Plant species identity matters when comparing the trophic impacts of native and non-native plants: insights from a community-wide bird-exclusion experiment

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Abstract:

Biological invasions can threaten biodiversity by outcompeting native species and disrupting food webs. Non-native invasive (NNI) species are now ranked as a leading cause for decline of biodiversity and protected species. NNI woody plants are one group of invasive species that now occupy many forest, grasslands, and wetlands as a result of human activity. In temperate forests of eastern North American, for example, understory plant communities are frequently dominated by non-native shrubs. For many species of insectivorous birds and mammals, non-native plants threaten populations by providing fewer food resources and/or foods of lower quality. Conservation practitioners expend significant effort to remove non-native plants, but evidence that this removal improves food quality or availability to wildlife is scant. Using a bird exclusion experiment, we compared arthropod abundance, biomass, and quality (protein content of herbivores and spiders), and bird foraging intensity predation effect size, among four NNI and six native woody plant species in a Connecticut, USA forest to examine how NNI plants affect the tri-trophic relationship of forest understory plants, branch-dwelling arthropods, and insectivorous songbirds. All four lines of evidence suggested that the four NNI plants we studied do not negatively affect arthropod prey availability or quality to songbirds. Compared to native plants, some NNI species like honeysuckle (*Lonicera morrowii*) supported higher arthropod biomass with a higher protein content. Conversely, one NNI, Japanese barberry, had fewer arthropods overall and spiders from it had significantly lower protein content. Contrary to predictions from other food web experiments, the predation effects of birds were of similar magnitude on native and NNI plants, suggesting insectivorous songbirds forage as intensively on NNI plants as they do on native plants. We recommend a more nuanced and regionally tailored approach to NNI plant management that targets species that low-quality foraging opportunities relative to the known quality of the local plant community.

Keywords:

Invasive species, invasive plants, non-native plants, insectivores, songbirds, forests, food webs, habitat improvement

Introduction:

Non-native invasive (NNI) species are a leading cause of global biodiversity decline (Bellard et al. 2016), with an estimated cost of management totaling $120 billion in the United States (Pimental et al. 2007) as a response to economic impacts that average $19.9 billion per year (Fantle-Lepczyk et al. 2021). Removal of invasive species is costly, but can be an effective way to restore ecosystem services. NNI plants are particularly challenging to manage in terrestrial ecosystems, with the cost of removal efforts still being difficult to estimate accurately for the U.S. or globally (Rai et al. 2022). Nevertheless, the costs of non-native plant management have not been trivial when quantified, reaching average annual totals of $82 million in California (California Invasive Plant Council, 2022) and $45 million in Florida (Hiatt et al. 2019). In principle, removing NNI plants improves habitat quality for native plants (Hartman and McCarthy, 2004) and native wildlife (Schneider and Miller, 2014). Notably, removal of particularly aggressive invasive plant species that form monocultures can drive recovery of arthropod assemblages, which are an important indicator of food availability for wildlife (Gratton and Denno, 2005). However, despite the dramatic efforts to remove established invasive plant populations from managed habitats, there is still not a consensus on whether such practices actually benefit the arthropod communities that are prey for wildlife (Robichaud et al. 2021, Traylor et al. 2022). Effective management requires knowledge of when removal of a given invasive species may not be justified based on restoration goals (D’Antonio and Meyerson 2002). Decisions about prioritizing some invasive species removal over others is critical since conservation resources are severely limited relative to the ecological challenge at hand (Arponen 2012, Courtois et al. 2018, Eppinga et al. 2021).

