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Non-native plant associations with wildfire, tree removals, and deer in the eastern United States

Abstract

Wildfires, tree removals, and deer herbivory are potential pathways for spread of non-native plants. I modeled the number of recorded non-native plant species by county compared to wildfire area, tree removals, and deer densities in the eastern United States and also eastern forests. Species richness of 1016 plant species in 780 primarily forested counties decreased with increased values of the three variables; models equally showed negative relationships. For model predictions, based on withheld samples of non-native species counts, percentage wildfire area alone had the greatest association (R^2 value of 31%) for non-native species richness in eastern forests; non-native species richness decreased with wildfire area until stabilizing at >1% wildfire area to a neutral relationship. For 1581 species in 2431 counties in the eastern U.S., the three variables each had an overall negative relationship with non-native species richness (R^2 value up to 14%), without a consensus by three regression types of most influential variables. These formal models suggest that wildfire, tree removals, and deer herbivory generally may be nominal pathways for non-native plant spread at landscape scales in the eastern United States.

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1 Introduction

Non-native plant species introductions to new locations, primarily by human vectors, generally continue to increase over time without any indication of saturation (Kerns et al. 2021). One avenue of research involves identifying factors that either facilitate or impede non-native plant spread. Disturbances that increase resource availability and open growing space create opportunities for spread by both natives and non-native species. However, studies testing disturbances of fire, tree removals, and herbivory demonstrate contrasting effects of both increasing and decreasing non-native plant richness (i.e., number of species) in response to disturbance (Parker et al. 2006; Alba et al. 2015; Abella and Springer 2015).

Fires, and associated fire management such as clearings for fire lines and lanes, create openings that are favourable for the spread of non-native species, while equipment for either prescribed burns or wildfire suppression may transport invasive species to disturbed sites. A global meta-analysis summarized that wildfires favoured composition and performance of non-native plants, while reducing performance of native plants; these effects were more pronounced in certain ecosystem types, including temperate forests (Alba et al. 2015). Conversely, prescribed fires benefited native plant composition over short time scales, but effects were neutral in temperate forests and grasslands (Alba et al. 2015). In the eastern United States, invasion by some non-native species increases with fire severity (Black et al. 2018). Fire characteristics may produce different effects because wildfires tend to disturb vegetation cover more severely than prescribed fires. In the U.S., low severity surface fires were frequent historically until fire exclusion after Euro-American settlement (Abrams et al. 2022). Although fire exclusion currently is effective in reducing large (≥ 200 ha) wildfires in the eastern U.S., tree densities have increased, which amplifies the potential for severe fires (Hanberry 2020). Humans have ignited wildfires since arrival to the continent; earliest systematic, national reports document < 5% of fires were attributed to lightning in the eastern U.S. during years 1915–1920 (USDA Forest Service 1920) and most recent wildfires likewise were started primarily by humans (Balch et al. 2017).

Tree removals and associated silvicultural operations create openings and disrupt vegetation cover and soil during construction of roads, skid trails, and landings. Plant propagules may be introduced via contaminated equipment. For 41 studies in the western U.S. and Canada, although tree removals and prescribed fire in combination resulted in the greatest increase in non-native plant richness and cover, non-native richness and cover remained minimal (Abella and Springer 2015). In the eastern U.S., tree removals were an important predictor of non-native plant species invasion (Eschtruth and Battles 2009), but tree removals primarily may increase non-native plants that are not invasive species along with native species (Belote et al. 2008).

Vertebrate herbivores reduce native plant biomass, disrupt vegetation cover and soil, and play a critical role in seed dispersal through digestion, or endozoochory, and also surface attachment, or epizoochory. In two meta-analyses, native vertebrate herbivores obstructed invasion by non-native plant species (Levine et al. 2004; Parker et al. 2006). Nonetheless, white-tailed deer (*Odocoileus virginianus*), which is the last remaining native large herbivore located throughout the eastern U.S. and particularly at greater densities within forests (Means 2006; Hanberry 2021a), may enable non-native plant invasion. Based on 23 study sites, deer indirectly increased the proportion of non-native plants via their negative influence on native plants (Averill et al. 2018). Conversely, about the same number of studies have reported neutral or mitigating effects on plant invasion by deer (Averill et al. 2018). Herbaceous vegetation but not woody vegetation is tolerant of herbivory, according to a meta-analysis of North American deer effects on vegetation (Habeck and Schultz 2015).

