**Negative effects of allelopathic plant invasion intensify as the growth season progresses**

Evan A. Perkowski1,\*, K. Carroll1, Jessie Mutz2, Snehanjana Chatterjee1, Xianyu Yang3, Lalasia Bialic-Murphy2,3, Stephanie N. Kivlin2, Susan Kalisz2,Nicholas G. Smith1

1Department of Biological Sciences, Texas Tech University, Lubbock, TX, USA

2Department of Ecology and Evolutionary Biology, University of Tennessee-Knoxville, Knoxville, TN, USA

3Institute of Integrative Biology, ETH Zürich, Zürich, Switzerland

**\***Correspondence to:

2901 Main St.

Lubbock TX 79409

[evan.a.perkowski@ttu.edu](mailto:evan.a.perkowski@ttu.edu)

**ORCIDs**

Evan A. Perkowski (0000-0002-9523-8892)

K. Carroll (0000-0002-5362-607X)

Jessie Mutz (0000-0003-3956-7760)

Snehanjana Chatterjee (0009-0004-1867-2996)

Xianyu Yang (0000-0002-7796-986X)

Lalasia Bialic-Murphy (0000-0001-6046-8316)

Stephanie N. Kivlin (0000-0003-2442-7773)

Nicholas G. Smith (0000-0001-7048-4387)

**Summary**

* Many invasive plants produce allelopathic compounds that disrupt plant-fungal symbioses in native species, with cascading effects on nutrient and water provisioning to support photosynthesis. Yet, the temporal dynamics of plant photosynthetic responses to allelopathic invaders remain poorly understood.
* We assessed the temporal dynamics of native plant responses to allelopathic invasion by collecting gas exchange measurements from two understory native species (*Trillium* spp. and *Maianthemum racemosum*) at two points during the growing season reflecting an open (early in the growing season) and closed (later in the growing season) tree canopy. Measurements were collected in plots where *Alliaria petiolata*, an allelopathic invader that disrupts AM fungal communities, was hand-weeded or left at ambient levels.
* Both native species exhibited significantly reduced net photosynthesis rates under ambient *A. petiolata* levels compared to the weeded treatment. Although the mechanisms driving this response were species-specific, negative effects of *A. petiolata* in both species were strongest later in the growing season.
* Late-season photosynthetic responses to *A. petiolata* coincided with a reduction in soil nutrient availability and moisture, suggesting that amplified late-season responses to the allelopathic invader may be associated with increased reliance on disrupted AM fungal communities for soil nutrients and water.

**Keywords**

*Alliaria petiolata*, AM fungi, photosynthesis, plant invasion, stomatal conductance, *V*cmax, *J*max

**Introduction**

Invasive plants often express unique traits that increase their likelihood of establishment in novel ecosystems. Allelopathy, defined as a secondary compound produced by a plant that negatively impacts neighboring plant species and/or soil microbial communities (Inderjit *et al.*, 2011), has emerged as a mechanism to explain the success of some invasive plant species (Callaway & Ridenour, 2004; Callaway *et al.*, 2008). Allelopathy negatively affects native plant performance and soil microbial community composition (Hale *et al.*, 2011, 2016; Hale & Kalisz, 2012; Brouwer *et al.*, 2015; Bialic-Murphy *et al.*, 2020, 2021; Qu *et al.*, 2021; Roche *et al.*, 2021; Zhang *et al.*, 2021) and is estimated to occur in approximately 52% of invasive plant species (Kalisz *et al.*, 2021). Despite the prevalence of allelopathy among invasive species, our understanding of the temporal effects of allelopathic plant invasion on the physiology of coexisting native plants remains limited. This knowledge gap hinders our understanding of how the disruptive impacts of allelopathic invasion on soil microbial communities scale to influence plant community dynamics.

Photosynthesis links ecosystem carbon, nutrient, and water cycles in terrestrial ecosystems (Hungate *et al.*, 2003). Through photosynthesis, plants convert carbon dioxide into simple sugars using enzymes such as Ribulose-1,5-bisphosphate carboxylase/oxygenase (Rubisco) that require large amounts of nutrients and energy to build and maintain (Evans & Seemann, 1989; Evans & Clarke, 2019). Aboveground conditions such as light availability, atmospheric CO2 concentration, vapor pressure deficit, and temperature regulate photosynthetic enzyme kinetics and substrate availability, rendering these factors key determinants of plant demand to acquire and allocate nutrients toward the construction and maintenance of photosynthetic enzymes and demand to maintain transpiration streams needed to support photosynthesis (Bernacchi *et al.*, 2001; Dong *et al.*, 2017, 2020, 2022; Smith *et al.*, 2019; Paillassa *et al.*, 2020; Westerband *et al.*, 2023). Whether plants can satisfy this demand in a given environment depends on nutrient and water availability, and the uptake and allocation of these resources to photosynthetic tissues. For example, increased light availability often increases the demand for soil nutrients and water to enhance photosynthetic capacity and stomatal conductance to optimize light use (Walters, 2005; Smith *et al.*, 2019). In resource-rich environments, plants can meet this increased demand by increasing nutrient and water uptake and allocating these resources to photosynthetic processes. However, plants cannot increase nutrient and water uptake to a similar extent in resource-limited environments, as resource availability is insufficient to acquire and satisfy the demand for photosynthetic enzymes. This scenario could cause individuals growing in resource-limited environments to display reduced physiological responses to increased light availability compared to individuals growing in resource-rich environments (Waring *et al.*, 2023) and could increase plant reliance on symbioses with soil microbial communities (e.g., mycorrhizal fungi) for soil resources (Treseder, 2004; van Diepen *et al.*, 2007).

Allelopathic compounds with antimicrobial properties can inhibit the growth and reproduction of soil microbial communities, such as mycorrhizal fungi, which are essential for providing nutrients and water to their host plants (Hale & Kalisz, 2012). Arbuscular mycorrhizal (AM) fungi form obligate symbioses with plants, exchanging mineral nutrients and water for photosynthate (Smith & Read, 2008). Antimicrobial compounds produced by allelopathic invaders can disrupt these symbioses by inhibiting AM fungal spore germination, fungal root colonization, and arbuscule formation, which can decrease AM fungal biomass, alter AM fungal species richness, and modify AM fungal community composition (Burke, 2008; Callaway *et al.*, 2008; Burke *et al.*, 2011; Cantor *et al.*, 2011; Anthony *et al.*, 2019; Bialic-Murphy *et al.*, 2021). These disruptions can lead to decreased nutrient and water uptake in plants that rely on AM fungi, even when allelopathic invaders do not directly modify soil nutrient or water availability (Bialic-Murphy *et al.*, 2021). This is because disruptions in AM fungal community function may increase the plant carbon cost for acquiring nutrients and water, causing plants to receive less resources provisioned by AM fungal partners for a given belowground carbon investment (Kummel & Salant, 2006; Hale *et al.*, 2016). This pattern may scale to alter resource allocation to photosynthetic enzymes, as emerging evidence suggests that increased costs of nutrient acquisition are associated with reduced nutrient allocation to photosynthetic enzymes (Perkowski *et al.*, 2021; Waring *et al.*, 2023). Thus, allelopathy-driven disruptions in AM fungal communities could cause native plants to be unable to satisfy the demand to build and maintain photosynthetic enzymes and/or maintain optimal stomatal conductance, which may explain why native species exhibit reduced net photosynthesis rates in response to allelopathic plant invasions (Hale *et al.*, 2011, 2016).