Plant invasions often have cascading impacts on ecological communities because they can directly modify both above-ground and soil food webs (McCary et al. 2016). Non-native invasive plants (hereafter referred to as ‘non-native’) are particularly prevalent in degraded habitats with a history of intensive land-use practices (Mosher et al. 2009, Wang et al. 2016. Furthermore, new non-native plant species are expected become established in anthropogenically modified habitats over time (Seebens et al. 2017). Consequently, understanding the mechanisms by which non-native plants disrupt food webs and identifying effective solutions have become priorities for ecologists and land managers. Typically, non-native plants dominate or form monocultures and displace native plant species, negatively impacting native animals indirectly (Fletcher et al. 2019). Some studies have shown lower quality arthropod prey is available to insectivorous birds and mammals in habitats dominated by non-native plants. (Gerber et al. 2008, Riedl et al. 2018). However, nutritional quality for herbivores is just one of multiple traits of non-native plants that impacts food webs. For example, compounds released from invasive plants through roots and decaying leaves can impact detritus-based food webs (Robison et al. 2021). Additionally, non-native plants have atypical architecture compared to native plants, leading to different compositions of arthropods independent of the host plant quality (Pearson 2009, Landsman et al. 2020). Each of these trait-based mechanisms provides some insight into the consequences of plant invasion, but interspecific comparisons are needed to help elucidate these pathways. For example, Lind and Parker (2010) compared a range of plant species testing the hypothesis that non-native plants have significantly different defensive chemistry than natives, but this hypothesis was only supported for a small proportion of the invasive plants examined.

In food web ecology, comparisons are often made between native and non-native congeners that are expected to have similar phytochemistry and thus shared defensive traits (Haan et al. 2021, Lampert et al. 2022). Similarly, in comparable habitats, areas dominated by invasive plants often have lower abundances of plant-feeding arthropods, particularly caterpillars (Richard et al. 2019). As a result of lower nutritional quality, invasive plants may have fewer herbivores, shrinking the biomass in the second trophic level (Clark and Seewagen 2019). It is expected that by removing non-native plants, native plants have an opportunity to recover, thus restoring ecosystem services (Hopfensperger et al. 2017). In landscaping scenarios, native plants which provide more insect prey are suggested as replacements for exotic shrubs to help bird populations (Narango et al. 2018, Kramer et al. 2019). By contrast, in managed forests, NNI plant removal is typically conducted without active replacement and relies on local native plants to move into recently cleared areas on their own (Flory and Clay 2009, Shields et al. 2015, Farmer et al. 2016, Cutway 2017). Importantly, for wildlife at higher trophic levels, the success of this management strategy depends on the presumed superiority of arthropod quantity or quality on native compared to non-native plants. However, this assumption has not been rigorously tested, both in general and particularly in the temperate forests of the northeastern United States.

Our study includes a comparison of a community of non-native plants to a community of native plants in a shared environment. We tested two hypotheses: (1) a ‘low food quantity hypothesis’, and (2) a ‘low food quality hypothesis’. In the low food quantity hypothesis, non-native plants are expected to have significantly lower prey available for insectivores compared to native plants coexisting in the same environment. In other forest regions in the eastern US, some non-native plants have relatively lower insect abundance and diversity (Tallamy et al. 2020). Furthermore, some insect guilds of high nutritional value to insectivores (e.g., caterpillars) are expected to be less abundant on NNI plants as well (Narango et al. 2018). Conversely, in the ‘low food quality’ hypothesis, prey items that are available on non-native plants are expected to have lower nutritional value (e.g., lower protein content) because non-natives are often low-quality food sources for herbivorous arthropods (Lieurance and Cipollini, 2013). We predicted lower arthropod quality on non-native plants than natives. Finally, in both hypotheses, insectivores are predicted to forage on non-native plants less than native plants because of lower prey abundance and quality (Riedl et al. 2018). Here, we tested these hypotheses in a Connecticut, U.S.A. forest through a predator exclusion experiment on multiple highly invasive and widely distributed NNI plant species, using forest songbirds as model insectivores. Compared to coexisting native woody plants, we expected NNI plants to support lower arthropod biomass and lower quality arthropods and be foraged on by insectivorous birds less intensively. For estimates of food quality, we used elemental analysis to compare the protein content (percent elemental Nitrogen) of arthropods collected from native plants to those collected from NNI plants within the same habitat.