Due to conflicting results of both increasing and decreasing number of non-native plant species in response to disturbances detected by stand-scale studies in the eastern U.S., another approach is to model relationships between number of non-native plant species and disturbances at multi-regional scales (i.e., 1 and 4 million km^2). I formally modelled non-native plant species richness compared to wildfire area (excluding prescribed fires due to neutral or positive benefits for native plants; Alba et al. 2015), tree removals, and deer densities by county in the eastern half of the United States. Additionally, I separately modelled associations only in eastern forests, where these disturbances increase in severity due to flame lengths extending into tree canopies and greatest tree removals and deer densities within forests. My objectives were to address the following questions: 1) What are the spatial patterns of number of non-native plants, percentage area of wildfires, tree removals, and deer densities in eastern forests and the entire eastern U.S.? and 2) What is the relationship between number of non-native plants and the disturbance variables of percentage area of wildfires, tree removals, and deer densities in eastern forests and the entire eastern U.S.? Although correlative, multi-regional models will contribute to the weight of evidence about whether these disturbances on balance impede or facilitate non-native plant spread. To my knowledge, this approach of complete coverage has not been employed to examine overall relationships of disturbances to non-native plant species richness as an alternative to meta-analyses for stand scale studies, which typically contain inconsistencies in comprehensive coverage, such as imbalanced study locations.

2 Materials and Methods

2.1 Study area

Study extents included both the entire eastern U.S., a 3.9 million km^2 extent, and also eastern forests only, a 1.2 million km^2 extent (Figure 1). Because of the large extents, a range of values and distributions in land cover, climate, topography, and soils occurs. Land cover for the eastern U.S. was 35% forest, 25% crops, 20% herbaceous vegetation primarily pasture, 10% wetlands, and 10% developed (2016 land cover; Homer et al. 2020). Mean annual temperature ranged from 0.7 to 25 °C (PRISM Climate Group 2022). Total annual precipitation ranged from 450 to 2320 mm (PRISM Climate Group 2022). Soils primarily were ultisols, alfisols, and mollisols (NRCS 2022).

2.2. Number of non-native plants by county for maps, summaries, and models

I determined number of non-native plants per U.S. county from recorded non-native species occurrences in the EDDMapS database, which is suited for county-scale analysis (Center for Invasive Species and Ecosystem Health 2020). For the EDDMapS database, non-native species occurrences were aggregated from databases, organizations, as well as citizen observers, resulting in a variety of collection methods, but often summarized by county, with > 6.6 million county records and > 5.3 million point records. Survey effort is unknown and may increase with human population densities; nonetheless, in balance, remote counties may be larger in area. Adhering to Gavier-Pizarro et al. (2010), I did not correct for area, because species richness and county area for the eastern half of the United States and eastern forests did not have a relationship (R^2 values of 0% for random forests and extreme gradient boosting regressors and 2% and 9.5%, respectively, for the cubist regressor; please see modelling information below).

2.3 Disturbance variables by county for maps, summaries, and models

Regarding disturbance variables, for percentage area of wildfire, I summed area burned per county during years 1992–2015, from the fire occurrence database of about 2 million geo-referenced wildfire records (Short 2017), and then relativized to percentage area by county. Tree removals, including harvest, by county were available at USDA Forest Inventory and Analysis Evalidator (USDA Forest Service, Forest Inventory and Analysis Program 2021) as mean annual removals of sound bole volume of trees (≥12.7 cm diameter; these values are densities at cubic meters/ha by county) for the latest complete inventory cycles, which typically occur during five years and vary by U.S. state. For white-tailed deer densities, I determined the mean density for each county based on deer density categories (1.85 deer/km^2 for the low density class, 5.8 deer/km^2 for the moderately low density class, 11.6 deer/km^2 for the moderately high density class, and 17.4 deer/km^2 for the high density class) for distributions from 2001 to 2005 (Adams et al. 2009; Hanberry and Hanberry 2020).

