**Symbiotic nitrogen fixation reduces belowground biomass carbon costs of nitrogen acquisition under low, but not high, nitrogen availability**

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

**Abstract**

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

**Keywords**

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

**Introduction**

Terrestrial ecosystems are regulated, in part, by interactions between carbon and nitrogen cycles (Hungate *et al.* 2003; LeBauer and Treseder 2008; Wieder *et al.* 2015). One key process linking these cycles is plant nitrogen acquisition, which involves the allocation of photosynthetically derived carbon belowground in exchange for nitrogen. Plants must allocate carbon belowground to acquire nitrogen, which implies that there are inherent carbon costs to the plant for acquiring nitrogen (Chapin *et al.* 1987a). Plants can acquire nitrogen through several strategies, including direct uptake from the soil (Barber 1962; Fisher *et al.* 2010) or by forming symbiotic associations with soil microbial communities such as nitrogen-fixing bacteria (Vance and Heichel 1991; Vitousek *et al.* 2002; Udvardi and Poole 2013). The carbon costs associated with acquiring nitrogen vary depending on the acquisition strategy and are influenced by abiotic factors that influence the supply of and demand for soil resources (Brzostek *et al.* 2014; Terrer *et al.* 2018; Taylor and Menge 2018; Friel and Friesen 2019; Allen *et al.* 2020; Perkowski *et al.* 2021; Lu *et al.* 2022). Variations in the cost to acquire nitrogen across biotic and abiotic thresholds may help explain the prevalence of different nitrogen acquisition strategies in different environments. However, these costs have not been quantified outside of a few studies (Terrer *et al.* 2018; Perkowski *et al.* 2021; Lu *et al.* 2022) even though they are included in nitrogen uptake models (Fisher *et al.* 2010; Brzostek *et al.* 2014; Allen *et al.* 2020) used in terrestrial biosphere models (Shi *et al.* 2016; Lawrence *et al.* 2019; Braghiere *et al.* 2022).

Carbon costs to acquire nitrogen vary in species with different nitrogen acquisition strategies. For instance, plants that acquire nitrogen through direct uptake pathways may have reduced carbon costs to acquire nitrogen compared to plants that form symbiotic relationships with soil microbes. This is because plants that rely on direct uptake only need to allocate carbon belowground to develop and maintain root systems, and do not need to allocate additional carbon belowground to maintain and exchange resources with microbial symbionts. However, the nitrogen acquired from a given belowground carbon investment may be greater than direct uptake 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). Plants from the *Fabaceae* family form a specialized symbiotic relationship with nitrogen-fixing bacteria, where nitrogen-fixing bacteria housed in root nodules are supplied with photosynthate for growth and metabolism in exchange for nitrogen fixed from the atmosphere. Thus, individuals who acquire nitrogen through symbiotic nitrogen fixation may exhibit reduced carbon costs to acquire nitrogen compared to alternative pathways that rely on soil-derived nitrogen, as nitrogen fixation allows plants to tap into a less finite pool of nitrogen and maximize nitrogen uptake per unit belowground carbon allocated belowground.

Abiotic factors, such as atmospheric CO2, light availability, and soil nutrient availability, also influence the carbon cost to acquire nitrogen (Brzostek *et al.* 2014; Terrer *et al.* 2018; Taylor and Menge 2018, 2021; Friel and Friesen 2019; Allen *et al.* 2020; Perkowski *et al.* 2021; Lu *et al.* 2022). Previous work suggests that increasing soil nitrogen availability tends to increase plant nitrogen uptake and decrease belowground carbon allocation, leading to a decrease in the carbon cost to acquire nitrogen (Perkowski *et al.* 2021; Lu *et al.* 2022). This belowground carbon allocation response to increasing nitrogen availability may be due to reduced soil resource mining (by roots or symbionts) needed to satisfy plant nitrogen demand under greater nitrogen availability. However, the magnitude of these responses may vary across nutrient acquisition strategies. For example, plants that form associations with symbiotic nitrogen-fixing bacteria often exhibit reduced physiological and growth responses to changes in nitrogen availability despite reduced investment toward nitrogen fixation with increasing nitrogen availability (Gutschick 1981; Taylor and Menge 2018; Friel and Friesen 2019; McCulloch and Porder 2021; Menge *et al.* 2023; Schmidt *et al.* 2023). While previous work notes that plants can still acquire nitrogen through symbiotic nitrogen fixation under high soil nitrogen availability (Menge *et al.* 2023), resource optimization theory suggests that reduced sensitivity of plant nitrogen uptake to changes in nitrogen availability in nitrogen-fixing plants may stem from preferential investment toward the acquisition strategy that confers the lowest carbon cost and greatest nitrogen gain (Bloom *et al.* 1985; Rastetter *et al.* 2001). If true, similar costs to acquire nitrogen in nitrogen-fixing species may be achieved across nitrogen availability gradients due to shifts away from nitrogen acquisition through nitrogen fixation to direct uptake as costs to acquire nitrogen through direct uptake decrease (Fisher *et al.* 2010; Brzostek *et al.* 2014; Perkowski *et al.* 2021).

