from 85 studies. Of these studies, 78 were field experiments, 6 were greenhouse experiments, and 1 was a growth chamber experiment. Of the field experiments, 166 independent sites were represented, spanning a broad global gradient and diverse array of biome types (Table S1; Fig. S1). The dataset also includes data comprising 170 species from 54 families, representing diverse growth forms, growth durations, nutrient acquisition strategy, and photosynthetic pathway.

*Moderator variables*

Mean monthly temperature, precipitation, and solar radiation spanning 1970-2000 were extracted using site latitude and longitude data for all field experiments using the Climatic Research Unit Time Series v4.09 (CRU TS v4.09) gridded data product (Harris *et al.*, 2020) downscaled to a 30 arc-second spatial resolution with WorldClim 2.1 (Fick & Hijmans, 2017). Site aridity was extracted using a complementary gridded data product (Global-AI\_PET\_v3) using the same period (1970-2000) and spatial resolution (30 arc-seconds) (Zomer *et al.*, 2022). This aridity product uses WorldClim 2.1 to calculate monthly aridity as a function of mean monthly precipitation per unit mean monthly potential evapotranspiration, estimating potential evapotranspiration using the Penman-Monteith approach. Accordingly, decreasing aridity index values correspond with increasingly arid environments.

Mean monthly temperature (°C), mean monthly precipitation (mm), mean daily solar radiation (kJ m-2 day-1), and mean monthly aridity (unitless) were extracted from the grid cell containing each site using the “extract” function in the “raster” R package (Hijmans, 2010). Solar radiation values (from kJ m-2 day-1) were converted to photosynthetically active radiation (μmol m-2 s-1) assuming a conversion factor of 2.1 μmol m-2 s-1per unit W m-2. Site mean growing season temperature (*T*g; °C), growing season aridity (*AI*g; unitless), and growing season PAR (*PAR*g; μmol m-2 s-1) were estimated using the months where mean temperature was above 0°C. All growing season climate data are reported in Table S1.

Species identity traits were included for all measurements that were collected at the species level. Specifically, we included information about species family, growth form (tree/shrub, graminoid, forb), growth duration (annual, perennial), photosynthetic pathway (C3, C4), N2-fixation ability (N2-fixer or non-fixer), and mycorrhizal type (AM, EcM, dual AM-EcM, facultative AM, ErM, and non-mycorrhizal). Mycorrhizal type was assigned from the FungalRoot database using the genus of each species (Soudzilovskaia *et al.*, 2020) and used to determine the mycorrhizal nutrient acquisition strategy following (Cheaib *et al.*, 2025a). Specifically, EcM, ErM, and dual AM-EcM species were assigned a scavenging mycorrhizal nutrient acquisition strategy while AM, facultative AM, and non-mycorrhizal species were assigned a mining mycorrhizal nutrient acquisition strategy. N2-fixation ability was determined based on whether species were in the *Fabaceae* family.

*Determination and analysis of individual and interaction effect sizes*

We used the natural logarithm of the response ratio (ln RR) to determine the individual effects of nitrogen, phosphorus, and nitrogen+phosphorus addition on leaf and whole-plant traits. For each observation *i* (i.e., trait per species per site per experiment), we calculated the natural logarithm of the response ratio (ln RR) as:

(1)

Where is the mean value of a treatment (i.e., nitrogen, phosphorus, or nitrogen+phosphorus addition) and is the mean value of the control treatment for each observation. We determined the weighted log-response ratio () across observations as:

(2)

Where ln RRi is the log-response ratio of observation *i* given in (1), *w*i is the weight of each log-response ratio, and *k* is the total number of observations. *w*i was calculated as the inverse of the variance (*v*i) of observation *i* (that is, *w*i = 1 / *v*i). *v*i was calculated as:

(3)

Where *s*t and *s*c are the standard deviations of the treatment and control groups, respectively, and *n*t and *n*c are the sample sizes of the treatment and control groups.

