

1 **“Symbiotic nitrogen fixation reduces carbon costs of nitrogen acquisition under low, but**
2 **not high, nitrogen availability”**

3 *Running title: Symbiotic N fixation reduces nitrogen acquisition costs under low soil N*
4

5 **Abstract**

6 Many plant species form symbiotic associations with nitrogen-fixing bacteria. Through this
7 symbiosis, plants allocate photosynthate belowground to the bacteria in exchange for nitrogen
8 fixed from the atmosphere. This symbiosis forms an important link between carbon and nitrogen
9 cycles in many ecosystems. However, the economics of this relationship under soil nitrogen
10 availability gradients is not well understood. Here, we used a manipulation experiment to
11 examine how costs of nitrogen acquisition vary under a factorial combination of soil nitrogen
12 availability and inoculation with *Bradyrhizobium japonicum* in *Glycine max* L. (Merr.). We
13 found that inoculation decreased structural carbon costs to acquire nitrogen and increased total
14 leaf area and total biomass, but these patterns were only observed under low fertilization.
15 Treatment differences were the result of increased plant nitrogen uptake coupled with no change
16 in belowground carbon allocation. These results suggest that symbioses with nitrogen-fixing
17 bacteria reduce carbon costs of nitrogen acquisition, but only when soil nitrogen is low, allowing
18 individuals to increase nitrogen allocation to structures that support growth. This pattern helps
19 explain the prevalence of plants capable of forming these associations in less fertile areas and
20 demonstrates patterns that can help guide models linking carbon and nitrogen cycles in terrestrial
21 ecosystems.

22
23 **Keywords**

24 carbon-nitrogen interactions; nitrogen fixation; whole plant growth; greenhouse; crops; nutrient
25 acquisition strategy

Introduction

Terrestrial ecosystem processes are regulated, in part, by interactions between carbon and nitrogen cycles. As a result, terrestrial biosphere models are beginning to include coupled carbon and nitrogen cycles to simulate past, present, and future atmosphere-biosphere fluxes more realistically (Hungate *et al.*, 2003; Prentice *et al.*, 2015; Kou-Giesbrecht *et al.*, 2023). Carbon and nutrient flux simulations tend to converge across terrestrial biosphere model products using past and present climate scenarios; however, often diverge under future environmental change scenarios (Friedlingstein *et al.*, 2014; Davies-Barnard *et al.*, 2020). This divergence could be due to an incomplete understanding of how changing environments modify processes that link ecosystem carbon and nitrogen cycles (Fay *et al.*, 2015; Wieder *et al.*, 2015; Meyerholt *et al.*, 2016).

Plant nitrogen acquisition is one process in terrestrial ecosystems that links carbon and nitrogen cycles. Plants acquire nutrients by allocating photosynthetically derived carbon belowground in exchange for nitrogen through different nitrogen acquisition strategies. These nitrogen acquisition strategies can include direct uptake pathways such as mass flow or diffusion (Barber, 1962), symbioses with mycorrhizal fungi or symbiotic nitrogen-fixing bacteria (Vance and Heichel, 1991; Marschner and Dell, 1994; Smith and Read, 2008; Udvardi and Poole, 2013), or through root exudation that supplies carbon to free-living soil microbial communities (Phillips *et al.*, 2011; Wen *et al.*, 2022).

Plants cannot acquire nitrogen without first allocating carbon belowground, which implies that there is an inherent carbon cost to the plant for acquiring nitrogen (Chapin *et al.*, 1987). This carbon cost for acquiring nitrogen may vary in species with different nitrogen acquisition strategies. For instance, carbon investment in roots for direct nitrogen uptake does not require costs beyond root development, as is the case for acquisition strategies that involve other soil microbiota. However, the nitrogen acquired from a given belowground carbon investment may be greater than direct uptake if plants increase root exudation to supply soil microbial communities with substrate needed to decompose organic matter and increase inorganic soil nitrogen substrate available for root uptake (Bengtson *et al.*, 2012; Meier *et al.*, 2017). Alternatively, the nitrogen acquired from a given belowground carbon investment may be greater if carbon is allocated to fungal symbionts in exchange for nitrogen mined from the soil or converted to inorganic nitrogen from soil organic matter (Phillips *et al.*, 2013; Liese *et al.*, 2018),

or if carbon is allocated to bacterial symbionts in exchange for nitrogen fixed from the atmosphere (Gutschick, 1981; Vitousek and Field, 1999; Rastetter *et al.*, 2001; Vitousek *et al.*, 2002). Variation in the cost to acquire nitrogen may help explain the prevalence of different nitrogen acquisition strategies in different environments, but these costs have not been quantified outside of a few studies (Terrer *et al.*, 2018; Perkowski *et al.*, 2021; Lu *et al.*, 2022) despite their inclusion in nitrogen uptake models (Fisher *et al.*, 2010; Brzostek *et al.*, 2014; Allen *et al.*, 2020) currently implemented in terrestrial biosphere models (Shi *et al.*, 2016; Lawrence *et al.*, 2019; Braghiere *et al.*, 2022).

