A tale of two studies: Detection and attribution of the impacts of invasive plants in observational surveys

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Abstract

1. Short-term experiments cannot characterize how long-lived, invasive shrubs influence ecological properties that can be slow to change, including native diversity and soil fertility. Observational studies are thus necessary, but often suffer from methodological issues.

2. To highlight ways of improving the design and interpretation of observational studies that assess the impacts of invasive plants, we compare two studies of nutrient cycling and earthworms along two separate gradients of invasive shrub abundance. By considering the divergent sampling strategies and statistical analyses of these two studies, and interpreting their contradictory results in the context of other studies, we also aim to better describe the impacts of the focal invader, Rhamnus cathartica.

3. In a new study of a single site in Minnesota, we observed positive correlations between buckthorn abundance and soil pH, soil nutrient pools, nutrient fluxes through leaf litterfall, earthworm abundance and root biomass. Multiple regression models showed these relationships persisted after accounting for variability in soil texture and tree species composition. For a separate, more expansive study in Illinois, other authors reported little to no correlation between buckthorn abundance and 10 soil properties, including earthworm abundance, pH and nutrient concentrations. However, like many other studies, their regression models only assessed predictors related to invader abundance. R²-values for models of ecosystem properties ranged from 0 to .79 (adjusted-R²) for our study in Minnesota and from <.05 to .16 (unadjusted) for the prior study in Illinois.

4. Differences in sampling error and use of predictor variables between the two studies likely explain the contrasting results.

5. Synthesis and applications. To reduce the uncertainty of conclusions from observational studies of invasive plants, future studies must ensure that heterogeneity of soils and vegetation is adequately accounted for in the sampling strategy and statistical analyses (e.g. analysis of covariance, multiple regression). Particular
1 | INTRODUCTION

Non-native plants that become invasive can cause a variety of negative ecological and economic impacts through their potential to influence ecosystem properties and corresponding ecosystem services (Eviner, Garbach, Baty, & Hoskinson, 2012; Pimentel, Zuniga, & Morrison, 2005). However, it is difficult to document the impacts of invasive plants because of the plethora of invasive plant species and methodological issues that hamper interpretation of individual studies (Hulme et al., 2013; Kumschick et al., 2015; Stricker, Hagan, & Flory, 2015). In North America, there are more than 200 woody plant species that are both non-native and invasive (Rejmánek, 2014), and it is especially challenging to assess their impacts due to the long life spans and slow growth rates of woody plants (compared to herbaceous species). It can take decades for woody invasive plants to mature and for the corresponding ecological impacts to be fully realized (Strayer, Eviner, Nesche, & Pace, 2006; Stricker et al., 2015). Yet, it is obviously not prudent for land managers to wait decades for input from scientists on the potential consequences of woody plant invasions.

Experiments that manipulate the abundance of invasive plants suffer not only from the temporal constraints identified above, but also from ethical issues and unique methodological issues (e.g. addition of invasive plants in non-invaded landscapes or disturbance in “removal” experiments; Kumschick et al., 2015; Stricker et al., 2015). Thus, observational studies are more feasible and common, especially for invasive woody plants (Stricker et al., 2015; Vilà et al., 2011). The most common type of observational study involves comparing a few uninvaded plots to a few invaded plots (Vilà et al., 2011). Several authors have discussed the problems ascertaining causality in these studies (Iannone, Heneghan, Rijal, & Wise, 2015; Kumschick et al., 2015; Stricker et al., 2015): which developed first, differences in invader abundance, or differences in other ecological factors (e.g. soil properties, community composition) that facilitated invasion but could be misinterpreted as “impacts” of invasion. Observational studies that assess ecological attributes along a gradient of invader abundance provide an opportunity to better document the magnitude and trajectory of potential ecological impacts (Hulme et al., 2013; Iannone et al., 2015), but such studies are both less common and still suffer from uncertainty regarding causality.