Next, we used Hedge’s *d* to determine the interactive effect of nitrogen and phosphorus addition on leaf and whole-plant traits (Yue *et al.*, 2017; Ding *et al.*, 2025). For each observation *i*, the interactive effect size of nitrogen and phosphorus addition (dNPi) was calculated as:

(4)

Where ,,, and refer to the mean of the nitrogen, phosphorus, nitrogen+ phosphorus, and control treatments, respectively, for each observation *i*. *s*int\_i refers to the pooled standard deviation across treatments, calculated as:

(5)

Where *N*ci, *N*ni, *N*pi, and *N*npi refer to the sample sizes of control, nitrogen, phosphorus, and nitrogen+phosphorus treatments, respectively. *S*ci, *S*ni, *S*pi, and *S*npi refer to the sample sizes of control, nitrogen, phosphorus, and nitrogen+phosphorus treatments, respectively, for each observation. In (6), *J*int\_i refers to a correction term for small sample size bias, calculated as:

(6)

We determined the weighted interaction effect size () of each trait across experiments as:

(7)

Where *d*NPi is the interaction effect size of observation *i* given in (6), *w*dnpi is the associated weight of each interaction effect size, and *k* represents the total number of observations. *w*dnpi was calculated as the inverse of the variance (*vd*NPi) of observation *i* (that is, *w*dnpi = 1 / *vd*NPi). *vd*NPi was calculated as:

(8)

*Data analysis*

We constructed a series of mixed-effects meta-regression models to understand the individual and interactive effects of nitrogen and phosphorus addition on leaf and whole-plant traits. Three separate models were created for each trait to assess the individual effects of nitrogen, phosphorus, and nitrogen+phosphorus addition using log-response ratios and their associated variances. We created a fourth model for each trait to assess the interactive effect of nitrogen and phosphorus addition using *d*NPi values and their associated variances and weights. We also assessed the role of climate or species identity moderated the response of each trait to nitrogen, phosphorus, or nitrogen+phosphorus addition by including *T*g, *AI*g, *PAR*g, N2-fixation ability (N2-fixer, non-fixer), and mycorrhizal nutrient acquisition strategy (mining, scavenging) as moderator variables. In all cases, we built mixed-effects meta-regression models using the ‘rma.mv’ function in the ‘metafor’ R package (Viechtbauer, 2010), manually specifying the weights of each observation as explained above, fitting each model using restricted maximum likelihood estimation, and including experiment as a random intercept term. We used the ‘orchaRd’ R package to assess and visualize moderator effects (Nakagawa *et al.*, 2023). Importantly, we could not assess the role of climate in modifying leaf photosynthetic traits, as there was not enough data collected from field experiments to test patterns with confidence.

Interactions between nitrogen and phosphorus addition on leaf and whole-plant traits were classified into three categories: additive, synergistic, and antagonistic interactions. Following Yue et al. (2017), null interaction effects (i.e. the 95% confidence intervals overlapped with zero) were classified as additive interactions, where the combined effect of nitrogen and phosphorus addition had similar effects as the sum of the individual effects of nitrogen and phosphorus addition. An interaction was classified as synergistic (i.e. the combined effect of nitrogen and phosphorus addition was stronger than predicted through individual effects) if positive individual effects of nitrogen and phosphorus addition corresponded with a significant positive interaction effect, if negative individual effects of nitrogen and phosphorus addition correspond with a significant negative interaction effect, or if mixed sign individual effects (e.g., one positive and one negative effect) corresponded with a significant negative interaction effect. An interaction was classified as antagonistic (that is, the combined effect of nitrogen and phosphorus addition was weaker than predicted through individual effects) if positive individual effects of nitrogen and phosphorus addition corresponded with a significant negative interaction effect, if negative individual effects of nitrogen and phosphorus addition corresponded with a significant positive interaction effect, or if mixed sign individual effects corresponded with a significant positive interaction effect.