While carbon costs to acquire nitrogen may vary in species with different nitrogen acquisition strategies, these costs are also likely dependent on external environmental factors such as atmospheric CO₂, light availability, and soil nutrient availability (Brzostek *et al.*, 2014; Taylor and Menge, 2018, 2021; Terrer *et al.*, 2018; Friel and Friesen, 2019; Allen *et al.*, 2020; Perkowski *et al.*, 2021; Lu *et al.*, 2022). For instance, the amount of photosynthate allocated belowground in exchange for nitrogen may increase with increased light and CO₂, as these factors reduce the cost to produce photosynthate (Taylor and Menge, 2018; Terrer *et al.*, 2018; Friel and Friesen, 2019; Perkowski *et al.*, 2021; Waring *et al.*, 2023). However, increasing soil nitrogen availability may alternatively reduce costs for nitrogen acquisition due to stronger increases in plant nitrogen acquisition per unit carbon allocated belowground. This pattern increases plant nitrogen uptake efficiency and may be the result of reduced soil resource mining (by roots or symbionts) needed to satisfy plant nitrogen demand. This response to increasing soil nitrogen availability may not be as robust in plant species with strong and specialized symbiotic relationships with nitrogen-acquiring partners that reduce the sensitivity of plant nitrogen uptake to changes in nitrogen availability (e.g., plant species that associate with symbiotic nitrogen-fixing bacteria) (Perkowski *et al.*, 2021).

In a recent study, Perkowski *et al.* (2021) showed that increasing soil nitrogen fertilization decreased carbon costs to acquire nitrogen in *Gossypium hirsutum* (L.) and *Glycine max* L. (Merr). *Gossypium hirsutum* can acquire nutrients via direct uptake pathways or through symbioses with arbuscular mycorrhizal fungi, while *G. max* can acquire nutrients via direct uptake pathways or through symbioses with nitrogen-fixing bacteria. In the experiment, the authors noted that carbon costs to acquire nitrogen in *G. max* were generally less responsive to increasing soil nitrogen fertilization than *G. hirsutum*. This pattern coincided with reduced *G.*

max root nodulation with increasing fertilization. The authors speculated that this response may have been driven by resource optimization, where *G. max* shifted their dominant mode of nitrogen acquisition from nitrogen fixation to direct uptake with increasing fertilization once the cost to acquire nitrogen via direct uptake became less than the cost to acquire nitrogen via nitrogen fixation (Bloom *et al.*, 1985; Rastetter *et al.*, 2001). However, the authors were not able to make robust conclusions about whether the carbon cost to acquire nitrogen responses to soil nitrogen fertilization differed between *G. hirsutum* and *G. max* due to differences in species nutrient acquisition strategy. This was because the two species are not phylogenetically related and adopt different growth forms and growth durations.

To understand how nitrogen fixation and soil nitrogen fertilization interact to influence carbon costs to acquire nitrogen, *Glycine max* L. (Merr.) seedlings were grown under two soil nitrogen fertilization treatments and two inoculation treatments in a full factorial greenhouse experiment. We used this experiment to test the following hypotheses:

- (1) Soil nitrogen fertilization will decrease carbon costs of nitrogen acquisition in both uninoculated and inoculated individuals. This will manifest as an increase in the amount of nitrogen acquired per belowground carbon investment, indexed by a stronger increase in plant nitrogen uptake than belowground carbon allocation.
- (2) Inoculation with nitrogen-fixing bacteria will decrease carbon costs to acquire nitrogen under low soil nitrogen availability. This is because carbon costs to acquire nitrogen through symbiotic nitrogen fixation will be less than the carbon cost to acquire nitrogen via direct uptake. However, inoculation will have no effect on carbon costs to acquire nitrogen under high soil nitrogen availability due to all plants shifting toward a similar, direct uptake-dominated mode of nitrogen acquisition.
- (3) Root nodulation and plant investment toward symbiotic nitrogen fixation will decrease with increasing soil nitrogen availability. This pattern will be due to reduced carbon costs to obtain nitrogen from direct uptake with increasing soil nitrogen fertilization.

Materials and methods

Experimental Design

Glycine max seeds were planted in 64, 6-liter pots (NS-600, Nursery Supplies, Orange, CA, USA) containing unfertilized potting mix (Sungro Sunshine Mix #2, Agawam, MA, USA). Pots and potting mix were steam sterilized at 95°C for three hours to eliminate any bacterial or fungal growth. Thirty-two randomly selected pots were planted with seeds inoculated with *Bradyrhizobium japonicum* (Verdesian N-Dure™ Soybean, Cary, NC, USA) following a brief surface sterilization in 20,000 ppm sodium hypochlorite for 5 minutes followed by three washes in ultrapure water (Scouten and Beuchat, 2002; Montville and Schaffner, 2004). The remaining 32 pots were planted with seeds that did not receive any inoculation treatment. Uninoculated seeds were also surface sterilized in 20,000 ppm sodium hypochlorite for 5 minutes followed by three ultrapure water washes to ensure that the only difference between seed treatments was the inoculation treatment.