Methods:

*Study System.* We performed a selective predator exclusion experiment on ten woody host plant species at Great Hollow Nature Preserve (New Fairfield, Connecticut, USA (41.507998 N, -73.530032 W). Great Hollow Nature Preserve is a 334-ha protected area that is comprised predominantly of mature, closed-canopy, second-growth deciduous and mixed forest. Historic disturbance of the land, mostly from past agricultural uses, has favored the establishment of many of the NNI plants that are now ubiquitous to the northeastern U.S. and often aggressively targeted for removal by land managers and conservation practitioners. We focused our experiment on a subset of these NNI plants, including Japanese barberry (*Berberis thunbergii)*, Morrow’s honeysuckle (*Lonicera morrowii*), burning bush (*Eunonymous alatus*), and autumn olive (*Eleagnus umbellata*). For comparison, we chose six native shrubs and trees that commonly occur with these NNI woody plants in the understory of closed-canopy Northeastern forests. They included striped maple (*Acer pennsylvanicum*), shadbush (*Amelanchier canadensis*), musclewood (*Carpinus caroliniana*), witch-hazel (*Hamamelis virginiana*), sweet birch (*Betula lenta*), and American beech (*Fagus grandifolia*). These ten NNI and native species collectively represented the dominant woody plants in the understory of our study area. Performing our experiment across these 10 species thus provided a community-wide perspective on the impacts of non-native plants on food webs, in the context in which invasive plant management decisions should be made (Westman 1990).

*Bird exclusion experiment.* From 4-27 May, 2021, we employed a predator exclusion experiment in a paired design following Singer et al. (2012). Briefly, insectivorous birds were prevented from foraging on branches of our 10 study species *via* a mesh netting that was draped over a single branch of a target plant. Mesh nets were affixed to the base of these individual branches using plastic zip-ties (exclusion treatment). Each of these branches were paired with a nearby (< 10m) unmanipulated control branch of the same plant species.). We set up 12 treatment pairs for each of the 10 focal plant species, resulting in a total of 240 individual host plants in the study. At the end of the set-up period on 27 May all 240 branches were gently tapped to dislodge arthropods to avoid bias caused by the disturbance of setting up the exclusion netting. After a 2-wk waiting period, we then sampled foliage-foraging arthropods with a branch-beating technique (Wagner 2005) every other week, for a total of three repeated samples per branch. We struck each branch with a 0.3m long dowel while hanging over a 1m2 ripstop fabric beat sheet and collected all invertebrates from the beat sheet into plastic vials or plastic zip-top bags using aspirators or soft-touch aluminum forceps. We kept the collected arthropods cool in the field in coolers with ice packs and then transferred them to a -80º C freezer at the end of each day.

*Taxonomic identification of arthropods.* We combined the three repeated samples from a given branch to provide a broad-scale estimate of total arthropod abundance (Clark et al. 2016) and then weighed (wet mass) the arthropods together on a 10-4 g microbalance. After identifying all invertebrates from a given branch to class, we sorted all insects in the orders Lepidoptera, Hemiptera, Hymenoptera to family. We identified true spiders (Araneae) and Opiliones to family as well. Following identification, we transferred each taxonomic group from a given branch to separate 0.6-2mL Eppendorf tubes and stored them at -80º C. In all, the four numerically dominant taxonomic groupings of arthropods included (1) Lepidoptera (caterpillars), (2) true spiders (Araneae), (3) herbivorous Hemiptera families (Aphidae, Cicadellidae, Membracidae, Miridae, and Pentatomidae), and (4) Orthoptera (families Gryllidae and Tettigoniidae.