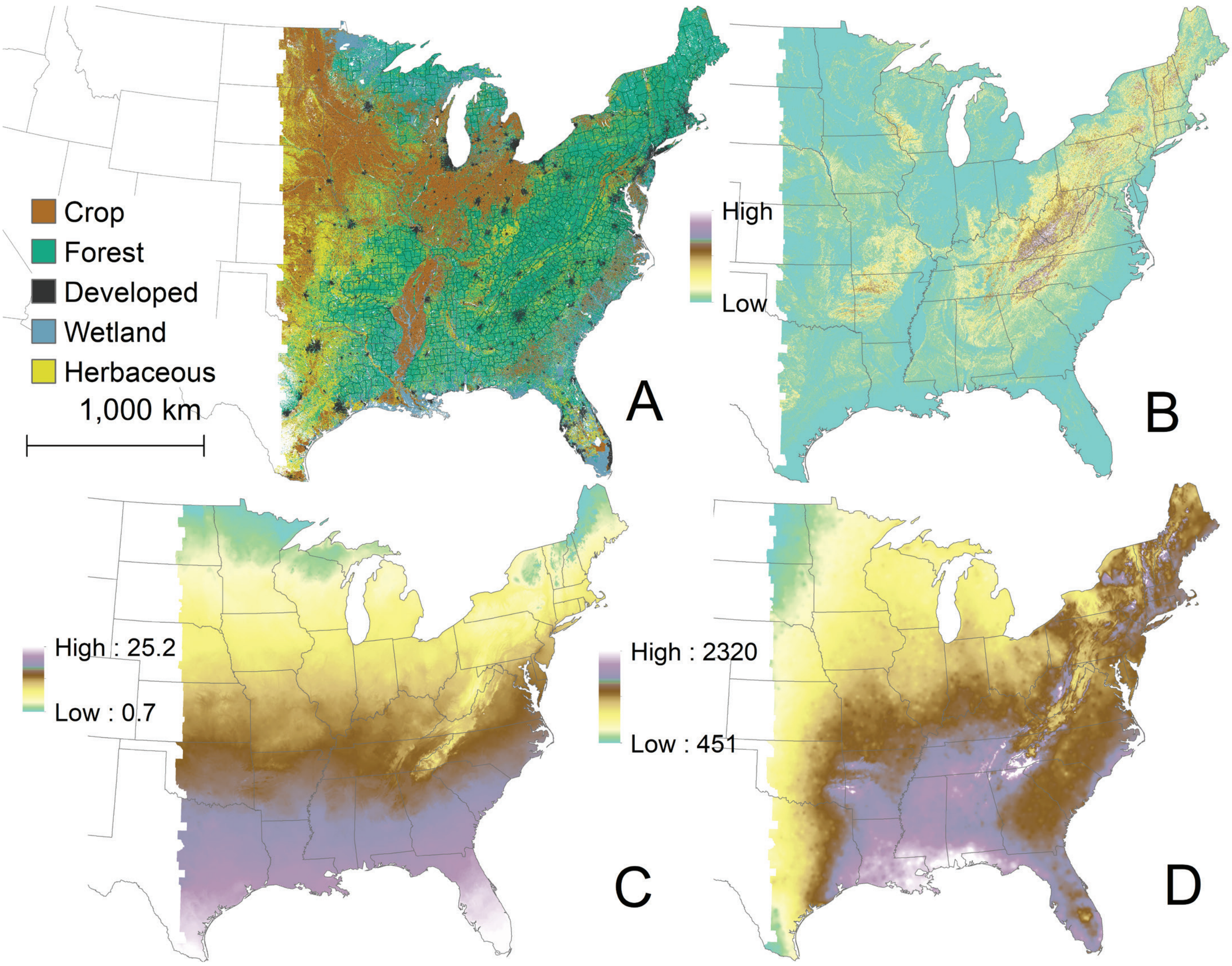

Figure 1. The study extents of the eastern U.S. and eastern forests (green) with land cover classes (A; 2016 land cover; Homer et al. 2020), topographic roughness (B; smaller values equal flatter areas with less topographic difference; Amatulli et al. 2020), mean annual temperature (C; °C; 1991–2020; PRISM Climate Group 2022), and total annual precipitation (D; mm; 1991–2020; PRISM Climate Group 2022).

2.4 Summarizing number of non-native plants by disturbance variables in eastern forests

To isolate eastern forests due to the specific, forest-centred nature of the disturbances, I selected 780 counties with percent area of forest ≥50% of all wildlands, where vegetation cover was ≥50% of land area (2016 land cover; Homer et al. 2020). There were not enough samples to accurately model forest subdivisions by forest type or region. To characterize eastern forests, I compared non-native plant species richness in low and high values of the predictor variables, according to approximately equal division of number of counties for percentage wildfire area and tree removal and the threshold for deer damage. For percentage wildfire area, the threshold between low and high values was 0.6. For tree removal, the threshold between low and high values was 1.25 cubic meters/ha. For deer densities, the threshold between low and high values was 5.8 deer/km^2.