Upon planting, all pots were immediately placed in one of four random blocks in a greenhouse and received one of two nitrogen fertilization treatments as 150 mL of a modified Hoagland's solution (Hoagland and Arnon, 1950) equivalent to either 70 or 630 ppm N twice per week for seven weeks. Nitrogen fertilization doses were received as topical agents to the soil surface and were modified to keep concentrations of other macronutrients and micronutrients equivalent (Table S1). Throughout the experiment, plants were routinely well-watered to minimize any chance of water stress. There was no evidence of growth limitation due to pot size at the time of biomass harvest, indicated by total biomass: pot volume ratios less than 1 g L⁻¹ within each treatment combination (Table S2-3; Fig. S1; Poorter *et al.*, 2012).

Plant trait measurements

All experimental individuals were harvested, and biomass was separated into major organ types (leaves, stems, roots, and root nodules when present) approximately seven weeks after experiment initiation. Leaf areas of all harvested leaves were measured using an LI-3100C (LI-COR Biosciences, Lincoln, Nebraska, USA). Total leaf area (cm²) was calculated as the sum of all leaf areas. All harvested material was dried in an oven set to 65°C for at least 48 hours, weighed, and ground to homogeneity. Total dry biomass (g) was calculated as the sum of dry leaf, stem, root, and root nodule biomass. Carbon and nitrogen content of each respective organ was quantified through elemental combustion (Costech-4010, Costech, Inc., Valencia, CA, USA) using subsamples of ground and homogenized organ tissue.

Structural carbon costs to acquire nitrogen were calculated as the ratio of total belowground carbon biomass to whole plant nitrogen biomass ($\text{g C g}^{-1} \text{N}$; Perkowski *et al.*, 2021). Belowground carbon biomass (g C) was calculated as the sum of total root carbon biomass and total root nodule carbon biomass. Total root carbon biomass was calculated by multiplying root carbon content by total root biomass, while total root nodule carbon biomass was calculated by multiplying root nodule carbon content by total root nodule biomass. Whole-plant nitrogen biomass (g N) was calculated by multiplying the nitrogen content of leaves, stems, roots, and root nodules by biomass of each respective organ type, then calculating the sum of nitrogen biomass of each organ type. This calculation only quantifies plant structural carbon costs to acquire nitrogen and does not account for additional carbon costs of nitrogen acquisition associated with root respiration, root exudation, or root turnover. An explicit explanation of the limitations for interpreting this calculation can be found in Perkowski *et al.* (2021) and Terrer *et al.* (2018).

Statistical analyses

A series of linear mixed-effects models were built to investigate the impacts of soil nitrogen fertilization and inoculation on *G. max* carbon costs to acquire nitrogen and investment toward symbiotic nitrogen fixation. All models included soil nitrogen fertilization, inoculation, and interactions between soil nitrogen fertilization and inoculation as categorical fixed effects. Block number was included as a random intercept term to account for any environmental heterogeneity within the greenhouse room. Models with this independent variable structure were constructed to quantify relationships between soil nitrogen fertilization and inoculation on structural carbon costs to acquire nitrogen, belowground carbon biomass, whole plant nitrogen biomass, total leaf area, total biomass, root nodule biomass: root biomass, root nodule biomass, and root biomass.

Shapiro-Wilk tests of normality were used to determine whether linear mixed-effects models satisfied residual normality assumptions (Shapiro-Wilk: $p > 0.05$). Models for whole-plant nitrogen biomass and total leaf area satisfied residual normality assumptions without data transformation. We attempted to satisfy residual normality assumptions by fitting the other models using dependent variables that were natural log transformed. If residual normality assumptions were still not met after a natural-log transformation (Shapiro-Wilk: $p < 0.05$), then models were fit using dependent variables that were square root transformed. All residual

normality assumptions were met with either a natural log or square root data transformation (Shapiro-Wilk: $p > 0.05$ in all cases). Specifically, models for structural carbon costs to acquire nitrogen, belowground carbon biomass, total biomass, root biomass, and biomass: pot volume satisfied normality assumptions when response variables were fit using natural log transformed data, while models for nodule biomass: root biomass and root nodule biomass satisfied such assumptions when response variables were fit using square-root transformations.

We used the ‘lmer’ function in the ‘lme4’ R package (Bates *et al.*, 2015) to fit each model and the ‘Anova’ function in the ‘car’ R package (Fox and Weisberg, 2019) to calculate Type II Wald's χ^2 and determine the significance ($\alpha = 0.05$) of each fixed effect coefficient. We then used the ‘emmeans’ R package (Lenth, 2019) to conduct post-hoc comparisons using Tukey's tests, where degrees of freedom were approximated using the Kenward-Roger approach (Kenward and Roger, 1997). All analyses were conducted and plots were created using R version 4.2.0 (R Core Team, 2021).