*Alliaria petiolata* (M. Bieb) Cavara & Grande (Family: Brassicaceae) is a model species for investigating the impacts of allelopathic plant invasion. This biennial herb from Eurasia invades temperate forest understories in North America, releasing glucosinolates into soil environments through root exudation and leaf litter (Rodgers *et al.*, 2008). Glucosinolates produced by *A. petiolata* hydrolyze into antimicrobial compounds such as allyl isothiocyanate, which inhibit AM spore germination, spore viability, root colonization, and arbuscule formation (Callaway *et al.*, 2008; Cantor *et al.*, 2011; Anthony *et al.*, 2019). Previous work has linked *A. petiolata* invasion with decreased AM fungal biomass, increased AM species richness, and altered fungal community composition (Burke, 2008; Burke *et al.*, 2011; Cantor *et al.*, 2011; Bialic-Murphy *et al.*, 2021). Disrupted AM fungal communities due to *A. petiolata* invasion have also been associated with negative impacts on native plant nutrient and water economics, population dynamics, and community composition (Hale *et al.*, 2016; Bialic-Murphy *et al.*, 2020, 2021; Roche *et al.*, 2021, 2023), with stronger negative impacts in native species that associate with AM fungi compared to those that do not (Callaway *et al.*, 2008; Roche *et al.*, 2021, 2023). These patterns occur despite evidence that *A. petiolata* invasions do not affect soil nutrient or water availability, suggesting that the breakdown of the AM fungal mutualism is the mechanism that drives native plant community responses to *A. petiolata* invasion (Bialic-Murphy *et al.*, 2021)

Previous work also indicates that *A. petiolata* reduces the net photosynthesis rates of coexisting native species (Hale *et al.*, 2011, 2016; Brouwer *et al.*, 2015). However, the mechanisms that regulate these responses are not fully understood. Photosynthetic responses to *A. petiolata* invasion could be driven by changes in photosynthetic capacity, indicating nutrient limitation, or by changes in stomatal conductance, indicating water limitation. Understanding whether changes in photosynthetic capacity or stomatal conductance drive native plant photosynthetic responses to *A. petiolata* invasion would provide valuable insight into the mechanism underlying these responses. Quantifying these process rates would also help understand whether photosynthetic responses to *A. petiolata* invasion are linked to AM fungal mutualism disruption. Furthermore, existing field research has primarily quantified photosynthetic responses to *A. petiolata* invasion at a single time point in the growth season, providing limited insight into the impacts of allelopathic plant invasion across the growth season as understory light availability and soil resource availability decrease. Studies that investigate the mechanisms that explain the photosynthetic responses to allelopathic invaders at different time points in the growing season would be valuable for assessing how leaf-level physiological responses to allelopathic plant invasion compare to its finer-scale impacts on AM fungal community composition and broader-scale effects on native plant productivity and survivorship.

Here, we assessed the temporal dynamics that drive the effects of allelopathic invasion on leaf-level photosynthetic processes of two coexisting native plant species. To do this, we collected gas exchange measurements from two understory native species growing in a long-term *A. petiolata* field manipulation experiment. Gas exchange measurements were collected at two time points that reflected an open (early in the growing season) and a closed (later in the growing season) tree canopy. At each measurement timepoint, we quantified net photosynthesis and stomatal conductance rates, stomatal limitation of net photosynthesis, apparent photosynthetic capacity, and relative chlorophyll content in plots where *A. petiolata* was either left at natural densities or manually removed. We used this experiment and sampling approach to test the following hypotheses:

1. Both native species will experience a reduction in net photosynthesis in the A. petiolata-ambient treatment compared to the A. petiolata-weeded treatment. These patterns will be associated with reduced apparent photosynthetic capacity, relative chlorophyll content, and stomatal conductance in A. petiolata-ambient plots.
2. The negative effects of *A. petiolata* treatment on leaf photosynthetic traits will vary based on the measurement time point.
   1. The negative effects of *A. petiolata* treatment on leaf photosynthetic traits will be strongest early in the growth season when soil resource demand is highest. Disrupted AM fungal symbioses will create resource stress, making it more difficult for AM-associating plants to acquire nutrients and water needed to satisfy leaf demand to build and maintain photosynthetic enzymes and maintain transpiration streams.
   2. Alternatively, the negative effects of *A. petiolata* treatment on photosynthetic traits will become more pronounced as the growth season progresses. This response may be driven by increased reliance on AM fungal partners for soil nutrients and water as resources deplete. However, declining light availability with canopy closure should decrease plant demand for soil resources, which may counterbalance any increase in reliance on AM fungal partners under reduced nutrient availability.

**Materials and Methods**

*Study site and experimental design*

This study was conducted at Trillium Trail Nature Reserve in Fox Chapel, PA (40.520 °N, -79.901 °W). The mean annual precipitation of the study area was 1006 mm yr-1 and the mean annual temperature was 11°C (2006-2020 U.S. Climate Normals; Palecki et al., 2021). Wire fences (2.5 m tall) were set up in 2002 at five 14 x 14 m experimental plots to exclude deer and other macroherbivores while allowing free movement of small mammals and birds. *Alliaria petiolata* was manually weeded at the beginning of each growth season from one half of each experimental plot since 2006, with *A. petiolata* remaining at natural densities in the other half of each plot. Manual weeding has been an effective strategy for *A. petiolata* removal (Roche *et al.*, 2021). This long-term split-plot experiment is located on 25-75% grade slopes. Soils were classified as Gilpin-Upshur-Atkins soils with dominant shale, sandstone, and red clay shale bedrock components. *Alliaria petiolata* treatments were set up parallel to the slope to prevent allelochemical leaching into the weeded side of the plot. Previous work conducted in this experiment has shown that A. petiolata-ambient plots exhibit decreased AM fungal biomass, decreased AM root colonization rates, and increased AM fungal richness compared to A. petiolata-weeded plots (Burke, 2008; Burke *et al.*, 2011; Cantor *et al.*, 2011), which has altered the AM fungal community composition between treatments (Bialic-Murphy *et al.*, 2021)

*Gas exchange measurements and calculations*

Gas exchange measurements were collected between April and June 2023 from fully expanded leaves of two perennial understory native species: *Trillium* spp. (*Trillium* *grandiflorum* (Michx.) Salisb and *Trillium erectum* L.) and *Maianthemum racemosum* L. Link. We use *Trillium* spp. to refer to *T. grandiflorum* and *T. erectum*, as these species are difficult to distinguish if they are not reproductive. *Trillium* spp. and *M. racemosum* are each understory perennial herbs with widespread distributions in temperate forests of North America (USDA NRCS, 2022), form rhizomes, and associate with AM fungi (Brundrett & Kendrick, 1987, 1990; Burke, 2008). Previous work indicates that the timing of aboveground phenology differs between the two species: *Trillium* spp. typically emerge in late April and senesce in July, while *M. racemosum* typically emerge in early May and senesce as late as November (Heberling *et al.*, 2019)

Gas exchange data were collected in three of the five experimental plots during two measurement periods: once early in the growth season when the tree canopy was open and tree canopy leaf out was occurring (April 19 through April 21 for *Trillium* spp. and May 5 through May 6 for *M. racemosum*) and once later in the growth season when the tree canopy was fully closed (June 12 through June 15 for both species). The first measurement period was conducted at different time points for *Trillium* spp. and *M. racemosum* because of differences in the timing of full leaf expansion between species (Heberling *et al.*, 2019).

Net photosynthesis (*A*net; μmol m-2 s-1), stomatal conductance (*g*sw; mol m-2 s-1), and intercellular CO2 (*C*i; μmol mol-1) concentrations were measured across a range of atmospheric CO2 concentrations (i.e., an *A*net/*C*i curve) using the Dynamic Assimilation™ Technique (Saathoff & Welles, 2021). This technique allows for high-throughput *A*net/*C*i curves that correspond well with traditional steady-state methods in herbaceous species (Tejera-Nieves *et al.*, 2024). We generated all *A*net/*C*i curves along a reference CO2 ramp down from 420 µmol mol-1 CO2 to 20 µmol mol-1 CO2, followed by a ramp up from 420 µmol mol-1 CO2 to 1620 µmol mol-1 CO2 after a 90-second wait period at 420 µmol mol-1 CO2. The ramp rate for each curve was set to 200 μmol mol-1 min-1, logging every five seconds, which generated 96 data points per response curve. All *A*net/*C*i curves were initiated after *A*net and *g*sw stabilized in a LI-6800 cuvette set to a 500 mol s-1 flow rate, 10000 rpm mixing fan speed, 1.5 kPa vapor pressure deficit, 25°C leaf temperature, 2000 μmol m-2 s-1 incoming light radiation, and initial reference CO2 set to 420 µmol mol-1. We extracted snapshot *A*net and *g*sw measurements using the initial measurement of each *A*net/*C*i curve at 420 µmol mol-1 CO2.