All plots and statistics were completed using R version 4.4.2 (R Core Team, 2021). Plots visualize individual and interaction effects for each response variable as the percentage change between control and treatment groups, calculated as .

**Results**

*Individual effects of nutrient addition*

Nitrogen addition significantly increased *N*mass (16.5% increase) and *N*area (13.3% increase) but decreased *M*area (3.6% decrease) and *P*mass (7.2% decrease) and had no effect on *P*area (Table S2; Fig. 2a). There was no effect of nitrogen addition on any photosynthetic trait (Table S3; Fig 2b). However, nitrogen addition increased aboveground biomass (38.5% increase) and did not change belowground biomass, leading to a reduction in the root:shoot ratio (28.9% decrease) and root mass fraction (14.6% decrease; Table S4; Fig. 2c).

Phosphorus addition significantly increased *P*mass (56.7% increase) and *P*area (69.8% increase), but had no effect on *M*area, *N*mass, or *N*area (Table S2; Fig 2d). There was no effect of phosphorus addition on any photosynthetic trait except for *J*max (19.4% increase; Table S3; Fig. 2e). Phosphorus addition weakly increased total biomass (16.8% increase) and aboveground biomass (21.1% increase), leading to a reduction in the root:shoot ratio (20.3% decrease) (Table S4; Fig. 2f).

Finally, nitrogen+phosphorus addition significantly increased *N*mass (11.3% increase), *N*area (16.2% increase), *P*mass (44.1% increase), and *P*area (46.7% increase) (Table S2; Fig. 2g). There was a weak positive effect of nitrogen+phosphorus addition on *A*sat (23.8% increase) and *J*max (29.9% increase), but there was no effect of nitrogen+phosphorus addition on *V*cmax, PNUE, or PPUE (Table S3; Fig. 2h). Nitrogen+phosphorus addition increased total biomass (46.0% increase) through an increase in aboveground biomass (87.2% increase) and no change in belowground biomass, leading to a reduction in the root mass fraction (13.7% decrease) and root:shoot ratio (33% decrease) (Table S4; Fig. 2i).

*Interaction effects*

Interaction effect sizes indicated that all trait responses to nitrogen+phosphorus addition except for aboveground biomass were the product of additive interactions (Table S5; Fig. 3). Aboveground biomass demonstrated a synergistic interaction to nitrogen and phosphorus addition, where there was a stronger effect of nitrogen+phosphorus addition on aboveground (87.2% increase; Table S4) than predicted through the sum of individual effects of nitrogen addition (38.5% increase; Table S4) and phosphorus addition (21.1% increase; Table S4).

**Figure 2**

A collage of graphs

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**Figure 2**. Individual effects of nitrogen addition (top row of panels), phosphorus addition (middle row of panels), and nitrogen+phosphorus addition (bottom row of panels) on traits related to leaf nutrient content (left column of panels), leaf photosynthesis (middle column of panels), and biomass partitioning (right column of panels). Large points indicate the meta-analytic mean (represented as % change, calculated as), error bars indicate 95% confidence intervals, and sample sizes are reported in parentheses. Significant treatment effects are noted with asterisks next to sample sizes (based on *Z*-score; \*: *p*<0.05, \*\*: *p*<0.01; \*\*\*: *p*<0.001). Key: *M*area=leaf biomass per unit leaf area, *N*mass=leaf nitrogen content per unit leaf biomass, *N*area=leaf nitrogen content per unit leaf area, *P*mass=leaf phosphorus content per unit leaf biomass, *P*area=leaf phosphorus content per unit leaf area, *A*sat=light-saturated net photosynthesis rate, *V*cmax=maximum rate of Rubisco carboxylation, *J*max=maximum rate of electron transport for RuBP regeneration, PNUE=photosynthetic nitrogen-use efficiency, PPUE=photosynthetic phosphorus-use efficiency, AGB=aboveground biomass, BGB=belowground biomass, RMF=root mass fraction, root:shoot=ratio of root biomass to shoot biomass.