2.5 Modelling the relationship of number of non-native plants to disturbance variables in the two study extents

Modelling the relationship of number of non-native plants to disturbance variables involved many repeated steps. I modelled the relationships within eastern forests and within the eastern U.S. Within each of the two study extents, I modelled the rela-

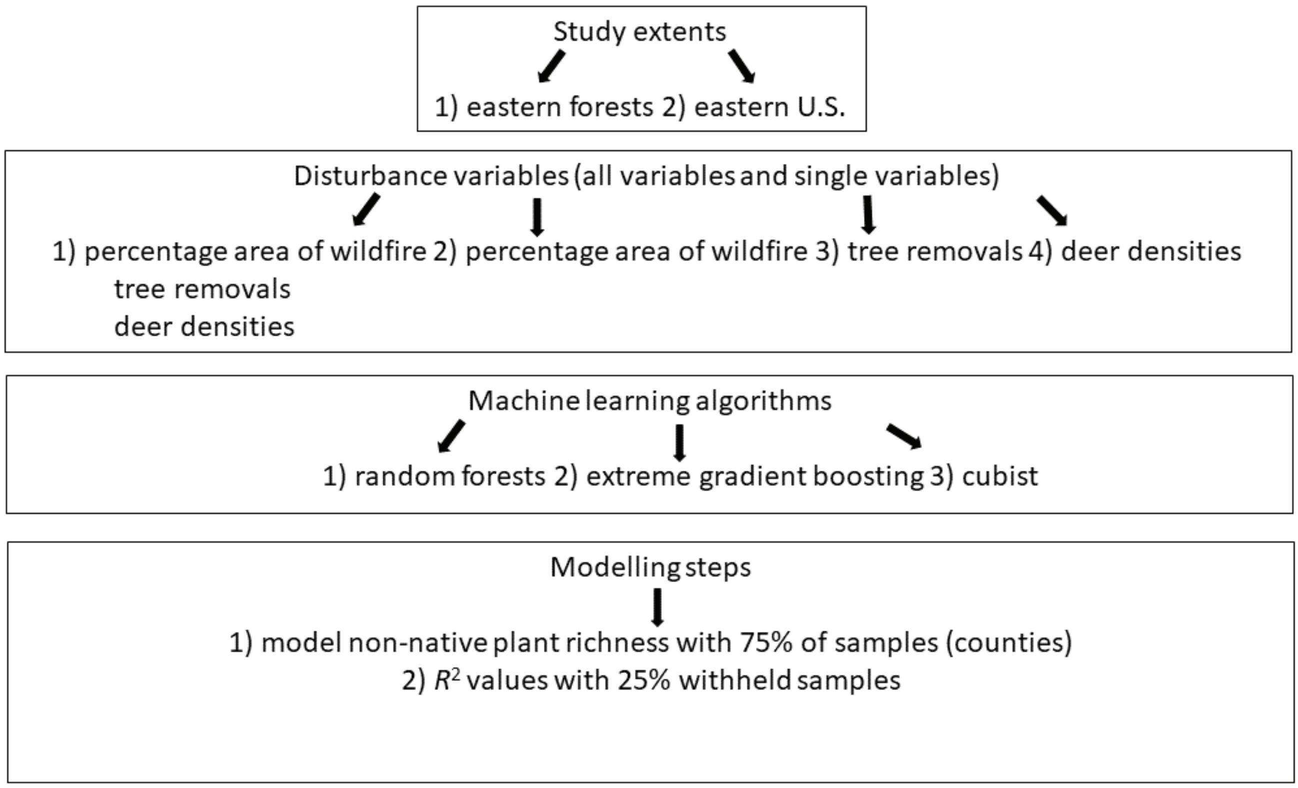

Figure 2. Flow chart of methods steps.

tionships between number of non-native plants to all three disturbance variables and each of the disturbance variables alone, a total of four different models for each study extent. For each study extent and the four disturbance variable options, I applied three different regressor algorithms. The modelling itself was subdivided into development of a model and then determination of R^2 values using withheld samples. For example, the first model was for eastern forests, all variables, and the random forests regression type, followed by determining R^2 values for predicted count of non-native plants with the model using withheld samples.