To understand how nitrogen fixation and soil nitrogen fertilization interact to influence belowground biomass carbon costs to acquire nitrogen, *Glycine max* L. (Merr.) seedlings were grown under two soil nitrogen fertilization treatments and were either inoculated or not inoculated with symbiotic nitrogen-fixing bacteria in a full factorial greenhouse experiment. We used this experiment to test the following hypotheses:

1. Soil nitrogen fertilization will decrease belowground biomass carbon costs of nitrogen acquisition in uninoculated and inoculated individuals. This decrease 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 belowground biomass carbon costs to acquire nitrogen under low soil nitrogen availability. This is because belowground biomass carbon costs to acquire nitrogen through symbiotic nitrogen fixation will be less than the belowground biomass carbon cost to acquire nitrogen via direct uptake. However, inoculation will not affect belowground biomass 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 belowground biomass carbon costs to obtain nitrogen from direct uptake with increasing soil nitrogen fertilization that will increase relative plant investment toward nutrient uptake through direct uptake pathways.

**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). The experiment used *G. max* seedlings to compare observed responses from previous work that was not able to disentangle species-specific effects on belowground biomass carbon costs to acquire nitrogen from the explicit effects of nitrogen fixation (Perkowski *et al.* 2021). 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 levels were chosen based on previous work using a larger number of fertilization treatments (Perkowski *et al*., 2021). Nitrogen fertilization doses were received as topical agents to the soil surface and were modified to keep concentrations of other macronutrients and micronutrients equivalent across the two treatments (Table S1). Throughout the experiment, plants were routinely well-watered to minimize any chance of water stress. Greenhouse maximum daytime temperatures averaged 42.4±3.9°C (mean ± standard deviation) across blocks, while minimum nighttime temperature averaged 19.8±1.9°C across blocks. 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 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 and before the onset of reproduction. 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.

Belowground biomass carbon costs to acquire nitrogen were calculated as the ratio of total belowground biomass carbon to whole plant nitrogen biomass (g C g-1 N; Perkowski *et al*., 2021). Belowground biomass carbon (g C) was calculated as the sum of total root carbon biomass and total root nodule carbon biomass. Total root biomass carbon was calculated by multiplying root carbon content by total root biomass, while total root nodule biomass carbon 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 belowground biomass 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* belowground biomass carbon costs to acquire nitrogen, total leaf area, and total biomass and investment toward symbiotic nitrogen fixation. Any uninoculated individuals that formed nodules were removed prior to model fitting. 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 belowground biomass carbon costs to acquire nitrogen, belowground biomass carbon, whole-plant nitrogen biomass, total leaf area, total biomass, root nodule biomass: root biomass, root nodule biomass, and root biomass.

A second series of linear mixed-effects models were build to investigate the impacts of soil nitrogen fertilization on *G. max* investment toward symbiotic nitrogen fixation. These models included only inoculated individuals. Models included soil nitrogen fertilization as the lone categorical fixed effect with block number included as a random effect. Two models with this independent variable structure were constructed to quantify relationships between soil nitrogen fertilization and root nodule biomass and the ratio of root nodule biomass to 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 belowground biomass carbon costs to acquire nitrogen, belowground biomass carbon, 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 χ2 and determine the significance (α=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**

*Belowground biomass carbon costs to acquire nitrogen*

Negative effects of inoculation (*p*<0.001; Table 1) on belowground biomass carbon costs to acquire nitrogen were only apparent under low soil nitrogen fertilization (inoculation-by-nitrogen fertilization interaction: *p*<0.05; Table 1; Fig. 1A). Increasing soil nitrogen fertilization decreased belowground biomass carbon costs to acquire nitrogen (*p*<0.001; Table 1)*.*

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

Positive effects of inoculation on whole-plant nitrogen biomass (*p*<0.001; Table 1) were only apparent under low soil nitrogen fertilization (inoculation-by-nitrogen fertilization interaction: *p*<0.001; Fig. 1C). Increasing soil nitrogen fertilization increased whole-plant nitrogen biomass (*p*<0.001; Table 1).