Here, we highlight opportunities to improve observational studies of invasive plants by contrasting the methods and results of two studies of Rhamnus cathartica (common buckthorn), a deciduous invasive shrub with a non-native range that includes most of the United States and Canada (USDA, 2017). Like several other invasive shrubs in North America, common buckthorn is unique compared to most co-occurring, deciduous natives because its leaves have higher concentrations of nutrients, develop earlier in spring, and senesce later in fall (Fridley, 2012; Jo, Fridley, & Frank, 2014, 2016). Consequently, many studies of buckthorn and similar invasive shrubs (e.g. Lonicera spp.) have focused on how these plants influence nutrient pools and fluxes in soil (Ewing, Lauko, & Anderson, 2015; Jo, Fridley, & Frank, 2017; Knight, Kurylo, Endress, Stewart, & Reich, 2007; McNeish & McEwan, 2016; Stokdyk & Herrman, 2016). These studies typically observe greater nutrient pools and fluxes in invaded stands and interpret these differences as evidence of an impact of the invader. However, Iannone et al. (2015) recently questioned this interpretation based on evidence from a unique, gradient-based study of common buckthorn. To reconcile contradictory conclusions regarding this widespread invader, and to improve the methods and interpretation of observational studies generally, regardless of the focal invasive species, we contrast the design and results of Iannone’s study with those of our own observational study of a gradient in buckthorn abundance.

This comparison of studies is primarily focused on how to address the factors that confound interpretations related to the causality of relationships between invader presence/abundance and other environmental characteristics, such as native diversity or nutrient cycling. We consider issues ranging from spatial variability and sampling design to which ecological factors to measure and how to analyse the data. Other authors have advocated for minimizing the differences in potentially confounding factors among invaded and uninvaded plots (e.g. soil type, disturbance history), or for measuring such factors both within and across studies to provide “context” (Kumschick et al., 2015); here, we provide specific theoretical and practical recommendations for improving the design and interpretation of observational studies that assess the impacts of invasive plants.

2 | MATERIALS AND METHODS

2.1 | Buckthorn gradient in Minnesota

This study was conducted at the Lee and Rose Warner Nature Center in Marine-on-Saint Croix, Minnesota (45.172626°, −92.831987°).
Mean temperatures are −9.6°C in January and 22.1°C in July. Mean annual precipitation is 830 mm. The area is topographically variable, but we focused on uplands characterized by mesic, deciduous forest dominated by *Quercus rubra* and *Q. alba* (typically >80 years old) and *Acer rubrum* (typically <50 years old). *Prunus serotina* and *Tilia americana* were sometimes present in the canopy. The forest was heavily invaded by European earthworms (Roth, 2015), resulting in a sparse litter layer (O) and non-existent O2 and O3 horizons.

Common buckthorn has been present at the site for >30 years, based on staff observations and annual wood growth rings of one very large buckthorn. Invasion fronts are visible in multiple locations (where dense stands with large, mature buckthorn gradually grade to an understory of small, sparse buckthorn). Thus, site history and spatial patterns of buckthorn size and density indicate that buckthorn presence and density are not likely driven by pre-existing variability in soils or prior disturbance or land management. This interpretation is consistent with patterns of buckthorn abundance in the Upper Midwest, U.S.A., where buckthorn appears to be spreading in a concentric manner from locations with dense, mature buckthorn stands (Moser, Fan, Hansen, Crosby, & Fan, 2016).

We studied 24 plots located along two separate gradients of buckthorn abundance, including 12 plots on sandy soils (45%–67% sand, 17%–31% silt, 15%–24% clay) and 12 plots on silty soils (12%–30% sand, 51%–67% silt, 19%–24% clay). The minimum and maximum distance between plots was 9 and 521 m. Sampling of vegetation and soils occurred between June 2012 and May 2013. Plots were selected to minimize variability in slope (4–16°), elevation (285–908 m), and distance between plots (maximum distance between plots was 9 and 521 m). In the subplots, buckthorn density ranged from 0 to 19.7 stems/m² and buckthorn basal area ranged from 0 to 9.6 cm²/m².

Soil properties were measured at the subplot-scale by combining the samples within each subplot. Root biomass was measured after sieving (2 mm) and hand picking soil collected from the top 15 cm of soil (due to malfunction of the deeper soil corer). To express soil nutrient pools in units of ground area, bulk density of the soil fraction <2 mm was measured using the volume of soil cores and the dry weight of sieved soil. Total organic carbon (C), total nitrogen (N), exchangeable cations (via ammonium-acetate extraction), total and Bray-1 extractable phosphorus (P) and soil pH were estimated using standard methods at the University of Minnesota Research Analytical Laboratory. Earthworm biomass, comprised entirely of non-native species due to prior glacial activity (Frelich et al., 2006), was measured in summer and fall of 2012 and 2013 after extracting earthworms from two quadrats (35 cm × 35 cm) per subplot using a mustard solution (Lawrence & Bowers, 2002).