**Figure 3**

A graph of a number of individuals

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**Figure 3**. Interaction effects of nitrogen and phosphorus addition on traits related to leaf nutrient content (a), leaf photosynthesis (b), and biomass partitioning (c). Large points indicate the meta-analytic mean (represented as % change, calculated as ), error bars indicate 95% confidence intervals, and sample sizes are reported in parentheses. Black colored points indicate additive interactions while red colored points indicate synergistic interactions. Significant interaction effects are also noted with asterisks next to sample sizes (based on *Z*-score; \*: *p*<0.05). All acronyms are as explained in Figure 2.

*Climate effects on plant responses to nitrogen addition*

Increasing growing season temperature decreased the response ratio that explained the effect of nitrogen addition on *N*mass and marginally decreased the ratio that explained the effect of nitrogen addition on *N*area, but did not modify *P*mass, *P*area, or *M*area responses to nitrogen addition (Table S6; Fig. 4X). While increasing temperature marginally decreased the response ratio that explained the effect of nitrogen addition on total biomass, temperature did not modify any other whole-plant trait response to nitrogen addition (Table S7).

Increasing growing season aridity decreased the response ratio that explained the effect of nitrogen addition on *N*mass and marginally decreased the response ratio that explained the effect of nitrogen addition on *N*area(Table S6; Fig. 4X). Aridity did not modify any leaf phosphorus or whole-plant trait response to nitrogen addition (Table S6).

Growing season light availability played no role in shaping leaf nutrient or whole-plant responses to nitrogen addition, except for marginally increasing the response ratio that explained the effect of nitrogen addition on root mass fraction (Table S6-7).

*Climate effects on plant responses to phosphorus addition*

Temperature did not modify the effects of phosphorus addition on *M*area, *N*mass or *N*area; however, increasing temperature decreased the response ratio that explained the effect of phosphorus addition on *P*mass and marginally decreased the ratio that explained the effect of phosphorus addition on *P*area (Table S6; Fig. 4X). Increasing temperature also marginally decreased the response ratio that explained the effect of phosphorus addition on total biomass, with no effect of temperature on any other whole-plant trait response to phosphorus addition (Table S7).

Increasing growing season aridity marginally decreased the response ratio that explained the effect of phosphorus addition on *P*mass and significantly increased the response ratio that explained the effect of phosphorus addition on *M*area (Table S6; Fig. 4X). There was no effect of growing season aridity on *N*mass, *N*area, or *P*area responses to phosphorus addition (Table S6). Increasing growing season aridity increased the response ratio that explained the effect of phosphorus addition on aboveground biomass and decreased the response ratio that explained the effect of phosphorus addition on the root:shoot ratio, but there was no effect of aridity on any other whole-plant trait response to phosphorus addition (Table S7).

Growing season light availability played no role in shaping leaf nutrient or whole-plant response to phosphorus addition (Table S7).

*Climate effects on plant responses to nitrogen and phosphorus addition*

Increasing temperature increased the response ratio that explained the effect of nitrogen+ phosphorus addition on *M*area and decreased the response ratio that explained the effect of nitrogen+phosphorus addition on *N*mass (Table S6). Temperature did not modify *N*area, *P*mass, or *P*area responses to nitrogen+phosphorus addition (Table S6). Increasing temperature marginally decreased the response ratio that explained the effect of nitrogen+phosphorus addition on total biomass; however, temperature did not modify any other whole-plant trait response to nitrogen+phosphorus addition (Table S7).

Increasing growing season aridity increased the response ratio that explained the effect of nitrogen+phosphorus addition on *M*area and decreased the response ratio that explained the effect of nitrogen+phosphorus addition on *P*mass (Table S6). There was no effect of aridity on any other leaf nutrient trait response to nitrogen+phosphorus addition (Table S6). Growing season aridity did not modify any whole-plant trait response to nitrogen+phosphorus addition (Table S7).