*A/Ci curve fitting and parameter estimation*

We fit *A*net/*C*i curves using the ‘fitaci’ function in the ‘plantecophys’ R package (Duursma, 2015). This function estimates the maximum rate of Rubisco carboxylation (*V*cmax; µmol m-2 s-1) and maximum rate of electron transport for RuBP regeneration (*J*max; µmol m-2 s-1) using the Farquhar et al. (1980) biochemical model of C3 photosynthesis. Triose phosphate utilization (TPU) limitation was included as an additional rate-limiting step in all curve fits and the temperature standardization default in the function was turned off. Dark respiration was estimated in each curve fit as a fixed proportion of *V*cmax. Michaelis-Menten coefficients for Rubisco affinity to CO2 (*K*c; μmol mol-1) and O2 (*K*o; mmol mol-1), and the CO2 compensation point *(Γ*\*; μmol mol-1) were calculated using leaf temperature and equations derived in Bernacchi et al. (2001):

(1)

(2)

(3)

In all three equations, *T*k is the mean leaf temperature (in Kelvin) during each *A*net/*C*i curve, and R is the universal gas constant (8.314 J mol-1 K-1). All curves were visually inspected for goodness-of-fit before extracting *V*cmax and *J*max estimates for hypothesis testing.

For all *A*net/*C*i curve fits, *V*cmax and *J*max were standardized to25°C (referenced as *V*cmax25 and *J*max25 from this point forward) using a modified Arrhenius equation. This temperature standardization removed the influence of enzyme kinetics on *V*cmax and *J*max, and, thus, reflected biochemical investment in the different underlying processes (Atkin & Tjoelker, 2003). Rate estimates were standardized to25°C using the formulation presented in Kattge and Knorr (2007):

(4)

where *k*25 represents the standardized *V*cmax or *J*max rate at 25°C, *k*obs represents the *V*cmax or *J*max estimate at the average leaf temperature measured inside the cuvette during the *A*net/*C*i curve. *H*a is the activation energy of *V*cmax (71,513 J mol-1; Kattge and Knorr, 2007) or *J*max (49,884 J mol-1; Kattge and Knorr, 2007). *H*d represents the deactivation energy of both *V*cmax and *J*max (200,000 J mol-1; Medlyn et al., 2002), and R represents the universal gas constant (8.314 J mol-1 K-1). *T*ref represents the standardized temperature of 298.15 K, and *T*obs represents the mean leaf temperature (K) during each *A*net/*C*i curve. ΔS is an entropy term (J mol-1°C-1) that Kattge and Knorr (2007) described as a linear relationship with acclimated growth temperature (*T*g, °C), where:

(5)

and:

(6)

We estimated *T*g as the mean temperature of the seven days leading up to each *A*net/*C*i curve, following that photosynthetic acclimation typically occurs along this timescale (e.g., as found in Smith and Dukes, 2018). Mean daily air temperature was estimated using data collected at a nearby weather station (station ID: USW000114762; coordinates: 40.35510° N, 79.92145° W) included in the Global Historical Climatology Network - Daily data product (Menne *et al.*, 2012). *V*cmax25 and *J*max25 estimates were used to calculate the ratio of *J*max25 to *V*cmax25 (*J*max25:*V*cmax25; unitless).

*Stomatal limitation*

The extent by which stomatal conductance limited net photosynthesis (unitless) was calculated following the approach described in Farquhar and Sharkey (1982), where:

(7)

where *A*net represents the measured net photosynthesis rate where atmospheric CO2 is 420 μmol mol-1. *A*mod represents the theoretical photosynthetic rate where *C*i = *C*a = 420 μmol mol-1 (that is, no stomatal resistance to gas exchange), calculated as:

(8)

where *V*cmax is the measured maximum rate of Rubisco carboxylation (i.e., not temperature-standardized to 25°C), *C*i,mod is the intercellular CO2 concentration where *C*i = *C*a, set to 420 μmol mol-1, *Γ*\* (μmol mol-1) is the CO2 compensation point in the absence of dark respiration, *K*m is the Michaelis-Menten coefficient for Rubisco-limited photosynthesis (μmol mol-1), and *R*d is the dark respiration rate, estimated as a fixed proportion of *V*cmax. *K*m was calculated as:

(9)

where *K*c and *K*o were calculated following Eqns. 1 and 2, respectively, while *O*i is the leaf intercellular O2 concentration, set to 210 μmol mol-1.

*Chlorophyll fluorescence measurements*

Relative chlorophyll content was measured after each *A*net/*C*i curve on the same leaf using a Soil Plant Analysis Development chlorophyll meter (SPAD, unitless) built into the MultispeQ V2.0 handheld device (PhotosynQ Inc., East Lansing, MI, USA).

*Soil characteristics*

To characterize plant-available nitrogen and phosphorus at the time of leaf gas exchange measurements, resin strips (Membranes International Inc., Ringwood, NJ, USA) were placed approximately 10 cm below the soil surface to quantify mobile ammonium (ppm), nitrate (ppm), and phosphate (ppm) concentrations in each plot. An initial batch of resin strips was incubated in the field between April 19 and June 1, 2023, followed by a second batch inserted in the same plot location between May 30 and June 29, 2023. A total of 36 strips, 12 for each nutrient, were placed in each plot to account for the high degree of spatial heterogeneity of soil nutrient availability in temperate forests (Akana *et al.*, 2023). Cation and anion concentrations were extracted from resin strips in 0.5 M potassium sulfate at a 1:5 dilution factor for ammonium, and nitrate, and 1M HCl for phosphate. Concentrations of each nutrient were determined through end products of standard colorimetric reactions (Weatherburn, 1967; Lajtha *et al.*, 1999; D’Angelo *et al.*, 2001; Doane & Horwáth, 2003). Soil inorganic nitrogen availability was estimated as the sum of the ammonium and nitrate concentrations. The soil inorganic nitrogen-to-phosphorus ratio was estimated as the ratio of soil inorganic nitrogen availability to soil phosphate availability.

Soil moisture data were collected using TOMST® TMS-4 data loggers (TOMST® s.r.o., Prague, Czech Republic). One data logger was placed in each *A. petiolata* treatment of each plot (i.e., 2 data loggers per plot) on April 26, 2023 and recorded soil moisture pulses every 15 minutes. Volumetric soil moisture content (%) was calculated using the calibration curves for a silt loam soil reported in Wild et al. (2019). We calculated the mean daily volumetric soil moisture content and used these values as the primary indicator of soil moisture throughout the measurement period.

*Data analysis*

We built a series of linear mixed-effects models to explore the effects of *A. petiolata* treatment and measurement period on soil nutrient availability. Each model included *A. petiolata* treatment (ambient, weeded) and measurement period (open, closed tree canopy) as fixed effects, with an additional interaction term between *A. petiolata* treatment and measurement period. Plot was included as a random intercept term. We constructed separate models with this independent variable structure for soil nitrate availability, soil ammonium availability, soil inorganic nitrogen (nitrate + ammonium) availability, soil phosphate availability, and the soil nitrogen-to-phosphorus ratio. The models for soil inorganic nitrogen availability and the soil nitrogen-to-phosphorus ratio were fitted using dependent variables that were natural-log transformed, while the model for soil ammonium availability was fitted after soil ammonium availability was square root-transformed to normalize model residuals (Shapiro-Wilk: *p*>0.05 in all cases).

Next, we built a linear mixed-effects model to explore the effect of *A. petiolata* treatment on volumetric soil moisture content across the measurement period. This model included *A. petiolata* treatment (ambient levels, weeded) and day of year (continuous) as fixed effects, with an added interaction term between *A. petiolata* treatment and day of year. Plot was included as a random intercept term.

Finally, we built a series of species-specific linear mixed-effects models to explore the effect of *A. petiolata* treatment and measurement period on leaf physiological traits of *Trillium* spp. and *M. racemosum*. Species were not concatenated into a single linear mixed-effect model for each trait because we did not seek to understand interspecies variability in measured traits. All models included *A. petiolata* treatment (ambient, weeded) and measurement period (open, closed tree canopy) as fixed effects, as well as an interaction term between *A. petiolata* treatment and measurement period. Plot was included as a random intercept term. We constructed separate models with this independent variable structure for each species for the following dependent variables: *A*net, *g*sw, stomatal limitation, *V*cmax25, *J*max25, *J*max25:*V*cmax25, and SPAD. Models for *A*net, *g*sw, *V*cmax25, and *J*max25 in *Trillium* spp. were fitted using dependent variables that were natural-log transformed to normalize model residuals, while models for stomatal limitation, *SPAD*, and *J*max25 in *M. racemosum* were fitted using dependent variables that were natural-log transformed to normalize model residuals (Shapiro-Wilk: *p*>0.05 in all cases).