*Elemental analysis of arthropods.* Our preliminary analyses suggested that two broad functional groups responded strongly to bird predation effects and varied significantly among native and non-native host plants, each representing a different trophic level above host plants: foliage-feeding herbivores (see Appendix 1a: Selection of herbivores for C:N analysis) and predatory true spiders (Araneae). These two groupings of arthropods are prey for foliage-gleaning insectivorous birds and their abundances are impacted by experimental manipulation of bird predation (Gunnarsson et al. 1996). We measured C:N ratios in these two groups as an indirect measure of protein (Smets et al. 2021), a macronutrient that strongly mediates food selection by breeding birds and is critical to offspring development (Robbins et al. 2005, add others). Generally, the insects feeing on individual plants have a similar C:N ratio as their host (Abbas et al. 2014). To assay elemental composition, we first pooled foliage-feeding herbivore taxa and true spiders across sampling periods for each branch in the bird exclusion treatment group. We limited our analyses to branches with birds excluded in order to quantify the nutritional quality of the arthropod community as it would be for the first bird foraging on a given branch. We then oven-dried arthropod samples at 60° C to a constant mass and homogenized any samples that weighed > 3 mg. We placed 1.5-3.5 mg of each sample into tin capsules and evaluated the mass of carbon and nitrogen with a Flash 1112 CHNSO elemental analyzer (CE Elantech inc. Lakewood, NJ, USA) by comparison with an aspartic acid standard curve (Sigma-Aldrich, St. Louis, MO, USA). We calculated percent nitrogen and carbon by dividing the mass of each element in a sample by total sample mass. We analyzed replicates for a subset of branches, producing mean within-sample coefficients of variation of 4.2% for nitrogen and 2.9% for carbon.

*Statistical analyses.* We employed a series of Generalized Linear Mixed Models (GLMMs) using the *lme4* package (Bates et al. 2015) in R version 4.1.2 (R Development Core Team, 2022). We included the following as response variables for each model: (1) total arthropod biomass sampled per plant, (2) spider abundance (Araneae), (3) caterpillar abundance (Lepidoptera), (4) True bug abundance (herbivorous Hemiptera) (5) Tree cricket, katydid, and grasshopper abundance (Orthoptera) (6) N content of herbivorous insects and (7) N content of spiders. Arthropod biomass was fitted as a normally distributed GLMM after log-transformation and included both host plant species and bird exclusion treatment as fixed effects, and branch as a random effect. All abundance models were fitted with a negative binomial GLMM. In abundance models, non-native status (yes or no) was a fixed effect along with bird-exclusion treatment, and branch and host-plant species were included as random effects. We pooled across the two sampling periods repeated samples on each branch in all analyses to produce a broader-scale estimate of total arthropod abundance per plant (see statistical methods in Clark et al. 2016). Nitrogen content models were fit as a normal distribution, but since all arthropod samples were pooled across sampling periods and only taken from exclusion branches, only host-plant species was used as a main effect (GLM). Post-hoc tests comparing changes in biomass, abundance, and nitrogen content were run using the *emmeans* package in R (Lenth 2016). Differences were investigated across all groupings using Scheffe’s method (following Midway et al. 2020) for P-value adjustment in unplanned contrasts. P-values and critical values were determined using the *car* package with analysis of deviance tests and χ2 test statistics (Fox et al 2015).

*Log-response ratios.* A follow-up GLM was employed using the LRR of exclusion treatments to investigate the interspecific variation in bird predation effects across all host plant species (Singer et al. 2012). Log-response ratios, when used to evaluate the effects of natural enemy exclusion, provide insight into whether the interaction strength of top-down effects vary according to different environmental variables (Chaguaceda et al. 2021, Wooton 1997). In this case, we used a LRR modified from Hedges et al. (1999) as the natural log of the combined arthropod biomass on exclusion branches divided by the arthropod biomass on control branches. LLR calculated in this way tests the prediction that bird predation is weaker on invasive plants, an implicit assumption of both the ‘low food quantity hypothesis’ and the ‘low food quality hypothesis’. LRR values above zero indicate that predator effects are biologically and statistically significant, while those that intersect with zero are not.