**Table 1** Analysis of variance results exploring effects of soil nitrogen fertilization, inoculation with *B. japonicum*, and interactions between soil nitrogen fertilization and inoculation on belowground biomass carbon costs to acquire nitrogen, whole-plant growth, and investment toward symbiotic nitrogen fixation\*

|  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | | **Carbon cost to**  **acquire nitrogen** | | **Belowground**  **biomass carbon** | | **Whole-plant**  **nitrogen biomass** | | **Total**  **leaf area** | | **Whole plant**  **biomass** | |
|  | df | χ2 | *p* | χ2 | *p* | χ2 | *p* | χ2 | *p* | χ2 | *p* |
| N fertilization (N) | 1 | 17.101 | **<0.001** | 0.062 | 0.804 | 281.094 | **<0.001** | 200.584 | **<0.001** | 35.592 | **<0.001** |
| Inoculation (I) | 1 | 15.443 | **<0.001** | 4.318 | **0.038** | 17.991 | **<0.001** | 23.242 | **<0.001** | 0.695 | 0.404 |
| N\*I | 1 | 4.460 | **0.035** | 0.264 | 0.607 | 12.771 | **<0.001** | 16.783 | **<0.001** | 0.759 | 0.384 |
|  |  |  |  |  |  |  |  |  |  |  |  |
|  |  | **Nodule biomass:**  **root biomass** | | **Nodule**  **biomass** | | **Root**  **biomass** | |  | |  | |
|  | df | χ2 | *p* | χ2 | *p* | χ2 | *p* |  |  |  |  |
| N fertilization (N) | 1 | 4.663 | **0.031** | 6.391 | **0.011** | 0.016 | 0.900 |  |  |  |  |
| Inoculation (I) | 1 | - | - | - | - | 3.884 | **0.049** |  |  |  |  |
| N\*I | 1 | - | - | - | *-* | 0.223 | 0.637 |  |  |  |  |

\*Significance determined using Type II Wald χ2 tests (α=0.05). *P*-values less than 0.05 are in bold and *P*-values between 0.05 and 0.1 are italicized. Models for nodule biomass:root biomass and root nodule biomass were fit using nitrogen fertilization as the lone fixed effect.

**Figure 1**

**A graph of different levels of fertilization

Description automatically generated**

**Figure 1** Effects of soil nitrogen fertilization and inoculation on *G. max* belowground biomass carbon costs to acquire nitrogen (panel A), belowground biomass carbon (panel B), and whole-plant nitrogen biomass (panel C). Soil nitrogen fertilization treatment is 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*

Positive effects of inoculation on total leaf area (*p*<0.001; Table 1) were only apparent under low soil nitrogen fertilization (inoculation-by-nitrogen fertilization interaction: *p*<0.001; Table 1; Fig. 2A). Increasing soil nitrogen fertilization 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 was not modified by inoculation (inoculation-by-nitrogen fertilization interaction: *p*>0.05; Table 1). Inoculation had no effect on total biomass (*p*>0.05; Table 1; Fig. 2B).

**Figure 2**

**A diagram of different stages of fertilization

Description automatically generated**

**Figure 2** Effects of soil nitrogen fertilization and inoculation on *G. max* total leaf area (panel A) and total biomass (panel B). Soil nitrogen fertilization treatment is 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*

Increasing soil nitrogen fertilization decreased root nodule biomass: root biomass (*p*<0.05; Table 1; Fig 3A) through a reduction in root nodule biomass (*p*<0.05; Table 1; Fig. 3B) and no change in root biomass (*p*>0.05; Table 1; Fig. 3c). Inoculation decreased root biomass (*p*<0.05; Table 1; Fig. 3C), a pattern was not modified by soil nitrogen fertilization (inoculation-by-fertilization interaction: *p*>0.05; Table 1).

**Figure 3**

**A graph of different types of fertilization

Description automatically generated**

**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 treatment is 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 relationships between *G. max* belowground biomass carbon and whole-plant nitrogen biomass. Inoculation with symbiotic nitrogen-fixing bacteria increased whole-plant nitrogen biomass, but this pattern was only observed under low nitrogen fertilization and was not associated with a change in belowground biomass carbon. Positive effects of inoculation on whole-plant nitrogen biomass diminished with increasing nitrogen fertilization, as there was no effect of inoculation treatment on whole-plant nitrogen biomass under high nitrogen fertilization. These patterns indicate that, under low soil nitrogen fertilization, inoculation with symbiotic nitrogen-fixing bacteria increased plant nitrogen uptake and the magnitude of nitrogen acquired per unit carbon allocated belowground compared to their uninoculated counterparts, supporting our hypothesis. Positive effects of inoculation on plant nitrogen uptake diminished with increasing nitrogen fertilization, as plants invested less toward symbiotic nitrogen fixation and likely invested more strongly in direct uptake pathways as costs to acquire nitrogen between direct uptake and symbiotic nitrogen fixation became more similar. Regardless, increasing nitrogen fertilization increased whole-plant nitrogen biomass, again while maintaining the same belowground biomass carbon, which increased the magnitude of nitrogen acquired per unit carbon allocated belowground in plants grown under the high nitrogen fertilization treatment.