Each model was fitted using the ‘lmer’ function in the ‘lme4’ R package (Bates *et al.*, 2015). Type II Wald’s χ2 and the significance (*α*=0.05) of each fixed effect coefficient was calculated using the ‘Anova’ function in the ‘car’ R package (Fox & Weisberg, 2019). We 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 & Roger, 1997). All analyses and plots were conducted in R version 4.1.0 (R Core Team, 2021). Data, analysis scripts, and plot scripts are available on Zenodo (DOI: [10.5281/13862911](https://doi.org/10.5281/zenodo.13862912)).

**Results**

*Soil characteristics*

Soil inorganic nitrogen availability was reduced by 75% (*p*<0.001, Table S1; Fig. 1a) and soil phosphate availability was reduced by 26% (*p*<0.001, Table S1; Fig. 1b) after tree canopy closure, leading to 63% decrease in the soil nitrogen-to-phosphorus ratio (*p*<0.001, Table S1; Fig. 1c). Soil nitrate availability decreased by 71% after the tree canopy closed (*p*<0.001, Table S1; Fig. S1), whereas soil ammonium availability did not change between measurement periods (*p*=0.255, Table S1; Fig. S1).

*Alliaria petiolata* treatment had no effect on soil inorganic nitrogen availability (*p*=0.371, Table S1; Fig. 1a), soil phosphate availability (*p*=0.108, Table S1; Fig. 1b), soil ammonium availability (*p*=0.370, Table S1; Fig. S1), or soil nitrate availability (*p*=0.106, Table S1; Fig. S1). However, the soil nitrogen-to-phosphorus ratio was 51% greater in the *A. petiolata*-ambient treatment compared to the *A. petiolata*-weeded treatment (*p*=0.038, Table S1; Fig. 1c) due to an insignificant 16% increase in soil inorganic nitrogen availability (*p*=0.370, Table S1) and insignificant 15% decrease in soil phosphate availability (*p*=0.106, Table S1; Fig. 1b) in the *A. petiolata*-ambient treatment compared to the *A. petiolata*-weeded treatment.

Soil moisture decreased as the growth season progressed (*p*<0.001; Table S2; Fig. 2) and was lower in the *A. petiolata*-ambient treatment than the *A. petiolata*-weeded treatment (*p*<0.001; Table S1).

**Figure 1**

**A chart of different types of soil

Description automatically generated**

**Figure 1** Effects of tree canopy and *A. petiolata* treatment on soil inorganic nitrogen availability (a), soil phosphate availability (b), and the soil nitrogen: phosphorus ratio (c). Tree canopy status is on the x-axis. Teal points and boxplots indicate measurements collected in plots where *A. petiolata* was weeded and gold points and boxplots indicate measurements collected in subplots where *A. petiolata* was present at ambient levels. Boxes represent the upper (75% percentile) and lower (25% percentile) quartiles, and whiskers represent 1.5 times the upper and lower quartile values. Lettering above each treatment group indicates statistically different groups where Tukey: *p*<0.05.

**Figure 2**

A graph showing the growth of a number of days

Description automatically generated with medium confidence

**Figure 2** Effects of *A. petiolata* treatment on mean daily volumetric soil moisture content across the 2023 growth season. Date is on the x-axis. Points reference daily volumetric soil water content averaged across the three plots used to collect gas exchange measurements. The teal points and trendline indicate measurements collected in plots where *A. petiolata* was weeded and gold points and trendline indicate measurements collected in plots where *A. petiolata* was present at ambient levels. Error ribbons represent the trendline standard error.

*Gas exchange*

For *Trillium* spp., net photosynthesis decreased by 64% after tree canopy closure (*p*<0.001, Table 1; Fig. 3a), a pattern that was associated with a 22% reduction in stomatal conductance (*p*<0.001, Table 1; Fig. 3c) and 55% reduction in stomatal limitation (*p*<0.001, Table 1; Fig. 3e) compared to measurements collected before tree canopy closure. Net photosynthesis rates were reduced in the *A. petiolata*-ambient treatment compared to the *A. petiolata*-weeded treatment (*p*=0.016, Table 1; Fig. 3a). However, this net photosynthesis response to *A. petiolata* treatment was only observed after tree canopy closure (*A. petiolata* treatment-by-canopy status interaction: *p*=0.028, Table 1; Fig. 3a). *Alliaria petiolata* treatment had no effect on stomatal conductance (*p*=0.701, Table 1; Fig. 3c) or stomatal limitation (*p*=0.481, Table 1; Fig. 3e).

For *M. racemosum*, net photosynthesis decreased by 59% after tree canopy closure (*p*<0.001, Table 1; Fig. 3b), a pattern that was associated with a 62% reduction in stomatal conductance (*p*<0.001, Table 1; Fig. 3d) and a 13% increase in stomatal limitation (*p*=0.004, Table 1; Fig. 3f) compared to measurements collected before tree canopy closure. Net photosynthesis decreased by 18% (*p*<0.001, Table 1) and stomatal conductance decreased by 27% (*p*<0.001, Table 1), while stomatal limitation increased by 28% (*p*<0.001, Table 1) in the *A. petiolata*-ambient treatment compared to the *A. petiolata*-weeded treatment. Net photosynthesis and stomatal conductance responses to *A. petiolata* treatment were observed regardless of measurement period (*A. petiolata* treatment-by-canopy status interaction: *p*>0.05 in both cases, Table 1), while stomatal limitation responses to *A. petiolata* treatment were only observed after tree canopy closure (*A. petiolata* treatment-by-canopy status interaction: *p*=0.024, Table 1; Fig. 3f).

*Relative chlorophyll content*

SPAD values were 26% greater in *Trillium* spp. (*p*<0.001, Table 1; Fig. S2) and 51% greater in *M. racemosum* (*p*<0.001, Table 1; Fig. S2) after tree canopy closure compared to before tree canopy closure. *A. petiolata* treatment had no effect on SPAD in either species (*p*>0.05 in both cases, Table 1).

**Table 1** Analysis of variance results for the effects of *A. petiolata* treatment and measurement period on leaf gas exchange\*

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  |  | ***A*net** | | ***g*sw** | | **Stomatal**  **limitation** | | ***SPAD*** | |
|  |  | *χ*2 | *p* | *χ*2 | *p* | *χ*2 | *p* | *χ*2 | *p* |
| ***Trillium* spp.** | |  |  |  |  |  |  |  |  |
|  | *A. petiolata* treatment (A) | 5.830 | **0.016** | 0.148 | 0.701 | 0.498 | 0.481 | 0.300 | 0.584 |
|  | Canopy status (C) | 1163.336 | **<0.001** | 23.864 | **<0.001** | 289.318 | **<0.001** | 73.833 | **<0.001** |
|  | A\*C | 4.833 | **0.028** | 0.622 | 0.430 | 0.132 | 0.717 | 0.496 | 0.481 |
| ***M. racemosum*** | |  |  |  |  |  |  |  |  |
|  | *A. petiolata* treatment (A) | 19.547 | **<0.001** | 20.507 | **<0.001** | 15.684 | **<0.001** | 1.792 | 0.181 |
|  | Canopy status (C) | 336.988 | **<0.001** | 157.676 | **<0.001** | 8.300 | **0.004** | 285.711 | **<0.001** |
|  | A\*C | 0.012 | 0.913 | 0.046 | 0.831 | 5.094 | **0.024** | 0.853 | 0.356 |

\*Significance determined using Type II Wald χ2 tests (α=0.05). *P*-values less than 0.05 are in bold. Key: *A*net = light-saturated net photosynthesis rate (μmol m-2 s-1), *g*sw = stomatal conductance (mol m-2 s-1), SPAD = relative chlorophyll content (unitless)

**Figure 3**

**A collage of graphs and charts

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**Figure 3** Effects of *A. petiolata* treatment and tree canopy status on net photosynthesis (*A*net, a-b), stomatal conductance (*g*sw, c-d), and stomatal limitation of net photosynthesis (e-f). The left column shows *Trillium* spp. responses, while the right column shows *M. racemosum* responses. Tree canopy status is on the x-axis. Teal points and boxplots indicate measurements collected in plots where *A. petiolata* was weeded and gold points and boxplots indicate measurements collected in plots where *A. petiolata* abundance was not manipulated. Boxes represent the upper (75% percentile) and lower (25% percentile) quartiles, and whiskers represent 1.5 times the upper and lower quartile values. Lettering above each treatment group indicates statistically different groups where Tukey: *p*<0.05.