Results

Structural carbon costs to acquire nitrogen

The interaction between soil nitrogen fertilization and inoculation ($p < 0.05$; Table 1) indicated that negative effects of inoculation ($p < 0.001$; Table 1) on structural carbon costs to acquire nitrogen were only apparent under low soil nitrogen fertilization (Tukey test comparing the inoculation effect under low soil nitrogen fertilization: $p < 0.001$), as there was no inoculation effect on structural carbon costs to acquire nitrogen under high soil nitrogen fertilization (Tukey test comparing the inoculation effect under high soil nitrogen fertilization: $p > 0.05$; Fig. 1A). Increasing soil nitrogen fertilization decreased structural carbon costs to acquire nitrogen ($p < 0.001$; Table 1; Fig. 1A).

Inoculation decreased belowground carbon biomass ($p < 0.05$; Table 1). This response was not modified by soil nitrogen fertilization (inoculation-by-fertilization interaction: $p > 0.05$; Table 1; Fig. 1B). Soil nitrogen fertilization had no effect on belowground carbon biomass ($p > 0.05$; Table 1).

The interaction between soil nitrogen fertilization and inoculation ($p < 0.001$; Table 1) indicated that positive effects of inoculation on whole-plant nitrogen biomass ($p < 0.001$; Table 1) were only apparent under low soil nitrogen fertilization (Tukey test comparing the inoculation

211 effect under low soil nitrogen fertilization: $p < 0.001$), as there was no effect of inoculation on
212 whole-plant nitrogen biomass under high soil nitrogen fertilization (Tukey test comparing the
213 inoculation effect under high soil nitrogen fertilization: $p > 0.05$; Fig. 1C). Increasing soil nitrogen
214 fertilization generally increased whole-plant nitrogen biomass ($p < 0.001$; Table 1).

215 **Table 1** Analysis of variance results exploring effect of soil nitrogen fertilization, inoculation with *B. japonicum*, and interactions
 216 between soil nitrogen fertilization and inoculation on structural carbon costs to acquire nitrogen, whole plant growth, and root
 217 nodulation*

		Carbon cost to acquire nitrogen		Belowground carbon biomass		Whole-plant nitrogen biomass		Total leaf area		Whole plant biomass	
	df	χ^2	<i>p</i>	χ^2	<i>p</i>	χ^2	<i>p</i>	χ^2	<i>p</i>	χ^2	<i>p</i>
N fertilization (N)	1	23.340	<0.001	0.076	0.782	358.695	<0.001	292.458	<0.001	52.427	<0.001
Inoculation (I)	1	16.749	<0.001	4.166	0.041	24.113	<0.001	35.095	<0.001	2.042	0.153
N*I	1	4.833	0.028	0.265	0.607	13.515	<0.001	17.898	<0.001	1.230	0.267

		Nodule biomass: root biomass		Nodule biomass		Root biomass	
	df	χ^2	<i>p</i>	χ^2	<i>p</i>	χ^2	<i>p</i>
N fertilization (N)	1	1.291	0.256	1.364	0.243	0.011	0.918
Inoculation (I)	1	27.375	<0.001	30.788	<0.001	3.268	<i>0.071</i>
N*I	1	0.493	0.483	1.005	0.316	0.254	0.614

218 *Significance determined using Type II Wald χ^2 tests ($\alpha=0.05$). *P*-values less than 0.05 are in bold and *P*-values between 0.05 and 0.1
 219 are italicized.