In September 2012, we installed two 10-gallon pots (c. 50 cm diameter) in each subplot and collected litterfall from the pots biweekly until December. Leaf litter from buckthorn, red maple and oak was separated from other species. Across plots, leaf litterfall from "other" species averaged 6.4% (SE = 1.1) of total annual leaf litterfall. Litter from the two oak species was composited in all but two plots to minimize sample processing and analyses. For those two plots, litter from *Q. alba* and *Q. rubra* had similar concentrations of N (0.83 and 0.84%, respectively) and base cations (18.5 and 18.2 mg/g, respectively, for the sum of Ca, K, Mg and Na). Litter was oven-dried (60°C), weighed and ground prior to nutrient analysis by the Research Analytical Laboratory. For each plot, the flux of nutrients via leaf litterfall for buckthorn, red maple, oak and other species was calculated by multiplying the total mass of leaf litter of each type by the nutrient concentration of that litter type. The total annual flux of each nutrient in leaf litterfall was calculated for each plot by summing the leaf litter fluxes of each litter type.

We used simple regression (one predictor) and multiple regression (multiple predictors) to examine the correlation of buckthorn abundance with nutrient pools and fluxes and other ecosystem properties. For both types of regression models, buckthorn basal area was used as the measure of buckthorn abundance because its distribution was normal following a log₁₀ transformation, while the distribution of buckthorn density remained right-skewed after transformation. We summed buckthorn basal area in the 3 m subplot (counting all stems) and in the remainder of the 12 m plot (counting stems ≥1.4 m tall) because this better reflected the relative abundance of buckthorn individuals that could influence biota and nutrient cycling within the subplot. For the multiple regression models, we used type III sums-of-squares and several additional predictors to assess whether effects of buckthorn were apparent after accounting for other factors that could be confounded with buckthorn effects due to their potential covariance with buckthorn abundance. The predictors were selected based on their potential to both: (1) vary among plots prior to establishment of buckthorn, and (2) influence the dependent variables of interest. Percent sand was included as a predictor to account for potential effects of soil texture on ecosystem properties (e.g. coarse-textured soils have lower capacity to retain organic C and N via aggregation and other organo-mineral interactions; Hassink, 1997). Slope was not included as a predictor because it was tightly correlated with percent sand (r = .72, p < .0001). The proportions of leaf litterfall attributed to "other" species and either maple or oak were included as predictors to account for potential effects of overstorey tree composition on ecosystem properties (e.g. as mediated by differences in litter chemistry between species). We did not include leaf litterfall percentages attributable to maple and oak in the same model because these predictors were tightly and inversely correlated (r = −.84, p < .0001). The final predictor was the mass of total leaf litterfall,
a proxy for stand productivity (to avoid circularity, this predictor was excluded from models of nutrient fluxes through leaf litterfall). Data were log- or square-root-transformed when necessary to approximate normality.

2.2 | Buckthorn gradient in Illinois

This study was conducted in the vicinity of Chicago, Illinois (USA). The authors used a unique "paired-point" approach, which blends the use of gradients of invader abundance with the more common approach of comparing invaded and uninvaded plots (Iannone et al., 2015). For 10 soil properties, the authors estimated the difference between one invaded plot (i.e. "point") and one uninvaded plot at each of 97 locations within 15 natural areas in a 5,500 km² region. Buckthorn abundance in the invaded plots varied from 0 to 14.5 cm² basal area/m² and from 0 to 44 saplings/m². Soil properties were measured for one large soil core (6 cm diameter; 10 cm depth) per plot and various measures of buckthorn abundance were measured in a 100 m² area surrounding each soil core. Measured soil properties included pH, litter mass, total carbon and nitrogen, exchangeable calcium, earthworm abundance, soil moisture and concentrations of nitrate and ammonium. Plots were selected "without considering differences in plant communities or soils that might exist" among the locations or between the uninvaded and invaded plots of each "paired-point." However, for each plot, the authors identified the potential soil type using the USDA NRCS Web Soil Survey and characterized the composition of overstorey trees and understorey plants. Simple linear regression or ranked regression was used to assess the relationships between buckthorn abundance and the difference between the paired invaded and uninvaded plots for each soil parameter. The significance of the intercept term was used to infer whether there was an average difference between invaded and uninvaded plots for each soil parameter. For more details, see Iannone et al. (2015).