*Photosynthetic capacity*

In *Trillium* spp., *V*cmax25 decreased by 76% (*p*<0.001, Table 2; Fig. 4a) and *J*max25 decreased by 75% (*p*<0.001, Table 2; Fig. 4c) following canopy closure. These patterns resulted in a 4% increase in *J*max25:*V*cmax25 after tree canopy closure compared to before tree canopy closure (*p*=0.007; Table 2; Fig. 4e). *Alliaria petiolata* treatment had no effect on *V*cmax25 (*p*=0.296; Table 2; Fig. 4a) or *J*max25:*V*cmax25 (*p*=0.386, Table 2; Fig. 4e). However, *J*max25 was reduced by 8% in the *A. petiolata*-ambient treatment compared to the *A. petiolata*-weeded treatment (*p*=0.045; Table 2; Fig. 4c), a pattern that was only observed after tree canopy closure (*A. petiolata* treatment-by-canopy status interaction: *p*=0.020; Table 2; Fig. 4c).

For *M. racemosum*, *V*cmax25 (*p*<0.001, Table 2; Fig. 4b) and *J*max25 (*p*<0.001, Table 2; Fig. 4d) each decreased by 57% after tree canopy closure compared to before tree canopy closure, while *J*max25:*V*cmax25 decreased by 5% (*p*=0.004, Table 2; Fig. 4f). The decrease in *J*max25:*V*cmax25 due to tree canopy closure was only observed in the *A. petiolata*-weeded treatment (*A. petiolata* treatment-by-canopy status interaction: *p*=0.073; Table 2; Fig. 4f). *Alliaria petiolata* treatment had no effect on *V*cmax25 (*p*=0.688, Table 2), *J*max25 (*p*=0.543, Table 2), or *J*max25:*V*cmax25 (*p*=0.113, Table 2).

**Table 2** Analysis of variance results for the effects of *A. petiolata* treatment and measurement period on apparent photosynthetic capacity\*

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
|  |  | ***V*cmax25** | | ***J*max25** | | ***J*max25:*V*cmax25** | |
|  |  | *χ*2 | *p* | *χ*2 | *p* | *χ*2 | *p* |
| ***Trillium* spp.** | |  |  |  |  |  |  |
|  | *A. petiolata* treatment (A) | 1.090 | 0.296 | 4.008 | **0.045** | 2.622 | 0.105 |
|  | Canopy status (C) | 1585.012 | **<0.001** | 2001.653 | **<0.001** | 7.314 | **0.007** |
|  | A\*C | 1.973 | 0.160 | 5.417 | **0.020** | 0.753 | 0.386 |
| ***M. racemosum*** | |  |  |  |  |  |  |
|  | *A. petiolata* treatment (A) | 0.162 | 0.688 | 0.370 | 0.543 | 2.510 | 0.113 |
|  | Canopy status (C) | 284.148 | **<0.001** | 391.314 | **<0.001** | 8.456 | **0.004** |
|  | A\*C | 0.219 | 0.640 | 0.045 | 0.832 | 3.221 | *0.073* |

\*Significance determined using Type II Wald χ2 tests (α=0.05). *P*-values less than 0.05 are in bold, while values where 0.05<*p*<0.1 are italicized. Key: *V*cmax25 = maximum rate of Rubisco carboxylation at 25°C (μmol m-2 s-1), *J*max25 = maximum rate of electron transport for RuBP regeneration at 25°C (μmol m-2 s-1), *J*max25:*V*cmax25 = ratio of *J*max25 to *V*cmax25 (unitless)

**Figure 4**

**A collage of graphs and charts

Description automatically generated**

**Figure 4** Effects of *A. petiolata* treatment and tree canopy status on the temperature-standardized maximum rate of Rubisco carboxylation (*V*cmax25; a-b), the temperature-standardized maximum rate of electron transport for RuBP regeneration (*J*max25; c-d), and the ratio *J*max25:*V*cmax25 (e-f). The left column shows *Trillium* spp. responses, while the right column shows *M. racemosum* responses. Tree canopy status is on the x-axis. Teal points and boxplots indicate measurements collected in subplots where *A. petiolata* was weeded, and gold points and boxplots indicate measurements collected in subplots where *A. petiolata* abundance was not manipulated. Boxes represent the upper (75% percentile) and lower (25% percentile) quartiles, and whiskers represent 1.5 times the upper and lower quartile values. Lettering above each treatment group indicates statistically different groups where Tukey: *p*<0.05.

**Discussion**

Both native species growing under ambient levels of *A. petiolata* exhibited significantly reduced net photosynthesis rates compared to those growing in the *A. petiolata*-weeded treatment, supporting our first hypothesis. For *Trillium* spp., the net photosynthesis response to the *A. petiolata* treatment was associated with a reduction in apparent photosynthetic capacity, but no change in stomatal conductance and stomatal limitation. Conversely, the net photosynthesis response in *M. racemosum* to *A. petiolata* treatment was associated with a reduction in stomatal conductance that increased stomatal limitation and no change in apparent photosynthetic capacity. Building on results reported in Bialic-Murphy *et al*. (2021), these observations suggest that *A. petiolata* invasion modifies net photosynthesis rates by altering nutrient uptake and allocation to photosynthetic enzymes in *Trillium* spp. and by altering water uptake and use for photosynthesis in *M. racemosum*.

While the mechanisms that drove photosynthetic responses to *A. petiolata* treatment were different between the two species, native plant responses to *A. petiolata* treatment were generally more pronounced after tree canopy closure for both species. This pattern negated our second hypothesis that the negative effects of allelopathic plant invasion would be greatest early in the season when understory demand for soil resources is greatest, although supported our alternative hypothesis that these effects would be strongest later in the growth season when soil resources were depleted. Indeed, stronger late-season photosynthetic responses to ambient levels of *A. petiolata* coincided with a reduction in soil nutrient availability and soil moisture as the growth season progressed, which may have increased reliance on AM fungal partners for soil resources. Disruptions in AM fungal mutualism function due to the allelopathic invader may have increased the cost of acquiring soil resources, potentially decreasing resource uptake and allocation to photosynthetic tissues. These patterns may have been exacerbated by the reduction in soil moisture in the *A. petiolata*-ambient treatment compared to the *A. petiolata*-weeded treatment, which may have further increased late-season reliance on disrupted AM fungal partners for soil resources in the *A. petiolata*-ambient treatment.

Overall, our results indicate that native plant responses to allelopathic plant invasion intensified as the growth season progressed, even though the mechanisms that drove individual species responses differed. These findings provide important insight into understanding plant responses to allelopathic plant invasion and highlight the need to understand these responses through time. Understanding the temporal impacts of plant invasions will improve our ability to predict the consequences of plant invasion on native plant community dynamics, providing an important link for understanding how the effects of plant invasion on belowground soil microbial communities scale to impact aboveground plant population demography and community function.

*Photosynthetic responses to A. petiolata presence are linked to altered nutrient and water economics*

Net photosynthesis rates were reduced in the *A. petiolata*-ambient treatment for both *Trillium* spp. and *M. racemosum*, but the mechanisms underlying these responses differed between species. *Trillium* spp. responses to *A. petiolata* treatment suggest that the allelopathic invader induced a form of nutrient limitation, modifying net photosynthesis by reducing apparent photosynthetic capacity through a shift in nutrient allocation to photosynthetic enzymes. The null effect of *A. petiolata* treatment on relative chlorophyll content and the temperature-standardized apparent maximum rate of Rubisco carboxylation (*V*cmax25) coupled with a reduction in the temperature-standardized apparent maximum rate of electron transport for RuBP regeneration (*J*max25) in the *A. petiolata*-ambient treatment implies that any reduction in nutrient provisioning toward photosynthetic enzymes may have been due to a reduction in the fraction of leaf nutrients allocated to bioenergetics (Niinemets & Tenhunen, 1997; Niinemets *et al.*, 1998; Waring *et al.*, 2023). Null effects of *A. petiolata* treatment on stomatal conductance and stomatal limitation indicate that *A. petiolata* invasions do not impact the water economics of *Trillium* spp., suggesting that the physiological responses to the allelopathic invader were driven entirely by shifts in nutrient economics.