Increasing growing season light availability increased the response ratio that explained the effect of nitrogen+phosphorus addition on *P*area, but light availability did not modify any other leaf nutrient response to nitrogen+phosphorus addition (Table S6). Increasing growing season light availability also increased the response ratio that explained the effect of nitrogen+phosphorus addition on belowground biomass, but there was no effect of light availability on any other whole-plant trait (Table S7).

*Species identity moderator effects*

Species significantly modified plant responses to nutrient additions (Table S8-S14). For example, non-fixing species generally exhibited significantly stronger leaf nitrogen content responses to nitrogen addition than N2-fixing species (Table S11) and scavenging mycorrhizal species generally exhibited significantly stronger leaf phosphorus content responses to phosphorus addition (Table S13). All species moderator effects are summarized in Tables S8-S14.

**Figure 4**

**A collage of graphs and diagrams

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**Figure 4** Effects of growing season climate and species identity on mass-based leaf nitrogen responses to nitrogen addition (top row of panels) and leaf phosphorus responses to phosphorus addition (bottom row of panels). From left to right, the top row of panels describes the growing season temperature (a), growing season aridity (b), ability to associate with nitrogen fixing bacteria (c), mycorrhizal nutrient acquisition strategy (d), and photosynthetic pathway effect on the leaf nitrogen content response to nitrogen addition. The bottom row of panels describes the growing season temperature (f), growing season aridity (g), ability to associate with nitrogen fixing bacteria (h), mycorrhizal nutrient acquisition strategy (i), and photosynthetic pathway (j) effect on the leaf phosphorus content response to phosphorus addition. For climate moderator plots, grey points indicate individual data points. Solid trendlines are drawn if climate significantly modified leaf nutrient responses to nutrient addition (*p*<0.05) and dashed trendlines are drawn if climate marginally modified leaf nutrient responses to nutrient addition (*p*<0.1). For species identity traits, large points indicate the meta-analytic mean (represented as % change, calculated as ) and error bars indicate 95% confidence intervals, with significant pairwise differences noted with asterisks above brackets (based on *Z*-score; \*: *p*<0.05, \*\*: *p*<0.01; \*\*\*: *p*<0.001).

**Discussion**

Here, we compiled a global dataset of full-factorial nitrogen and phosphorus addition experiments to evaluate how nutrient enrichment alters leaf and whole-plant functional traits. Specifically, we asked: (i) how nitrogen, phosphorus, and nitrogen+phosphorus addition influence leaf nutrient concentrations, photosynthetic traits, and biomass allocation; (ii) whether trait responses to nitrogen+phosphorus addition are due to additive, synergistic, or antagonistic interactions; and (iii) if trait responses are mediated by climate or species identity. Our results show that nitrogen and phosphorus addition primarily influence leaf nutrient content and whole-plant traits, with limited effects on leaf-level photosynthetic capacity. Results also show that plant responses to nitrogen+phosphorus addition are largely governed by additive interactions, except aboveground biomass, which demonstrated a synergistic interaction. Climate and nutrient acquisition strategies moderated some trait responses to nutrient enrichment, demonstrating stronger trait responses to nutrient additions in regions with greater demand for soil resources and in species that rely mostly on soil-derived nutrients. These findings are consistent with previous work showing limited impacts of nutrient addition on leaf-level photosynthesis (Liang *et al.*, 2020; Waring *et al.*, 2023; Stocker *et al.*, 2025), stronger plant responses in regions with high climatic demand for soil resources (Cheaib *et al.*, 2025b) and stronger responses in species that rely on plant-available soil nutrients (Perkowski *et al.*, 2021, 2025; Cheaib *et al.*, 2025a). Finally, our findings reinforce existing analyses showing that plant trait responses to multiple global change factors are often additive (Yue *et al.*, 2017; Ding *et al.*, 2025).