3 | RESULTS

3.1 | Buckthorn gradient in Minnesota

Using simple regression, we identified a positive correlation (p < .05) between buckthorn abundance and many dependent variables, including soil pH, total soil nitrogen, fine root biomass, earthworm biomass, the concentrations of nitrogen, calcium, and potassium in leaf litter, and the annual flux of nitrogen, calcium and potassium in leaf litter (mean $R^2 = .34$, range of $R^2 = .17-.67$; Figures 1–3). After accounting for additional predictors in multiple regression models, the significance of the apparent buckthorn effect diminished for soil pH ($p = .12$) and the annual flux of both N and Ca in leaf litterfall ($p = .11$ and .27, respectively), while the buckthorn effect remained significant ($p < .05$) or marginally significant (.05 < p < .1) for root biomass, earthworm biomass, total N and exchangeable Ca in soil, concentrations of N, Ca and K in leaf litterfall, and the annual flux of K in leaf litterfall (Figures 1–3). There was no apparent correlation, using both simple and multiple regression, between buckthorn abundance and several variables, including total C and P in soil, exchangeable K in soil, and both the concentration and annual flux of P in leaf litterfall. The additional predictors, especially percent sand and the percent of litterfall attributable to maple, oak, and other species, had significant relationships with most dependent variables (Figures 1–3). This is evident in higher adjusted-$R^2$ values of multiple regression models, both for variables that were correlated with buckthorn abundance ($M = 0.49$, range = 0.07–0.79) and variables that were not ($M = 0.49$, range = 0–0.79).

3.2 | Buckthorn gradient in Illinois

The authors reported higher values in the invaded plots, on average, for seven soil parameters, including pH, moisture, litter mass (during spring only), total carbon, total nitrogen and ammonium concentrations (Iannone et al., 2015). Yet, buckthorn abundance was not correlated with the magnitude of the differences between pairs of invaded and uninvaded plots for most of the measured soil properties, including pH, moisture, earthworm abundance, total carbon and nitrogen, the C:N ratio and exchangeable calcium. Contrasting with the average difference between invaded and uninvaded plots, buckthorn abundance was significantly negatively correlated with litter mass. Independent indicators of buckthorn abundance were positively and negatively correlated with nitrate concentrations (corresponding to sapling density and basal area, respectively). The $R^2$-values for these significant correlations varied from .05 to .16.

4 | DISCUSSION

The apparent impacts of plant invasions are known to be variable and context-dependent (Hulme et al., 2013; Kumschick et al., 2015; Ricciardi, Hoopes, Marchetti, & Lockwood, 2013; Vila et al., 2011). To highlight sources of uncertainty in observational studies of invasive impacts and provide guidance for future studies, we discuss how the contrasting results of our study and that of Iannone et al. (2015) might be explained by methodological differences that influence the detection of potential effects of invasive plants. We also consider the need to interpret the results of such observational studies in the context of relevant experimental observations, hypotheses and conceptual frameworks (e.g. ecological stoichiometry and mass balance of nutrient cycles). Then, we briefly discuss the relevance of this "tale of two studies" for land management and for observational studies of other invasive shrubs.

4.1 | Why is buckthorn abundance correlated with soil properties in one study and not the other?

The lack of strong relationships with buckthorn abundance in the Illinois-study (Iannone et al., 2015) might be explained by limitations of its sampling strategy and statistical analyses. In forests, soil texture and element pools are known to be highly variable spatially,
even over distances of 1–5 m (Garten, Kang, Brice, Schadt, & Zhou, 2007; Loescher, Ayres, Duffy, Luo, & Brunke, 2014; Schöning, Totsche, & Kögel-Knabner, 2006). Thus, for the buckthorn gradient in Illinois, collection of a single soil core per plot likely resulted in high sampling error and low accuracy of each plot’s measured soil properties. This high potential sampling error within plots would
translate into high uncertainty in the estimated differences between “invaded” and “uninvaded” plots (the dependent variable in that study’s regression models). The mismatch in spatial scales of soil and vegetation sampling in the Illinois-study could also hinder detection of a relationship between soil properties and buckthorn abundance; vegetation was characterized in a 100 m² area surrounding each 6 cm diameter soil core (0.03 m²). Further, by selecting plots within a large study area (5,500 km²) “without considering differences in plant communities or soils” between pairs of invaded and uninvaded plots, the authors of the Illinois-study expanded their scope of inference, but also increased the chance that each pair of plots differed with respect to other factors that influence soil biota and nutrients (e.g. soil texture, the composition of overstorey tree species, disturbance history). Without predictor variables that account for these other differences among plots, this sampling strategy would further reduce the ability to detect correlations between buckthorn abundance and the pair-wise differences in soil properties between invaded and uninvaded plots. For example, theory and observations suggest impacts of plants on ecosystems are proportional to their abundance (Grime, 1998; Laughlin, 2011; Vile, Shipley, & Garnier, 2006); thus, effects of subdominant plants such as buckthorn are likely difficult to detect without accounting for spatial variability in the presence and abundance of overstorey tree species, which have unique traits and corresponding impacts on soils (e.g. Mueller et al., 2012, 2016). Similarly, pre-existing variability in soil texture and pH, which strongly influence nutrient pools and biota (Fierer, Strickland, Liptzin, Bradford, & Cleveland, 2009; Hassink, 1997), could easily mask impacts of invasive shrubs on nutrients and biota (e.g. earthworms) in soils.
4.2 | How should correlations between invader abundance and ecosystem properties be evaluated and interpreted?