In contrast, *M. racemosum* responses to *A. petiolata* treatment may have been due to increased water limitation, as reduced net photosynthesis rates in the *A. petiolata*-ambient treatment were driven by a reduction in stomatal conductance that increased late-season stomatal limitation. While these effects could have been due to direct phytotoxic effects of *A. petiolata* on *M. racemosum* through reductions in soil moisture, similar net photosynthesis and stomatal conductance patterns were observed in a controlled greenhouse experiment under well-watered conditions (Hale et al., 2016). These patterns corresponded with null effects of *A. petiolata* treatment on apparent photosynthetic capacity, supporting previous work suggesting that physiological responses of *M. racemosum* to *A. petiolata* invasion are associated with changes in water economics, not nutrient economics (Hale *et al.*, 2011, 2016).

The differences in the physiological responses of *Trillium* spp. and *M. racemosum* may be due in part to differences in leaf economic strategy. While *Trillium* spp. and *M. racemosum* share many functional and ecological traits, such as forming rhizomes, reproducing clonally, acquiring nutrients and water through direct uptake pathways or symbioses with AM fungi, and emerging at similar times (Brundrett & Kendrick, 1987, 1990; Heberling *et al.*, 2019), these two species differ in leaf lifespan, placing them at different positions along the leaf economics spectrum (Wright *et al.*, 2004; Reich, 2014). In *Trillium* spp., shorter leaf lifespans may require rapid nutrient and water uptake to allow for fast growth and reproduction, leading to high leaf nutrient demand to build and maintain photosynthetic enzymes. In contrast, longer leaf lifespans in *M. racemosum* may foster resource-conservative strategies that favor long-term investment in photosynthetic tissues with reduced leaf nutrient demand to build and maintain photosynthetic enzymes and greater water demands to support photosynthesis across a longer growing season. Indeed, *M. racemosum* had lower temperature-standardized maximum rates of Rubisco carboxylation than *Trillium* spp*.* on average (*V*cmax25 mean ± SD: 76.4 ± 40.9 μmol m-2 s-1 in *Trillium* spp. compared to 48.4 ± 19.6 μmol m-2 s-1 in *M. racemosum*), reflecting a more resource-conservative strategy.

The greater demand for photosynthetic enzyme production and maintenance in *Trillium* spp. may explain why its photosynthetic capacity was reduced in the *A. petiolata*-ambient treatment, especially if individuals relied more heavily on disrupted AM fungi for nutrient uptake. In other words, disrupted AM fungal communities due to *A. petiolata* presence may have made it more difficult for *Trillium* spp. individuals to satisfy demand to build and maintain photosynthetic enzymes, inducing nutrient stress and reducing net photosynthesis rates despite *A. petiolata* having no direct effect on soil nutrient availability. In contrast, resource conservative strategies for *M. racemosum* may have allowed individuals to satisfy nutrient demand to build and maintain photosynthetic enzymes irrespective of whether individuals were associated with disrupted AM fungal partners. However, longer leaf lifespans may have increased demand for maintaining transpiration streams needed to support net photosynthesis across the growing season. If true, reduced soil moisture across the growing season paired with reduced soil moisture in the *Alliaria*-ambient treatment may have caused individuals to no longer be able to satisfy demand for maintaining transpiration rates to needed to maintain net photosynthesis. Isotopic tracer studies paired with water manipulation experiments may be useful for confirming these conjectures and would allow us to better understand the carbon-for-resource exchange that regulates plant-AM symbioses.

*Photosynthetic responses to A. petiolata presence intensify as the growing season progresses*

We hypothesized that the effects of *A. petiolata* treatment on leaf-level photosynthesis would be more apparent early in the growing season when understory demand for maintaining photosynthetic enzymes and a desired transpiration stream is greatest (Heberling *et al.*, 2019). Contrary to this hypothesis, the effects of *A. petiolata* treatment were absent (for *Trillium* spp.) or relatively weak (for *M. racemosum*) before tree canopy closure. For *M. racemosum*, the early-season reduction in net photosynthesis and stomatal conductance was associated with lower soil moisture in the *A. petiolata*-ambient treatment compared to the *A. petiolata*-weeded treatment, which may have caused individuals to close stomata as a water-savings mechanism or alternatively rely on disrupted AM fungal partners for water.

Limited early-season photosynthetic responses to *A. petiolata* treatment may be attributed to resource optimization that caused individuals to favor investment toward direct uptake regardless of *A. petiolata* treatment. Resource optimization theory predicts that, given multiple potential acquisition strategies (e.g., direct uptake, mycorrhizal symbioses, etc.), plants should prioritize investment toward the resource uptake strategy that minimizes the cost and maximizes the uptake efficiency of acquiring soil resources (Bloom *et al.*, 1985; Rastetter *et al.*, 2001; Kummel & Salant, 2006). Thus, plants should invest more strongly in direct uptake pathways early in the growing season when soil resources are more abundant, as costs to acquire soil resources through direct uptake pathways are often reduced under high resource availability (Perkowski *et al.*, 2021, 2024; Lu *et al.*, 2022). Therefore, limited photosynthetic responses to *A. petiolata* treatment early in the growing season may have been due to investment toward direct uptake that allowed individuals to satisfy demand to build and maintain photosynthetic enzymes and maintain transpiration while minimizing any negative consequence of relying on AM fungal partners for resources.

Alternatively, we hypothesized that the effects of *A. petiolata* treatment on leaf-level photosynthesis would intensify as the growing season progressed. Our findings support this hypothesis, as both native species exhibited stronger reductions in net photosynthesis rates when individuals grew under ambient levels of *A. petiolata* after tree canopy closure than before tree canopy closure. This pattern was associated with decreased nitrogen availability, phosphorus availability, and soil moisture following tree canopy closure. Late-season photosynthetic responses were observed despite *A. petiolata* treatment having no direct effect on nitrogen or phosphorus availability, although soil moisture was reduced in the *A. petiolata*-ambient treatment compared to the *A. petiolata*-weeding treatment. These patterns suggest that late-season photosynthetic responses to *A. petiolata* treatment may have been due to increased reliance on disrupted AM fungal partners as the cost to acquire resources through direct uptake increased with reduced nutrient and water availability (Perkowski *et al.*, 2021, 2024). This may have been further exacerbated by stronger soil moisture reductions in the *A. petiolata*-ambient treatment. Future work involving isotopic tracers (e.g., Hodge & Fitter, 2010) or soil resource manipulation experiments that cross AM fungal community compositions (e.g., Gustafson & Casper, 2004) would be a useful next step for linking soil microbial community, soil resource availability, and photosynthetic responses to *A. petiolata* invasion.

Overall, these findings highlight the necessity of quantifying the temporal effects of plant invasion on coexisting native plant populations. Ecophysiological studies have traditionally focused on assessing the impacts of allelopathic invaders on the physiological processes of coexisting native species at single timepoints. While data from these studies are useful for understanding snapshot effects of plant invasion on native population physiology, they risk providing misleading results when using these responses to understand consequences of plant invasion on native population and community dynamics. This may be especially the case dynamic systems where tree canopies close and soil resource availability change. Experiments that assess the impacts of plant invasion across multiple timepoints, as shown here, provide important insight into understanding the temporal nuances that underpin the effects of plant invasion on native populations and provide important empirical data that will improve our ability to reliably predict the impacts of plant invasion on plant population and community dynamics. Furthermore, soil microbial and plant communities operate on largely different spatiotemporal scales, which poses a big challenge when scaling soil microbial dynamics up to plant community dynamics. Quantifying the temporal effects of plant invasion on coexisting native plant populations may allow us to better integrate and scale the effects of plant invasions on belowground soil microbial and plant community dynamics.