*The impact of inoculation on belowground biomass carbon costs to acquire nitrogen depend on soil nitrogen availability*

[stopped here 07/23] Our results provide direct evidence that, under low soil nitrogen availability, increased nitrogen uptake through symbioses with nitrogen-fixing bacteria reduces belowground biomass 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 the ability to form symbioses with nitrogen-fixing bacteria are the primary drivers of this response. Despite a strong inoculation effect on nitrogen uptake in the low soil nitrogen fertilization treatment, there was no impact (positive or negative) of inoculation on nitrogen uptake in the high soil nitrogen fertilization treatment, yielding similar carbon costs to acquire nitrogen between inoculation treatments. Similar results were shown in a previous cross-species study that observed similar belowground biomass carbon costs to acquire nitrogen under high nitrogen fertilization between a nitrogen-fixing and non-fixing species and reduced belowground biomass carbon costs to acquire nitrogen in the nitrogen-fixing species under low nitrogen fertilization (Perkowski *et al.* 2021). The differential role of symbiotic nitrogen fixation on belowground biomass 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 increasing plant nitrogen uptake 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; Braghiere 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 carbon allocation*

Plant nitrogen uptake increased with increasing soil nitrogen fertilization and inoculation under low soil nitrogen. Belowground carbon allocation was not impacted by any of our treatments. The increase in nitrogen uptake 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. Meta-analyses also 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 the belowground 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. Thus, models that omit variability in costs to acquire nitrogen are likely to bias estimates of plant carbon-nitrogen economics across environmental gradients. 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 belowground biomass carbon costs and future studies should be performed to validate this assumption.

*Soil nitrogen fertilization reduces plant investment toward symbiotic nitrogen fixation*

Plant investment toward symbiotic nitrogen fixation decreased with increasing nitrogen fertilization in inoculated plants. Root nodule biomass and the ratio of root nodule biomass to root biomass were each reduced in the high nitrogen fertilization treatment compared to the low nitrogen fertilization treatment. This result followed our expectations and previous results showing that plants decrease reliance on nitrogen-fixing symbionts as soil nitrogen availability increases (Vitousek *et al.* 2002; Perkowski *et al.* 2021), though recent work suggests that plants can still acquire nitrogen through symbiotic nitrogen fixation under high nitrogen availability (Menge *et al.* 2023).

*Study limitations*

This study has a few limitations that deserve recognition and limit the generality of the 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 *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. Finally, the belowground biomass carbon cost to acquire nitrogen metric used in this study does not account for changes in belowground carbon allocation due to root turnover, respiration, or root exudation. It is possible that nitrogen fertilization and inoculation with symbiotic nitrogen-fixing bacteria may modify metabolic pathways that alter carbon investment (e.g., bacterial respiration). Future studies should carefully assess whether these carbon pools should be measured as failure to measure these pools could risk underestimating the belowground biomass carbon cost of nitrogen acquisition.

*Conclusions*

Here, we used a single-pair symbiosis to quantify the impact of symbiotic nitrogen fixation on belowground biomass carbon and whole-plant nitrogen biomass under varying soil nitrogen environments. Regardless of nitrogen fertilization level, individuals that were inoculated with symbiotic nitrogen-fixing bacteria exhibited no change in belowground carbon allocation compared to their uninoculated counterparts. However, inoculated individuals increased plant nitrogen uptake under low nitrogen fertilization only, which increased the magnitude of nitrogen acquired from a given belowground carbon investment. There was no effect of in

similar belowground biomass carbon under the low

exhibited reduced belowground biomass carbon costs to acquire nitrogen under the low soil nitrogen fertilization treatment compared to uninoculated counterparts. In contrast, there was no effect of inoculation treatment on belowground biomass carbon costs of nitrogen acquisition under the high soil nitrogen fertilization treatment. Belowground biomass carbon cost to acquire nitrogen differences between treatment combinations were entirely due to changes in plant nitrogen uptake rather than belowground carbon allocation. 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 support aboveground growth. These results indicate that symbiotic nitrogen fixation may provide a competitive advantage to plants growing in nitrogen-poor soils, though these advantages diminish with increasing nitrogen availability as investment in nitrogen uptake through direct uptake pathways increase. 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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