Figure 1

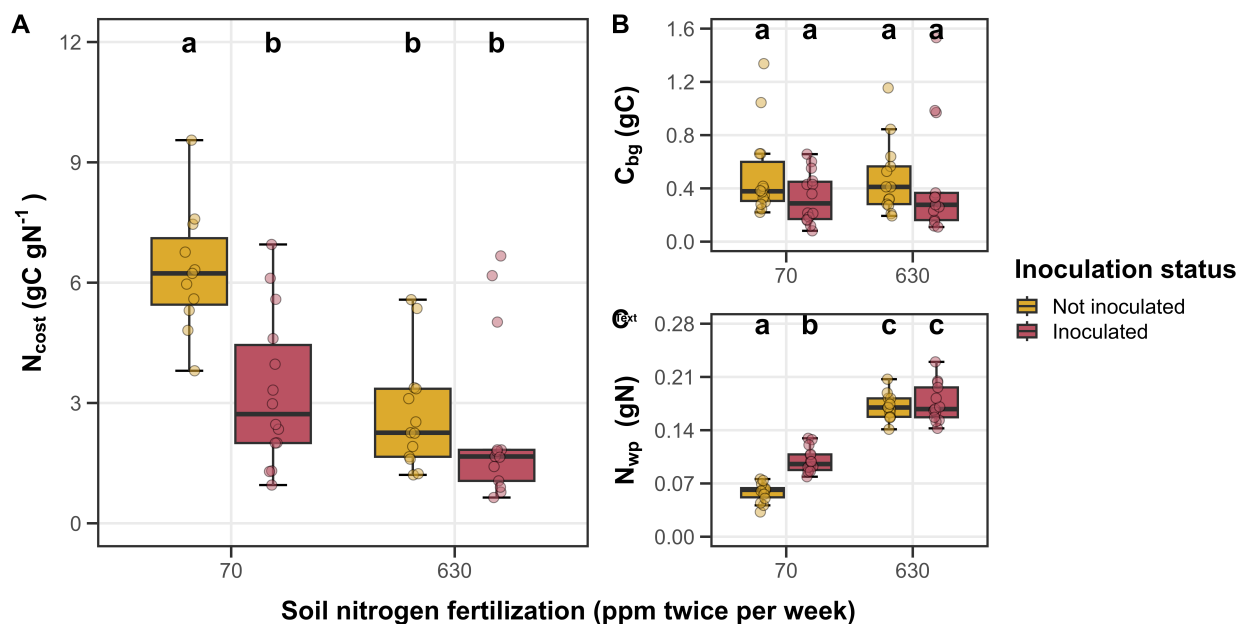


Figure 1 Effects of soil nitrogen fertilization and inoculation on *G. max* structural carbon costs to acquire nitrogen (" N_{cost} "; panel A), belowground carbon biomass (" C_{bg} "; panel B), and whole-plant nitrogen biomass (" N_{wp} "; panel C). Soil nitrogen fertilization is represented on the x-axis, while inoculation treatment is represented by colored boxplots. Yellow shaded boxplots indicate individuals that were not inoculated with *B. japonicum*, while red shaded boxplots indicate individuals that were inoculated with *B. japonicum*. Boxes are the upper (75% percentile) and lower (25% percentile) quartile. The whiskers are the minimum and maximum value, calculated as 1.5 times the upper and lower quartile value. Colored dots are individual data points, jittered for visibility. The lettering above each box indicates the results from post-hoc Tukey's tests with different lettering indicating statistically different groups (Tukey: $p < 0.05$).

Whole-plant growth

The interaction between soil nitrogen fertilization and inoculation ($p < 0.001$; Table 1) indicated that positive effects of inoculation on total leaf area ($p < 0.001$; Table 1) were only apparent under low soil nitrogen fertilization (Tukey test comparing the inoculation effect under low soil nitrogen fertilization: $p < 0.001$), as there was no inoculation effect on total leaf area under high soil nitrogen fertilization (Tukey test comparing the inoculation effect under high soil nitrogen fertilization: $p > 0.05$; Fig. 2A). Increasing soil nitrogen fertilization generally increased total leaf area ($p < 0.001$; Table 1; Fig. 2A).

Increasing soil nitrogen fertilization increased total biomass ($p < 0.001$; Table 1; Fig. 2B). This pattern that was not modified by inoculation (inoculation-by-fertilization interaction: $p > 0.05$; Table 1). Inoculation had no effect on total biomass ($p > 0.05$; Table 1; Fig. 2B).

Figure 2

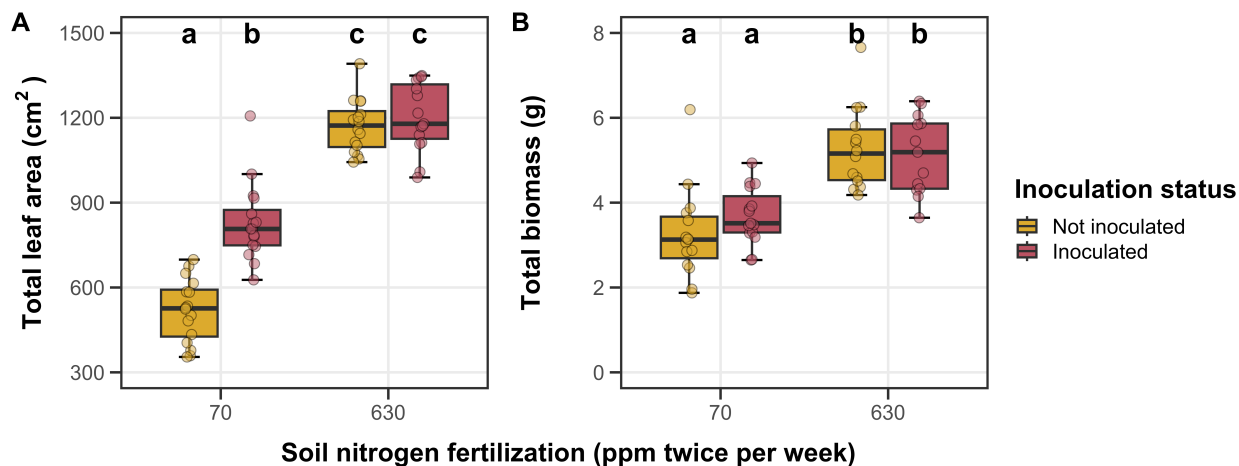


Figure 2 Effects of soil nitrogen fertilization and inoculation on *G. max* total leaf area (panel A), total biomass (panel B). Soil nitrogen fertilization is represented on the x-axis, while inoculation treatment is represented by colored boxplots. Yellow shaded boxplots indicate individuals that were not inoculated with *B. japonicum*, while red shaded boxplots indicate individuals that were inoculated with *B. japonicum*. Boxes are the upper (75% percentile) and lower (25% percentile) quartile. The whiskers are the minimum and maximum value, calculated as 1.5 times the upper and lower quartile value. Colored dots are individual data points, jittered for visibility. The lettering above each box indicates the results from post-hoc Tukey's tests with different lettering indicating statistically different groups (Tukey: $p < 0.05$).