*Using leaf physiology to assess linkages between aboveground and belowground responses to allelopathic plant invasion*

Native species’ physiological responses to *A. petiolata* treatments have direct implications for understanding the integrated negative effects of *A. petiolata* invasion on the belowground soil microbial community and aboveground plant community form and function. *Alliaria petiolata* disrupts the belowground AM fungal community composition by reducing AM fungal biomass and root colonization rates while also increasing AM fungal richness (Burke, 2008; Burke *et al.*, 2011; Cantor *et al.*, 2011; Anthony *et al.*, 2019; Roche *et al.*, 2021; Bialic-Murphy *et al.*, 2021). This allelopathic invader also negatively affects the abundance and survivorship of AM native plants that coexist with *A. petiolata* in its non-native range (Callaway *et al.*, 2008; Bialic-Murphy *et al.*, 2020; Roche *et al.*, 2021, 2023). Our results indicate that photosynthetic responses to *A. petiolata* are directionally similar its impacts on AM fungal community and plant community dynamics, suggesting that the effects of *A. petiolata* invasion across these levels of organization may be inherently linked and scalable through its impacts on native plant physiology. In other words, disruptions in AM fungal community composition due to *A. petiolata* invasion modify nutrient and water provisioning and uptake in native plant species, which decreases net carbon assimilation and, over time, has negative consequences for plant community survivorship and fitness.

*Conclusions*

The *A. petiolata*-ambient treatment negatively affected leaf-level photosynthetic processes in two native AM fungal-associating understory perennial species. While these patterns were driven by species-specific mechanisms, the negative effects of *A. petiolata* presence were stronger in both species after the tree canopy closed and soil resource availability decreased. These patterns highlight the need to understand species-specific responses to allelopathic invasion and other anthropogenic stressors to native ecosystems, and to specifically consider the temporal scale by which these factors might modify native plant communities. Our results provide important insight into understanding the mechanisms that drive photosynthetic responses to allelopathic plant invasion and are a critical piece of empirical data needed to link the effects of allelopathic plant invasion on belowground soil microbial communities with its effects on plant population and community dynamics. Furthermore, these findings indicate that understanding the temporal effects of invasion on coexisting native species may be important for predicting the effects of invasion and other anthropogenic drivers of environmental change on population and community dynamics.

**Acknowledgements**

Seth Wyckoff, Marissa Huber, and Kate Loveday assisted with field measurements. SK and SNK was supported by NSF Award #2217353. EAP, KC, SC, and NGS were supported by NSF award #2217354. We thank the Borough of Fox Chapel for permission to conduct research in the Trillium Trail Nature Reserve and for assistance with plot maintenance.

**Competing interests**

The authors declare no competing interests.

**Author Contributions**

The sampling approach was the product of discussions between EAP, JM, LB-M, SNK, SK, and NGS. EAP conducted field work in collaboration with KC, JM, SC, and NGS. EAP conducted the analyses and wrote the first draft of the manuscript. Manuscript feedback was provided by all co-authors. The experiment has been maintained by SK since its inception. All authors support submission of this manuscript to *New Phytologist*.

**Data Availability**

All data, analysis scripts, and plot scripts are publicly available (DOI: [10.5281/13862911](https://doi.org/10.5281/zenodo.13862912)).

**References**

**Akana PR, Mifsud IEJ, Menge DNL**. **2023**. Soil nitrogen availability in a temperate forest exhibits large variability at sub-tree spatial scales. *Biogeochemistry* **164**: 537–553.

**Anthony MA, Stinson KA, Trautwig AN, Coates-Connor E, Frey SD**. **2019**. Fungal communities do not recover after removing invasive *Alliaria petiolata* (garlic mustard). *Biological Invasions* **21**: 3085–3099.

**Atkin OK, Tjoelker MG**. **2003**. Thermal acclimation and the dynamic response of plant respiration to temperature. *Trends in Plant Science* **8**: 343–351.

**Bernacchi CJ, Singsaas EL, Pimentel C, Portis AR, Long SP**. **2001**. Improved temperature response functions for models of Rubisco-limited photosynthesis. *Plant, Cell and Environment* **24**: 253–259.

**Bialic-Murphy L, Brouwer NL, Kalisz S**. **2020**. Direct effects of a non-native invader erode native plant fitness in the forest understory. *Journal of Ecology* **108**: 189–198.

**Bialic-Murphy L, Smith NG, Voothuluru P, McElderry RM, Roche MD, Cassidy ST, Kivlin SN, Kalisz S**. **2021**. Invasion‐induced root–fungal disruptions alter plant water and nitrogen economies (M Rejmanek, Ed.). *Ecology Letters* **24**: 1145–1156.

**Brouwer NL, Hale AN, Kalisz S**. **2015**. Mutualism-disrupting allelopathic invader drives carbon stress and vital rate decline in a forest perennial herb. *AoB PLANTS* **7**: 1–14.

**Brundrett MC, Kendrick B**. **1987**. The mycorrhizal status, root anatomy, and phenology of plants in a sugar maple forest. *Canadian Journal of Botany* **66**: 1153–1173.

**Brundrett MC, Kendrick B**. **1990**. The roots and mycorrhizas of herbaceous woodland plants: I. Quantitative aspects of morphology. *New Phytologist* **114**: 457–468.

**Burke DJ**. **2008**. Effects of *Alliaria petiolata* (garlic mustard; Brassicaceae) on mycorrhizal colonization and community structure in three herbaceous plants in a mixed deciduous forest. *American Journal of Botany* **95**: 1416–1425.

**Burke DJ, Weintraub MN, Hewins CR, Kalisz S**. **2011**. Relationship between soil enzyme activities, nutrient cycling and soil fungal communities in a northern hardwood forest. *Soil Biology and Biochemistry* **43**: 795–803.

**Callaway RM, Cipollini D, Barto K, Thelen GC, Hallett SG, Prati D, Stinson K, Klironomos J**. **2008**. Novel weapons: Invasive plant suppresses fungal mutualists in America but not in its native Europe. *Ecology* **89**: 1043–1055.

**Callaway RM, Ridenour WM**. **2004**. Novel weapons: Invasive success and the evolution of increased competitive ability. *Frontiers in Ecology and the Environment* **2**: 436–443.

**Cantor A, Hale A, Aaron J, Traw MB, Kalisz S**. **2011**. Low allelochemical concentrations detected in garlic mustard-invaded forest soils inhibit fungal growth and AMF spore germination. *Biological Invasions* **13**: 3015–3025.

**D’Angelo E, Crutchfield J, Vandiviere M**. **2001**. Rapid, Sensitive, Microscale Determination of Phosphate in Water and Soil. *Journal of Environmental Quality* **30**: 2206–2209.

**van Diepen LTA, Lilleskov EA, Pregitzer KS, Miller RM**. **2007**. Decline of arbuscular mycorrhizal fungi in northern hardwood forests exposed to chronic nitrogen additions. *New Phytologist* **176**: 175–183.

**Doane TA, Horwáth WR**. **2003**. Spectrophotometric determination of nitrate with a single reagent. *Analytical Letters* **36**: 2713–2722.

**Dong N, Prentice IC, Evans BJ, Caddy-Retalic S, Lowe AJ, Wright IJ**. **2017**. Leaf nitrogen from first principles: field evidence for adaptive variation with climate. *Biogeosciences* **14**: 481–495.

**Dong N, Prentice IC, Wright IJ, Evans BJ, Togashi HF, Caddy-Retalic S, McInerney FA, Sparrow B, Leitch E, Lowe AJ**. **2020**. Components of leaf‐trait variation along environmental gradients. *New Phytologist* **228**: 82–94.

**Dong N, Prentice IC, Wright IJ, Wang H, Atkin OK, Bloomfield KJ, Domingues TF, Gleason SM, Maire V, Onoda Y, *et al.*** **2022**. Leaf nitrogen from the perspective of optimal plant function. *Journal of Ecology* **110**: 2585–2602.

**Duursma RA**. **2015**. Plantecophys - an R package for analysing and modelling leaf gas exchange data. *PLOS ONE* **10**: e0143346.

**Evans JR, Clarke VC**. **2019**. The nitrogen cost of photosynthesis. *Journal of Experimental Botany* **70**: 7–15.

**Evans JR, Seemann JR**. **1989**. The allocation of protein nitrogen in the photosynthetic apparatus: costs, consequences, and control. *Photosynthesis* **8**: 183–205.