*Nitrogen and phosphorus addition play a stronger role in modifying leaf nutrient content and whole-plant traits than photosynthetic traits*

Leaf nutrient responses to nitrogen and phosphorus additions were generally stronger in magnitude than photosynthetic responses. Specifically, nitrogen addition played no role in modifying photosynthetic traits, while phosphorus addition weakly increased *J*max and had no effect on any other photosynthetic trait. Despite this, we observed strong positive effects of nitrogen addition on leaf nitrogen content and phosphorus addition on leaf phosphorus content. This decoupling between leaf nutrients and photosynthesis implies that nutrient addition may have decreased the relative fraction of leaf nitrogen and phosphorus allocated to photosynthesis and therefore increased the fraction of nutrients allocated to non-photosynthetic pools (e.g., structure). These changes in the fractional pool of leaf nutrients allocated to photosynthesis has been observed in response to nitrogen addition (Waring *et al.*, 2023; Perkowski *et al.*, 2025), but not phosphorus, in part because determining fractional pools of leaf phosphorus beyond metabolic processes remains a challenge. Regardless, these patterns contrast the current formulation of photosynthesis in many nutrient-coupled models, where photosynthetic capacity is often predicted as a function of leaf nitrogen and phosphorus content across environmental gradients (Achat *et al.*, 2016; Rogers *et al.*, 2017; Stocker *et al.*, 2025). Our results suggest that static leaf nutrient-photosynthesis relationships may lead to an overestimation of the terrestrial carbon sink, as these static relationships will likely overestimate leaf-level photosynthesis and whole plant productivity in environments with elevated nutrient inputs.

Additionally, whole-plant responses to nutrient additions were generally stronger than photosynthetic responses to nutrient additions. These responses seem paradoxical on the surface, as increased biomass accumulation cannot occur without an increase in carbon assimilation. However, these patterns could be driven by optimized resource allocation to photosynthetic enzymes that maximizes resource allocation to whole-plant growth, following patterns expected from eco-evolutionary optimality theory (Stocker *et al.*, 2025; Perkowski *et al.*, 2025). Eco-evolutionary optimality theory predicts that investment in photosynthetic enzymes is determined by photosynthetic demand for soil resources associated with climate (Smith *et al.*, 2019, 2024; Harrison *et al.*, 2021; Stocker *et al.*, 2025; Perkowski *et al.*, 2025), where changes in soil resource supply should only increase photosynthesis when demand remains unsatisfied (Stocker *et al.*, 2025). The theory posits that plants should allocate excess nutrients not needed to satisfy leaf-level demand toward the construction of additional leaves, leading to a stronger increase in total leaf area and whole-plant productivity than leaf-level photosynthesis. These responses indicate that limited photosynthetic responses to nutrient addition may be attributed to leaf-level nutrient demand for photosynthetic enzymes being satisfied, leading to stronger investment in nutrients toward the construction of additional optimally coordinated leaves.vTo date, support for this theory has primarily been observed across nitrogen availability gradients and nitrogen manipulation experiments (Dong *et al.*, 2017, 2020, 2022; Liang *et al.*, 2020; Paillassa *et al.*, 2020; Stocker *et al.*, 2025; Perkowski *et al.*, 2025), though some work indicates that these patterns may also apply across phosphorus availability gradients (Westerband *et al.*, 2023). Our findings suggest that these same optimization patterns may also apply phosphorus manipulation experiments, a key result given recent efforts to incorporate eco-evolutionary optimality (Harrison *et al.*, 2021; Smith *et al.*, 2024; Ren *et al.*, 2025) and the phosphorus cycle (Allen *et al.*, 2020; Braghiere *et al.*, 2022) into terrestrial biosphere models.