Plant investment toward symbiotic nitrogen fixation

Inoculation increased root nodule biomass: root biomass ($p < 0.001$; Table 1; Fig 3A). This pattern was not modified by soil nitrogen fertilization (inoculation-by-fertilization interaction: $p > 0.05$; Table 1). Soil nitrogen fertilization had no effect on root nodule biomass: root biomass ($p > 0.05$; Table 1; Fig 3A).

Inoculation increased root nodule biomass ($p < 0.001$; Table 1; Fig 3B). This pattern was not modified by soil nitrogen fertilization (inoculation-by-fertilization interaction: $p > 0.05$; Table 1). Soil nitrogen fertilization had no effect on root nodule biomass ($p > 0.05$; Table 1; Fig. 3B).

Inoculation had a marginal negative effect on root biomass ($p < 0.1$; Table 1; Fig. 3C). This pattern was not modified by soil nitrogen fertilization (inoculation-by-fertilization interaction: $p > 0.05$; Table 1). Soil nitrogen fertilization had no effect on root biomass ($p > 0.05$; Table 1; Fig. 3C).

Figure 3

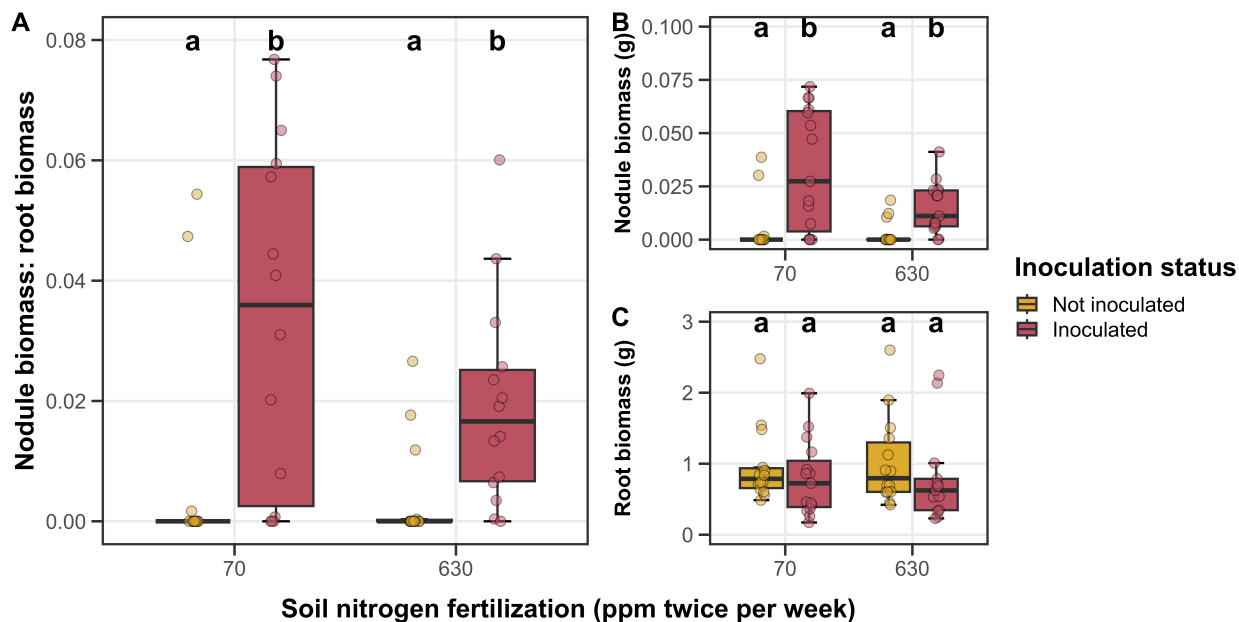


Figure 3 Effects of soil nitrogen fertilization and inoculation on *G. max* nodule biomass: root biomass (panel A), nodule biomass (panel B), and root biomass (panel C). Soil nitrogen fertilization is represented on the x-axis, while inoculation treatment is represented by colored boxplots. Yellow shaded boxplots indicate individuals that were not inoculated with *B. japonicum*, while red shaded boxplots indicate individuals that were inoculated with *B. japonicum*. Boxes are the upper (75% percentile) and lower (25% percentile) quartile range. The whiskers are the minimum and maximum value, calculated as 1.5 times the upper and lower quartile value. Colored dots are individual data points, jittered for visibility. The lettering above each box indicates the results from post-hoc Tukey's tests with different lettering indicating statistically different groups (Tukey: $p < 0.05$).