While other authors have highlighted the need to cautiously interpret the causality of correlations between invasive plant abundance and ecosystem properties and to consider potentially confounding factors that could pre-date and covary with invasive abundance (Kumschick et al., 2015), few authors have provided specific recommendations for the design and analysis of observational studies. We advocate for measuring relevant predictor variables (i.e. covariates) and using multiple regression, path analysis, or ANCOVA as a means to assess whether apparent effects of invasive plants are statistically independent of the effects of those additional predictors. In our study, the abundance of buckthorn was significantly correlated with both nutrient cycling and earthworm abundance even after accounting for effects of additional predictors that strongly influence those ecosystem properties. Those relationships could still be confounded by unmeasured factors, such that our conclusions remain tentative without experimental verification. However, when combined with a well-documented history of site-level land management and disturbance, our use of predictors related to soil texture, overstorey composition and plant productivity lend greater credence to the hypothesis that buckthorn can alter nutrient cycles and soil biotic communities.

It is also critical to consider the extent to which such correlations are consistent with hypotheses and conceptual frameworks that are grounded in ecological theory and experiments (Hulme et al., 2013; Ricciardi et al., 2013), such as ecological stoichiometry or mass balance of nutrient cycles. Common buckthorn and other invasive shrubs in North America, such as Frangula alnus and Lonicera spp., are known to have high concentrations of nutrients in their leaves and leaf litter (Jo et al., 2014, 2016; McNeish & McEwan, 2016; Figure S1) and many experiments show that plants with such
traits have unique impacts on soil biota and nutrient cycles (Curry & Schmidt, 2007; Lee et al., 2017). For example, both experimental observations and theory related to ecological stoichiometry show that soil biota such as earthworms should achieve greater growth and population size when consuming litter that better matches their own nutrient stoichiometry (Hobbie et al., 2006; Ott et al., 2014), such as calcium-rich buckthorn litter (Figure S1). Thus, after consideration of ecological theory and results from experiments and observational studies, it is more plausible to conclude that buckthorn and similar invasive shrubs impact earthworm populations and nutrient cycles (e.g. this study) than to conclude that there is no impact of invasion (e.g. Iannone et al., 2015).

A mass balance approach can provide additional support for the impact of buckthorn on nutrient cycles and yield insights into the mechanisms of impact. If, as we observed, the presence and abundance of buckthorn do not diminish the total leaf litterfall flux or the nutrient content of litterfall from other plants (Figure 2; Figure S2), then the mere presence of dense buckthorn stands with nutrient-rich litter is evidence of altered nutrient cycling. In fact, we showed that the concentrations of N and K in litter of other species were positively correlated with buckthorn abundance (Figure S2); this suggests buckthorn invasion could influence nutrient uptake of co-occurring species or that translocation of nutrients from buckthorn litter to other litter might occur after leaf senescence (i.e. during early stages of litter decomposition). The apparent enhancement of N and K fluxes from leaf litterfall to soil in buckthorn stands (Figure 2) is perhaps facilitated by another unique trait of buckthorn as compared to co-occurring neighbours: the early leaf-out and late leaf senescence of buckthorn, a phenological trait it also shares with other invasive shrubs in North America (Fridley, 2012). This could facilitate nutrient uptake during a time when other plants are dormant and potential for nutrient leaching is thus higher (sensu Smith, Fridley, Goebel, & Bauerle, 2014). Enhanced nutrient retention in plots invaded by buckthorn is also consistent with the positive correlations between buckthorn abundance and root biomass (Figure 3). Finally, by comparing the magnitude of apparent buckthorn effects for the N flux through leaf litter (+ nearly 1 g m⁻² year⁻¹ in the most invaded plots; Figure 2) and the N pool in shallow soils (+c. 100 g/m²; Figure 1), it is evident that the large effect of buckthorn on soil N is unlikely to be fully explained by increased plant uptake of mineral N and the corresponding increase in organic N inputs to soil through litterfall. This difference in apparent effect sizes suggests buckthorn could alter another pathway of N flow into or out of soils, such as associative N-fixation, as suggested by Ewing et al. (2015), or incorporation of N from the forest floor into mineral soils due to increased earthworm abundance (Figure 3; Frelich et al., 2006). Such insights are only possible in studies that assess multiple, interrelated aspects of ecosystem function; thus, we second the recommendations of Hulme et al. (2013) and Eviner et al. (2012) that observational studies of invasive impacts should aim to measure several related response variables (e.g. not just soil nutrient pools but also the nutrient fluxes into and out of soils).