**Farquhar GD, von Caemmerer S, Berry JA**. **1980**. A biochemical model of photosynthetic CO2 assimilation in leaves of C3 species. *Planta* **149**: 78–90.

**Farquhar GD, Sharkey TD**. **1982**. Stomatal conductance and photosynthesis. *Annual Review of Plant Physiology* **33**: 317–345.

**Fox J, Weisberg S**. **2019**. *An R companion to applied regression*. Thousand Oaks, California: Sage.

**Hale AN, Kalisz S**. **2012**. Perspectives on allelopathic disruption of plant mutualisms: A framework for individual- and population-level fitness consequences. *Plant Ecology* **213**: 1991–2006.

**Hale AN, Lapointe L, Kalisz S**. **2016**. Invader disruption of belowground plant mutualisms reduces carbon acquisition and alters allocation patterns in a native forest herb. *New Phytologist* **209**: 542–549.

**Hale AN, Tonsor SJ, Kalisz S**. **2011**. Testing the mutualism disruption hypothesis: physiological mechanisms for invasion of intact perennial plant communities. *Ecosphere* **2**: art110.

**Heberling JM, Cassidy ST, Fridley JD, Kalisz S**. **2019**. Carbon gain phenologies of spring-flowering perennials in a deciduous forest indicate a novel niche for a widespread invader. *New Phytologist* **221**: 778–788.

**Hungate BA, Dukes JS, Shaw MR, Luo Y, Field CB**. **2003**. Nitrogen and climate change. *Science* **302**: 1512–1513.

**Inderjit, Wardle DA, Karban R, Callaway RM**. **2011**. The ecosystem and evolutionary contexts of allelopathy. *Trends in Ecology and Evolution* **26**: 655–662.

**Kalisz S, Kivlin SN, Bialic-Murphy L**. **2021**. Allelopathy is pervasive in invasive plants. *Biological Invasions* **23**: 367–371.

**Kattge J, Knorr W**. **2007**. Temperature acclimation in a biochemical model of photosynthesis: a reanalysis of data from 36 species. *Plant, Cell & Environment* **30**: 1176–1190.

**Kenward MG, Roger JH**. **1997**. Small sample inference for fixed effects from restricted maximum likelihood. *Biometrics* **53**: 983.

**Kummel M, Salant SW**. **2006**. The economics of mutualisms: Optimal utilization of mycorrhizal mutualistic partners by plants. *Ecology* **87**: 892–902.

**Lajtha K, Driscoll CT, Jarrell WM, Elliott ET**. **1999**. Soil phosphorus. In: Standard Soil Methods for Long-Term Ecological Research. 115.

**Lenth R**. **2019**. emmeans: estimated marginal means, aka least-squares means.

**Medlyn BE, Dreyer E, Ellsworth DS, Forstreuter M, Harley PC, Kirschbaum MUF, Le Roux X, Montpied P, Strassemeyer J, Walcroft A, *et al.*** **2002**. Temperature response of parameters of a biochemically based model of photosynthesis. II. A review of experimental data. *Plant, Cell & Environment* **25**: 1167–1179.

**Menne MJ, Durre I, Vose RS, Gleason BE, Houston TG**. **2012**. An overview of the global historical climatology network-daily database. *Journal of Atmospheric and Oceanic Technology* **29**: 897–910.

**Paillassa J, Wright IJ, Prentice IC, Pepin S, Smith NG, Ethier G, Westerband AC, Lamarque LJ, Wang H, Cornwell WK, *et al.*** **2020**. When and where soil is important to modify the carbon and water economy of leaves. *New Phytologist* **228**: 121–135.

**Palecki M, Durre I, Applequist S, Arguez A, Lawrimore JH**. **2021**. U.S. Climate Normals 2020: U.S. Hourly Climate Normals (1991-2020). *NOAA National Centers for Environmental Information*.

**Perkowski EA, Waring EF, Smith NG**. **2021**. Root mass carbon costs to acquire nitrogen are determined by nitrogen and light availability in two species with different nitrogen acquisition strategies. *Journal of Experimental Botany* **72**: 5766–5776.

**Qu T, Du X, Peng Y, Guo W, Zhao C, Losapio G**. **2021**. Invasive species allelopathy decreases plant growth and soil microbial activity. *PLoS ONE* **16**: 1–12.

**R Core Team**. **2021**. R: A language and environment for statistical computing.

**Roche MD, Pearse IS, Bialic-Murphy L, Kivlin SN, Sofaer HR, Kalisz S**. **2021**. Negative effects of an allelopathic invader on AM fungal plant species drive community-level responses. *Ecology* **102**: 1–12.

**Roche MD, Pearse IS, Sofaer HR, Kivlin SN, Spyreas G, Zaya DN, Kalisz S**. **2023**. Invasion-mediated mutualism disruption is evident across heterogeneous environmental conditions and varying invasion intensities. *Ecography* **2023**: 1–11.

**Rodgers VL, Stinson KA, Finzi AC**. **2008**. Ready or not, garlic mustard is moving in: *Alliaria petiolata* as a member of eastern north American forests. *BioScience* **58**: 426–436.

**Saathoff AJ, Welles J**. **2021**. Gas exchange measurements in the unsteady state. *Plant Cell and Environment* **44**: 3509–3523.

**Smith NG, Dukes JS**. **2018**. Drivers of leaf carbon exchange capacity across biomes at the continental scale. *Ecology* **99**: 1610–1620.

**Smith NG, Keenan TF, Prentice IC, Wang H, Wright IJ, Niinemets Ü, Crous KY, Domingues TF, Guerrieri R, Ishida FY, *et al.*** **2019**. Global photosynthetic capacity is optimized to the environment. *Ecology Letters* **22**: 506–517.

**Smith SE, Read DJ**. **2008**. *Mycorrhizal Symbiosis*.

**Tejera-Nieves M, Seong DY, Reist L, Walker BJ**. **2024**. The Dynamic Assimilation Technique measures photosynthetic CO2 response curves with similar fidelity to steady-state approaches in half the time. *Journal of Experimental Botany* **75**: 2819–2828.

**Treseder KK**. **2004**. A meta‐analysis of mycorrhizal responses to nitrogen, phosphorus, and atmospheric CO2 in field studies. *New Phytologist* **164**: 347–355.

**USDA NRCS**. **2022**. The PLANTS Database. *(http://plants.usda.gov, 18 November 2022). National Plant Data Team, Greensboro, NC 27401-4901 USA.*

**Walters RG**. **2005**. Towards an understanding of photosynthetic acclimation. *Journal of Experimental Botany* **56**: 435–447.

**Waring EF, Perkowski EA, Smith NG**. **2023**. Soil nitrogen fertilization reduces relative leaf nitrogen allocation to photosynthesis. *Journal of Experimental Botany* **74**: 5166–5180.

**Weatherburn MW**. **1967**. Phenol-hypochlorite reaction for determination of ammonia. *Analytical Chemistry* **39**: 971–974.

**Westerband AC, Wright IJ, Maire V, Paillassa J, Prentice IC, Atkin OK, Bloomfield KJ, Cernusak LA, Dong N, Gleason SM, *et al.*** **2023**. Coordination of photosynthetic traits across soil and climate gradients. *Global Change Biology* **29**: 856–873.

**Wild J, Kopecký M, Macek M, Šanda M, Jankovec J, Haase T**. **2019**. Climate at ecologically relevant scales: A new temperature and soil moisture logger for long-term microclimate measurement. *Agricultural and Forest Meteorology* **268**: 40–47.

**Zhang Z, Liu Y, Yuan L, Weber E, van Kleunen M**. **2021**. Effect of allelopathy on plant performance: a meta-analysis. *Ecology Letters* **24**: 348–362.

**Supporting Information**

**Table S1** Analysis of variance results exploring the role of *A. petiolata* treatment and measurement period on soil nutrient availabilities

**Table S2** Analysis of variance results exploring the role of *A. petiolata* treatment and day of year on soil moisture

**Figure S1** Effects of *A. petiolata* treatment and tree canopy status on soil nitrate and ammonium availability

**Figure S2** Effects of *A. petiolata* treatment and tree canopy status on relative chlorophyll content in *Trillium* spp. and *M. racemosum*.