To model the spatial relationship between the predictor variables and non-native plant species richness in eastern forests and the eastern U.S., I applied three ensemble machine learning algorithms of random forests, extreme gradient boosting, and cubist regressors in the caret package (Figure 2; Kuhn 2008; R Core Team 2021). Ensemble learning methods aggregate results of many decision trees or rule-based models to output the most optimal result, helping to minimize the influence of error. Each algorithm will have different approaches for modelling (e.g., Khaledian and Miller 2020; Zhang et al. 2021). For example, the random forests regressor runs models in parallel (i.e., bagging) and averages results to reduce variance (i.e., overfitting). The extreme gradient boosting and cubist regressors run models in sequence (i.e., boosting) to increase the weight of better models and reduce bias. Extreme gradient boosting has a modification to prevent overfitting of conventional gradient boosting. The cubist regressor is unique in creating a linear regression for each data subset of each decision tree. I trained each model with 10-fold cross-validation and then I determined R^2 values for predicted count of non-native plants using the model of the explanatory variables on 25% of samples that were withheld from modelling (e.g., 25% of 780 counties). Lastly, I repeated the process with single variables. To display the sign (i.e., negative or positive) of predictor variable relationships with non-native species richness, I displayed partial plots for the strongest models (Greenwell 2017).

3 Results

For spatial patterns, non-native plant species richness in the eastern half of the U.S. overall was less abundant in the central agricultural and grassland interior and the southeastern forested region (Figure 3). The percentage area of wildfire was greatest in these regions (Figure 4), indicating that this variable will have an inverse relationship with non-native species richness. In comparison, the southeastern U.S. had the greatest forestry disturbance, due to pine plantations, but forestry disturbance was less common in the non-forest agricultural and grassland interior (Figure 5). Equally, deer densities were greater in the southeastern region, along with parts of the northern region, but less common in the agricultural and grassland interior (Figure 6). These spatial patterns suggest weak potential relationships with non-native plant species richness.

Summarizing non-native species richness in relation to disturbances in eastern forests, the non-native plant dataset had 1016 unique species or subspecies in 780 U.S. counties. Based on thresholds of disturbance values, non-native plant species richness decreased with greater percentage of wildfire area,

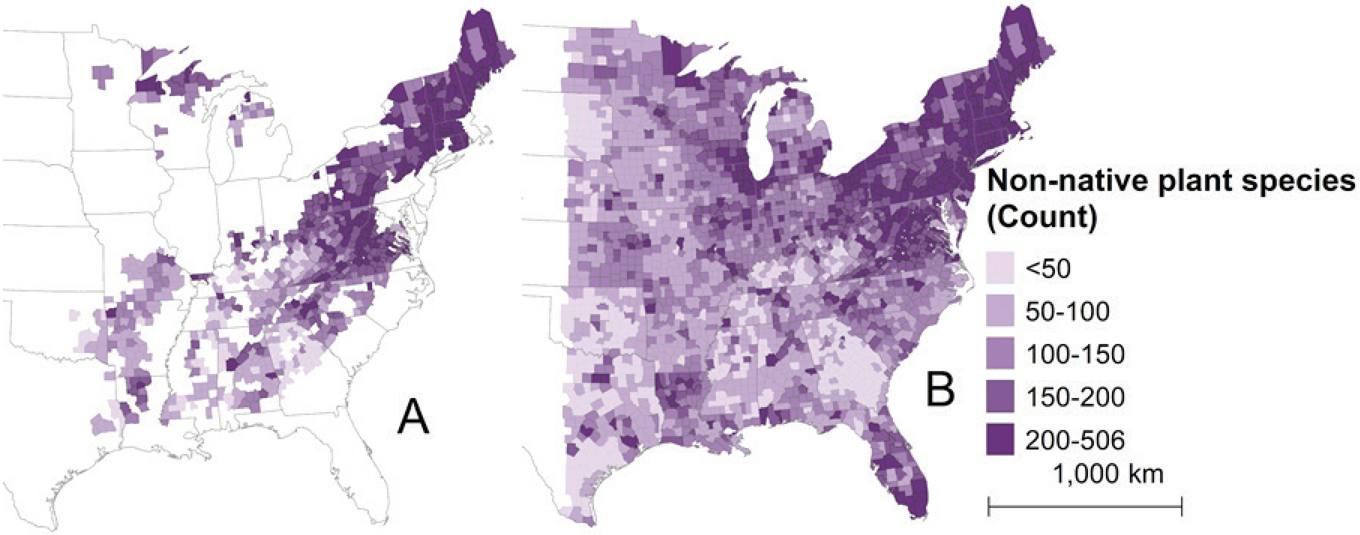

Figure 3. Recorded number of non-native plant species (EDDMapS database; Center for Invasive Species and Ecosystem Health 2020) by county in eastern forests (A) and the eastern United States (B).