Discussion

Here, we quantified the interactive effect of soil nitrogen fertilization and inoculation with symbiotic nitrogen-fixing bacteria on *G. max* structural carbon costs to acquire nitrogen using a full-factorial greenhouse manipulation experiment. We found that inoculation reduced carbon costs to acquire nitrogen under the low soil nitrogen fertilization treatment; however, there was no effect of inoculation treatment on carbon costs to acquire nitrogen under the high soil nitrogen fertilization treatment. This pattern was observed despite no significant differences in belowground carbon allocation across the treatments. Instead, inoculated individuals grown under the low soil nitrogen fertilization treatment exhibited greater whole-plant nitrogen uptake than uninoculated individuals. These results suggest that symbioses with nitrogen-fixing bacteria exhibit reduced costs of nitrogen acquisition under low nitrogen availability by enhancing nitrogen uptake efficiency compared to individuals restricted to nitrogen acquisition through direct uptake pathways. That said, structural carbon costs to acquire nitrogen were the lowest under high soil nitrogen fertilization irrespective of inoculation treatment, a pattern also driven by enhanced plant nitrogen uptake coupled with no change in belowground carbon allocation. Overall, results indicate that increased nitrogen supply, either through symbiotic nitrogen under low soil nitrogen fertilization or direct uptake under high soil nitrogen fertilization, reduces costs of nitrogen acquisition by enhancing nitrogen uptake efficiency.

The impact of inoculation on plant carbon costs to acquire nitrogen depend on soil nitrogen availability

Our results provide direct evidence that, under low soil nitrogen availability, nitrogen uptake through symbioses with nitrogen-fixing bacteria reduces structural carbon costs to acquire nitrogen compared to nitrogen uptake through direct uptake pathways. This result corroborates results from past theory (Vitousek *et al.*, 2002), modeling exercises (Brzostek *et al.*, 2014), and cross-species experimental studies (Perkowski *et al.*, 2021). Here, we used individuals of the same species to confirm that symbioses with nitrogen-fixing bacteria are the primary drivers of this response. Despite a strong inoculation effect on carbon costs to acquire nitrogen under the low soil nitrogen fertilization treatment, there was no impact (positive or negative) of inoculation on carbon costs to acquire nitrogen at the high soil nitrogen fertilization treatment. Similar results were shown in a previous cross-species study that observed similar carbon costs to

acquire nitrogen under high fertilization between a nitrogen-fixing and non-fixing species and reduced carbon costs to acquire nitrogen in the nitrogen-fixing species under low soil nitrogen availability (Perkowski *et al.*, 2021). The differential role of symbiotic nitrogen fixation on carbon costs to acquire nitrogen under the two nitrogen fertilization treatments may help to explain the greater prevalence of plants capable of symbiotic nitrogen fixation where soil nitrogen availability is low (Monks *et al.*, 2012), as expected from theory (Vitousek and Field, 1999; Vitousek *et al.*, 2002; Menge *et al.*, 2008) and simulated in plant nitrogen uptake models (Brzostek *et al.*, 2014).

Our results indicate that symbiotic nitrogen fixation may provide a competitive advantage in nitrogen-poor soils by reducing plant carbon costs for acquiring nitrogen and enhancing nitrogen uptake efficiency relative to direct uptake pathways. However, the longer-term outcomes of this advantage are difficult to predict because nitrogen fixation brings in nitrogen to the ecosystem that may alleviate nitrogen limitation in non-fixing plant species. Additionally, long-term consequences of these dynamics are difficult to predict because nitrogen-fixing species may inhibit nitrogen fixation to minimize resource facilitation to neighboring non-fixing species (Nasto *et al.*, 2017; Taylor and Menge, 2021). Other bottom-up (e.g., soil resources) and top-down (e.g., herbivory) factors may also limit the competitive ability of species that associate with symbiotic nitrogen-fixing bacteria in terrestrial ecosystems (Eisele *et al.*, 1989; Ritchie *et al.*, 1998; Vitousek and Field, 1999; Rastetter *et al.*, 2001; Vitousek *et al.*, 2002, 2013). Longer term field and mesocosm experiments (e.g., Finzi and Rodgers, 2009; Taylor *et al.*, 2017; Lai *et al.*, 2018) coupled with targeted model experiments (e.g., Brzostek *et al.*, 2014; Allen *et al.*, 2020; Braghieri *et al.*, 2022) could help to clarify the role of these different drivers.

Soil nitrogen availability and inoculation modify whole-plant nitrogen, but not belowground structural carbon

Reduced carbon costs to acquire nitrogen with both increasing soil nitrogen fertilization and inoculation under low soil nitrogen were the result of increased plant nitrogen uptake. Belowground structural carbon allocation was not impacted by any of our treatments, suggesting that treatment effects on carbon costs to acquire nitrogen were driven by an increase in plant nitrogen uptake efficiency. The increase in nitrogen uptake in our study was predominantly used to support aboveground tissue, which demonstrated a strong increase under increasing soil

nitrogen fertilization and with inoculation when soil nitrogen was low. Specifically, increases in plant nitrogen uptake were associated with increased total leaf area, which likely increased total biomass due to greater surface area for light interception and whole-plant primary productivity. Theory suggests that increasing nitrogen availability (from soil or symbionts) should increase relative plant investment in aboveground tissues (Ågren and Franklin, 2003), as was observed here. Indeed, meta-analyses find consistent positive increases in aboveground biomass with increasing soil nitrogen availability but inconsistent impacts on belowground biomass (Li *et al.*, 2020).