Results:

We observed significant variation in total arthropod biomass among our ten focal host-plant species (Fig. 1, GLMM, *P* = 0.001, χ2 = 26.62, d.f. = 9). Collectively, native plants did not have significantly higher biomass than non-native plants in a grouped planned contrast (*P* = 0.133, *t* ratio = 1.5, d.f. = 223). Honeysuckle had higher biomass than the three other non-native plant species (Fig 1). Native plants varied in biomass, with musclewood, sweet birch and witch-hazel exhibiting relatively higher biomass than the other native plants (Fig 1). We did not observe statistically significant variation in the effect size of bird predation as measured by LRR (Fig. 2, GLM, *P* = 0.294, χ2 = 10.73, d.f. = 9). Furthermore, bird predation LLR was not significantly lower on non-native species than native species in a grouped planned contrast (*P* = 0.364, *t* ratio = 0.954, d.f. =106). However, predation effects were above zero for all native and NNI species, except for musclewood, but exclusion branches of musclewood were associated with relatively high occupancy of aquatic insect orders (Fig S1).

Bird predation effects on abundance of arthropods among native-and non-native plants differed for each taxonomic group. Araneae abundance as higher on non-native plants overall (Fig. 3A, GLMM, *P* < 0.001, χ2 = 19.19, d.f. = 1), while bird effects on Araneae abundance were significant on both native and non-native plants (Fig. 3A, GLMM, *P* < 0.001, χ2 = 57.18, d.f. = 1). Hemiptera abundance was not significantly different between native to NNI plants (Fig 3B, GLMM, *P* = 0.488, χ2 = 0.479, d.f. = 1), and bird predation did not significantly reduce Hemipteran abundance (Fig. 3B, GLMM, *P* = 0.141, χ2 = 2.15, d.f. = 1). Bird predation effects were significant for lepidoptera (Fig. 3C, GLMM, *P* < 0.001, χ2 = 25.7, d.f. = 1) and although there were fewer Lepidoptera on non-native plants (Fig. 3C, GLMM, *P* = 0.022, χ2 = 5.19, d.f. =1), bird predation effects did not significantly differ between natives and non-natives (GLMM interaction term for native vs. non-native plants and bird predation effect, *P* = 0.614, χ2 = 0.25, d.f. =1). Finally, we observed similar abundances of Orthoptera on both native and non-native plants (Fig. 3D, GLMM, *P* = 0.941, χ2 = 0.005, d.f. = 1). Birds significantly reduced the abundance of orthoptera on both plant groups (Fig. 3D, GLMM, *P* < 0.001, χ2 = 15.6, d.f. =1).

We observed significant variation in the %N content by mass for herbivores among host plants (Fig. 4A, GLM, *P* < 0.001, χ2 = 38.4, d.f. = 9). For non-native plants, our grouped planned contrast suggested significantly higher %N content by mass compared to natives (Fig 4A, planned contrast, *P* = 0.001, *t* ratio = -3.33, d.f. = 341). N content was highest on honeysuckle than any other plant (Fig 4A). Spider %N content by mass varied significantly among plants overall (Fig. 4B, GLM, *P* < 0.001, χ2 = 59.61, d.f. =9), with lower values on non-native than native plants (Fig 4B, planned contrast, *P =* 0.002, *t* ratio = 3.19, d.f. =341). %N content was dramatically lower on Japanese barberry than any other plant species (Fig 4B).

Discussion:

Introduced organisms have had a dramatic impact on ecosystems and economies, with some conservative estimates for monetary impacts of $1.26 trillion US dollars in North America since 1960 (Crystal-Ornelas et al. 2021). A problem of this scope requires careful strategic planning in which the most damaging non-native species are prioritized. Our results suggest important contexts in which non-native plants are poorer food opportunities for wildlife. First, our study revealed surprisingly higher quantity of arthropod prey on honeysuckle (Lonicera) compared to natives, failing to universally support the ‘low food quantity hypothesis’. Second, we saw important differences in the composition of prey on non-native plants, with caterpillars being rarer and less available to birds, directly supporting the ‘low food quantity hypothesis’ for this taxonomic group, but a reverse pattern was observed for spiders. Support for ‘low food quality hypothesis’ was mixed, with extremely variable nitrogen content of the arthropod community. For herbivores nitrogen content as significantly higher on invasive plants, but for spiders it was significantly lower. Investigation of host-plants specific patterns suggest that the variance in food quality on non-native plants encompasses the range of quality of food found on native plants in the same habitat.