*Plant responses to* *nitrogen+phosphorus addition are largely governed by additive interactions*

A central focus of this meta-analysis was to assess whether plant responses to nitrogen+ phosphorus addition were driven by additive, synergistic, or antagonistic interactions. Existing syntheses suggest that ecosystem and plant responses to multiple global change factors are often driven by additive interactions (Yue *et al.*, 2017; Ding *et al.*, 2025). Except for a recent meta-analysis showing that aboveground biomass responds synergistically to nitrogen+phosphorus addition (Fang *et al.*, 2024), global syntheses have rarely addressed the interactive effects of nitrogen and phosphorus addition on leaf nutrient, photosynthetic, or whole-plant traits. Our analysis shows that leaf and whole-plant responses to nitrogen+phosphorus addition were indeed largely driven by additive interactions. This was the case for all traits except for aboveground biomass, which demonstrated a synergistic interaction. These findings indicate that most plant trait responses to nitrogen+phosphorus addition are no different than the sum of the individual effects of nitrogen and phosphorus addition, with stronger effects of nitrogen+phosphorus addition on aboveground biomass than the sum of its individual effects.

Our results revealed a synergistic interaction that defined the aboveground biomass response to nitrogen+phosphorus addition, supporting findings from previous work (Fay *et al.*, 2015; Fang *et al.*, 2024)

*Plant responses to nutrient additions are mediated through climatic demand and species identity*

Following expectations, trait responses to nutrient addition were strongest under climatic conditions where photosynthetic demand was highest. Specifically, the effects of nitrogen addition on *N*mass and *N*area were strongest in colder, drier climates, as indicated by a negative effect of increasing temperature and aridity index on the responses of *N*mass and *N*area to nitrogen addition. Similar patterns were observed with phosphorus, where the effects of phosphorus addition on *P*mass and *P*area were strongest in colder and drier climates due to negative effects of increasing temperature and aridity index on the responses of *P*mass and *P*area to phosphorus addition.

*Climatic demand determines plant responses to nutrient addition*

The effects of nitrogen addition on *N*mass and *N*area were strongest in colder, drier climates, as indicated by a negative effect of increasing *T*g and *AI*gon the responses of *N*mass and *N*area to nitrogen addition. Similar patterns were observed with phosphorus, where the effects of phosphorus addition on *P*mass and *P*area were strongest in colder and drier climates due to negative effects of increasing *T*g and *AI*gon the responses of *P*mass and *P*area to phosphorus addition. These patterns scaled to modify leaf trait responses to nitrogen+phosphorus addition, where nitrogen+phosphorus addition effects on *N*mass and *P*mass were strongest under

*Future research needs and directions*

Unfortunately, we could not investigate the role of climate in modulating photosynthetic responses to nitrogen and phosphorus addition. This constraint was due to the limited number of full-factorial nitrogen and phosphorus experiments that are conducted in the field, representing a clear future area of needed research and key knowledge gap that remains in our understanding of how photosynthetic processes respond to nutrient additions. Previous work has shown that climatic factors which influence demand play a predictable and key role in determining leaf nitrogen allocation responses to nitrogen and phosphorus addition (Cheaib et al., 2025). Our work supports these findings by showing that leaf nutrient allocation responses to nitrogen and phosphorus addition are dependent on climate and associated demands for soil resources. However, similar field analyses that scale these patterns to photosynthetic traits remain lacking. Quantifying these responses is particularly important, as recent work has highlighted that the fraction of leaf nutrients (nitrogen in this case) allocated to photosynthetic tissues decrease in response to increasing nitrogen availability and are dependent on climate-related demand for soil resources (Waring et al., 2023; Cheaib et al., 2025; Perkowski et al., 2025). Without field experiments that quantify leaf photosynthetic responses to nutrient treatments, we unable to comment on whether these responses scale with leaf nutrient allocation responses in ways that are predicted through eco-evolutionary optimality.

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