Our findings provide an empirical benchmark for models that use carbon costs of nitrogen acquisition to simulate terrestrial carbon-nitrogen dynamics (e.g., Brzostek *et al.*, 2014; Shi *et al.*, 2016; Braghiere *et al.*, 2022). Integrating our results with findings presented in Perkowski *et al.* (2021), changes in cost of nitrogen acquisition due to increasing soil nitrogen availability or ability to associate with symbiotic nitrogen-fixing bacteria should be the result of stronger differences in plant nitrogen uptake than belowground carbon allocation. However, it must be noted that, in both studies, additional carbon costs that resulted from differences in root exudation, turnover, or respiration were not quantified. It is unclear whether these unaccounted allocation patterns are proportional to structural belowground carbon costs and future studies should be performed to validate this assumption.

Soil nitrogen fertilization does not significantly reduce plant investment in nitrogen fixing bacteria symbiosis

Inoculated plants exhibited similar levels of nodulation under both soil nitrogen fertilization treatments. This indicates that the level of nitrogen availability did not impact the strength of the symbiosis between *G. max* and *B. japonicum*. This result was counter to the expectation that increasing soil nitrogen availability would reduce plant reliance on nitrogen fixing symbionts (Vitousek *et al.*, 2002; Perkowski *et al.*, 2021). However, there was a negative, albeit nonsignificant, trend in the effect of increasing fertilization on plant investment toward symbiotic nitrogen fixation, where individuals grown under high soil nitrogen availability had mean root nodule biomass and root nodule biomass:root biomass values that were 46% and 40% less than individuals grown under low soil nitrogen availability. Regardless, null effects of soil nitrogen availability on plant investment toward symbiotic nitrogen fixation may imply stronger

bacterial control over the symbiosis than previously thought. If true, greater carbon costs for nitrogen acquisition may have been observed in inoculated plants grown under high soil nitrogen if increased amounts of unquantified plant carbon were allocated toward bacterial respiration. Carbon and nitrogen tracing experiments would be useful for examining this hypothesis.

Study limitations

This study has a few limitations that deserve recognition and limit the generality of our observed responses. First, effects of soil nitrogen fertilization on root nodulation may be nonlinear, and a two-level fertilization experiment is not equipped to address possible nonlinearities that might explain the interaction between soil nitrogen fertilization and root nodulation. Future work should consider conducting similar experiments using a larger number of nitrogen fertilization treatments than presented here. Additionally, this study used a single plant species and an inoculant comprising a single bacterial species. While this allowed us to isolate mechanisms that drove *G. max* responses to nitrogen fertilization and inoculation independent of phylogeny or genetic diversity, a key factor that limited inferences in Perkowski *et al.* (2021), future work should consider conducting similar experiments using a larger number of leguminous species, as well as multi-species mixes of different *Rhizobium* or other *Actinobacteria* species. Doing so would better allow us to generalize patterns observed here and would more accurately replicate soil microbial communities that are observed in nature.

Conclusions

Here, we used a single-pair symbiosis to quantify the impact of symbiotic nitrogen fixation on structural carbon costs to acquire nitrogen under varying soil nitrogen environments. We find that symbiotic nitrogen fixing bacteria reduced structural carbon costs to acquire nitrogen under the low soil nitrogen fertilization treatment, but no effect of inoculation on these costs under the high soil nitrogen fertilization treatment. Carbon cost to acquire nitrogen differences between treatment combinations were entirely due to changes in plant nitrogen uptake rather than belowground structural carbon investments, suggesting that symbiotic nitrogen fixation allowed plants to maximize nitrogen uptake efficiency under low soil nitrogen environments. Treatments that increased plant nitrogen uptake corresponded with enhanced total leaf area and total biomass, suggesting that additional plant nitrogen acquired was being allocated to aboveground

biomass. These results indicate that symbiotic nitrogen fixation may provide a competitive advantage to plants growing in nitrogen-poor soils by enhancing nitrogen uptake efficiency. These findings can be used to help improve simulations of carbon-nitrogen economics in terrestrial biosphere models.

Supplementary data

Table S1 Summary table containing volumes of compounds used to create modified Hoagland's solutions for each soil nitrogen fertilization treatment.

Table S2 Analysis of variance results exploring effect of nitrogen fertilization, inoculation with *B. japonicum*, and interactions between soil nitrogen fertilization and inoculation status on whole plant biomass: pot volume

Table S3 Marginal mean, degrees of freedom, and 95% confidence intervals of whole plant biomass: pot volume values across nitrogen fertilization and inoculation treatment combinations

Figure S1 Effects of soil nitrogen fertilization and inoculation status on whole plant biomass: pot volume

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