Two broad mechanisms cause non-native plants to have different branch-dwelling arthropod communities compared to natives, and these mechanisms may explain the patterns we saw with bird predation and arthropod communities. First, the nutritional quality of these plants is considered lower compared to native plants. By virtue of having less nitrogen or other nutrients, or increased defensive chemistry, herbivores are often less abundant and diverse on NNI than native plants (van Hengstum et al. 2013). Second, the branch architecture or leaf shape of NNI plants provide novel microhabitat for arthropods and thus create a distinct community from those found on native plants (Bultman and DeWitt 2008, Landsman et al. 2021). We observed higher spider abundance on our non-native plants, similar to other observations with invasive plants like Japanese stiltgrass (Landsman et al. 2020). Likely differences in twig and leaf architecture provide superior scaffolding and hunting territory (Bultman and DeWitt 2007). Conversely, we found herbivores like caterpillars were less abundant on non-native plants, likely owing to their inferior nutritional quality, but other mechanisms, such as increased threat from spider predation may also be important. Equivalent abundances of another major herbivore functional group, the Orthoptera, suggest that mobile grazing generalists may not be as constrained by the lower nutritional quality of non-native plants, as they can forage on both types of hosts.

One of the gaps in past research on non-native plant invasions is the limited ability of previous studies to assess how much invader-driven changes in arthropod communities translate into altered interactions between arthropods and their predators. Our study allowed us to investigate this question by combining quantification of the arthropod community on a range of host plants with a predator exclusion experiment to quantify top-down effects. Moreover, we considered trends in broad taxonomic groups, which can be informative for aggregating effects over complex systems (*sensu* Wagner et al. 2021). Accordingly, we did in fact find differences between native and non-native plants in the abundances of caterpillars and spiders as well as differences in nitrogen content of those groups ranging from around 0.5% in aggregate to 1% in specific contrasts. These differences in nitrogen content translate to differences in protein content of approximately 3 – 6% (McDonald et al. 2011, Smets et al. 2021), which, while not extreme, are detectable by songbirds and can result in substantial differences in body condition (Bairlein 1998, Klasing 1998, Razeng and Watson 2015). Nevertheless, despite these differences we were surprised to see comparably strong predation effects on native and non-native plants, indicating that birds actively forage on and take prey from all available host species. Thus, it appears that the introduction of non-native plants has not greatly impacted the interactions among higher trophic levels at our study site. It is important to note, however, that some native plants believed to be high-quality insect hosts and food sources for birds (provide examples and citations) were rare or absent from our study site’s understory, where non-native plants were dominant (Tarr 2022), potentially inflating the overlap in quality between the native and non-native shrub communities. Similarly, it is unknown whether there are any notable downstream nutritional consequences of shifts in arthropod abundance and nitrogen content for songbirds, even in the absence of changes in predatory behavior.

One of the key priorities for invasive species research includes understanding the context of the environments that are being invaded or have been invaded (Ricciardi et al. 2021). Non-native plants are prevalent in these environments, in part, due to ecological disturbances caused by human activity (Homes et al. 2021). Current management practices attempt to ameliorate the impacts of non-native plants on wildlife through physical or chemical removal (Weidlich et al. 2020). However, our results suggest that native plant community is a critical comparison point. For example, forest composition and structure may be more important for some arthropod groups for determining density and abundance even on non-native plants (Traylor et al. 2022). It should be established in a given region whether native woody plants are superior foraging opportunities for songbirds, especially since invasive plant removal tactics themselves can have unintended, negative impacts (Kettenring and Adams 2001). One particularly surprising observation in this study was the range in quality of the arthropod community supported by our focal native plants. While, for example, witch hazel supported a greater total biomass, shadbush was substantially lower and largely indistinguishable from non-natives in both of those measures. Consequently, the relative value of removing a non-native shrub will depend on the particular pairwise comparisons being made at a given site. Overall, our results suggest that a more nuanced management strategy for habitat improvement goals in northeastern USA forests in which the native plant community is considered as the reference point in invaded habitats rather than assume that all non-natives are poorer food resources for wildlife.

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