4.3 | What are the implications for buckthorn management?

Although observational studies cannot determine causality, speculation is required to inform land management. For example, if, the correlation between high nutrient availability and buckthorn presence or abundance is mostly indicative of a positive response of buckthorn to pre-existing gradients in soil fertility (Iannone et al., 2015), then land managers could efficiently anticipate and mitigate buckthorn invasion by monitoring and managing sites with nutrient-rich soils. Yet, this strategy would fail if the impacts of buckthorn abundance on soil fertility are greater than the impacts of soil fertility on buckthorn invasion and abundance, as seems likely from our study. Further, if buckthorn invasion increases nutrient retention, its removal might be less beneficial in riparian areas or ecosystems with high rates of nutrient leaching.

4.4 | A broader consideration of observational studies

As noted by Iannone et al. (2015), other observational studies of the potential impacts of common buckthorn invasion are difficult to interpret because of uncertainty regarding causality (Ewing et al., 2015; Heneghan et al., 2006; Heneghan, Steffen, & Fagen, 2007; Knight, 2006). This uncertainty is also common in observational studies of similar invasive shrubs, including F. alnus (Stokdyk & Herrman, 2016) and Lonicera spp. (Collier, Vankat, & Hughes, 2002; Hartman & McCarthy, 2008; Kolbe, Townsend-Small, Miller, Culley, & Cameron, 2015; Kuebbing, Classen, & Simberloff, 2014; McEwan, Arthur, & Alverson, 2012). Like the majority of research on common buckthorn, none of these studies used covariates to account for additional ecological factors (e.g. soil texture, overstorey community composition) when assessing the effects of an invader’s abundance. One exception is a study by Frappier, Eckert, and Lee (2003); consistent with the approach we advocate, those authors showed the abundance of F. alnus was negatively correlated with the diversity and abundance of native understory plants, even in multiple regression models that included soil pH, soil texture, canopy cover and basal area of overstorey tree species. However, the low R²-values of their regression models (.19–.28) suggest some key predictors were not included.

5 | CONCLUSIONS

Recent meta-analyses and reviews simultaneously highlight the important role of observational studies in estimating the impacts of invasive plants, particularly woody invaders, while warning of the problems related to causality of observed relationships. By comparing our study of common buckthorn with another recent study with similar aims, but with different design and results, we have provided a theoretical and methodological case that buckthorn is more likely than not to alter nutrient cycling and soil biota. Given the similar traits of buckthorn and other invasive shrubs in North America, this study also bolsters conclusions regarding those focal species (e.g. Lonicera
spp.; McNeish & McEwan, 2016). Future observational studies of invasive plants could be improved by considering the specific methodological strengths and weaknesses of the two studies discussed here, ultimately reducing the uncertainty regarding impacts of invasive plants. We propose that, because both type-I errors (false identification of invasive impacts) and type-II errors (failure to detect invasive impacts) are costly (Mapstone, 1995), designers of observational studies should err on the latter side of the practical trade-off between: (1) the ecological and geographical scope of a study (e.g. the number of plots and sites), and (2) the ability to sufficiently characterize each plot and site, including measurement of covariates that reduce the risk of both type-I and type-II errors when testing the statistical effects of invasive species. Improved observational studies are critically needed to allow land managers to target the most relevant invasive species for eradication and identify strategies for restoration.

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K.E.M. and A.G.L. contributed equally to study design, data collection and analysis and writing; A.M.R. and T.J.S.W. assisted in study design and data collection; S.E.H. and P.B.R. assisted in study design. All authors contributed critically to drafts and gave final approval for publication.

DATA ACCESSIBILITY
Data are available from the Dryad Digital Repository https://doi.org/10.5061/dryad.h3h1n (Mueller et al., 2017).

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