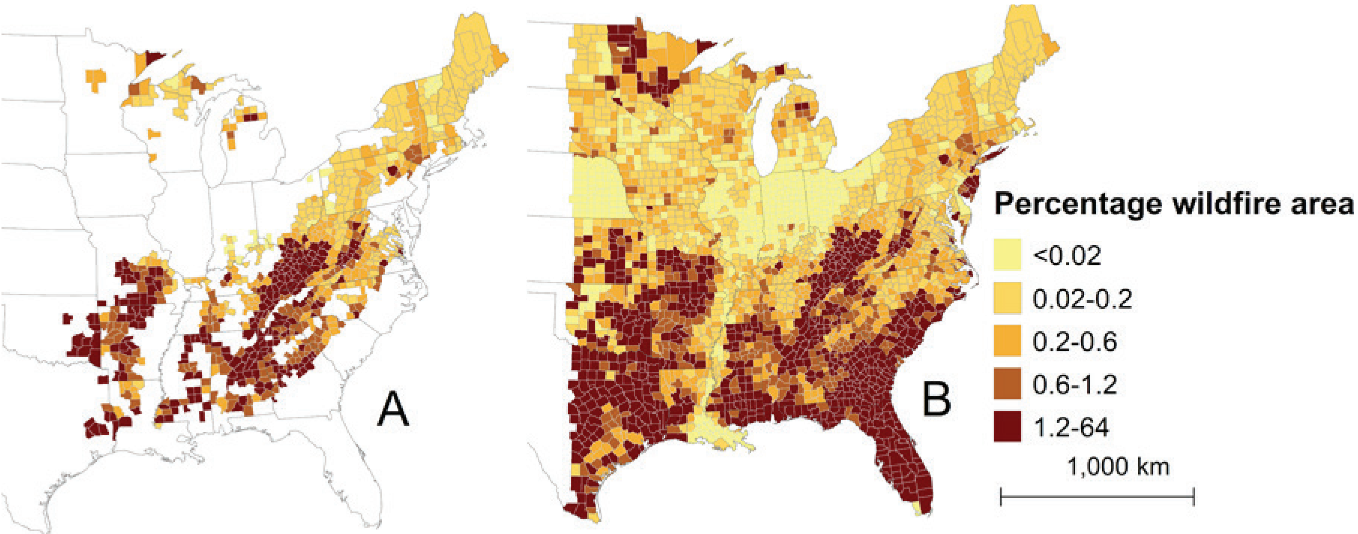

Figure 4. Percentage wildfire area (fire occurrence database; Short 2017) by county in eastern forests (A) and the eastern United States (B).

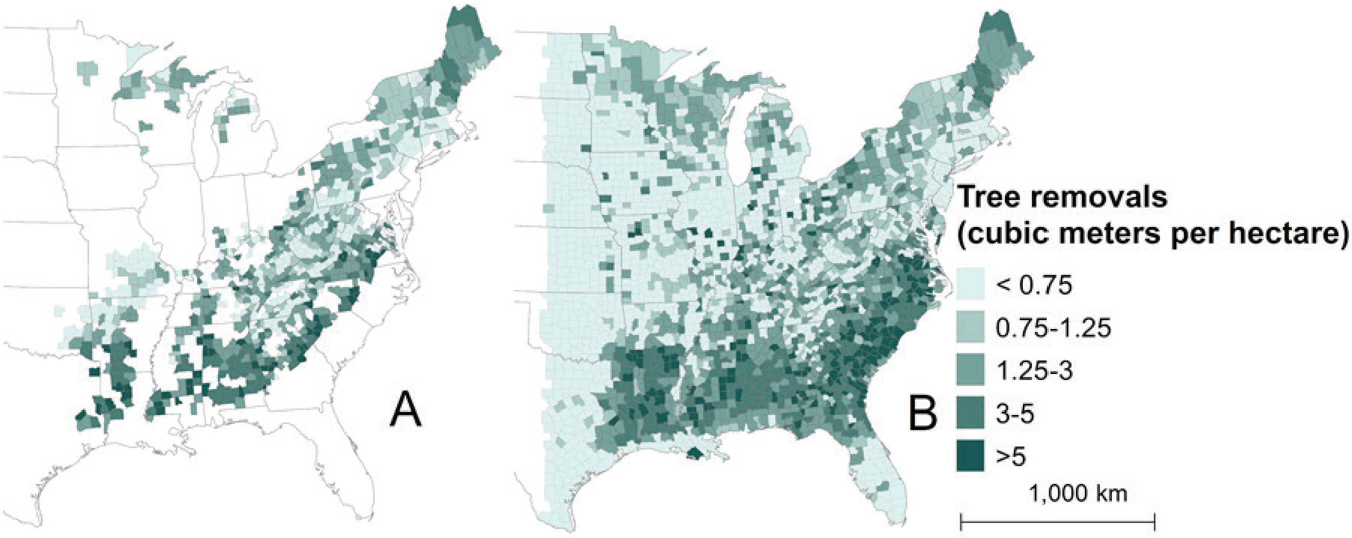

Figure 5. Average annual volume of tree removals (≥12.7 cm diameter; cubic meters/ha; Evalidator database; USDA Forest Service, Forest Inventory and Analysis Program 2021) by county in eastern forests (A) and the eastern United States (B).

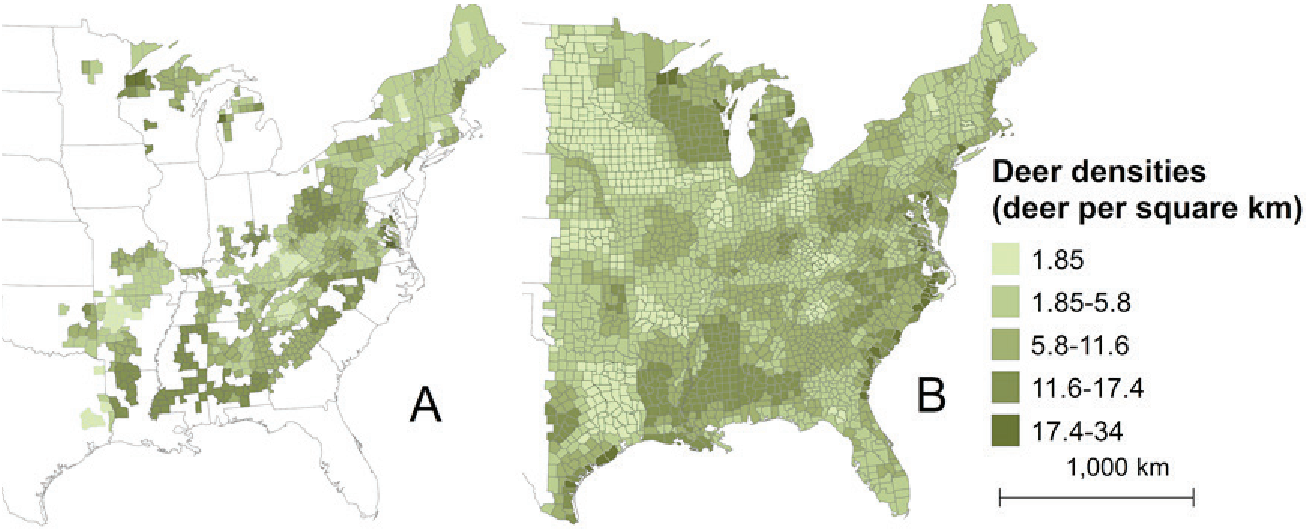

Figure 6. Deer densities (deer/km^2; Adams et al. 2009; Hanberry and Hanberry 2020) by county in eastern forests (A) and the eastern United States (B).

from 167 non-native plants at the lesser wildfire area (in 389 counties) to 95 non-native plants at greater wildfire area (391 counties). Non-native plant species richness decreased with greater tree removal, from 146 non-native plants at the lesser density (in 376 counties) to 117 non-native plants at greater density (404 counties). Non-native plant species richness decreased with greater deer density, from 139 non-native plants at the lesser density (with 325 counties) to 125 non-native plants at greater density (455 counties).

In modelling of eastern forests, R^2 values for percentage fire area alone was similar to R^2 values for the three variables combined; R^2 values ranged from 15% (extreme gradient boosting regressor) to 31% (cubist regressor; for predictions of withheld observations of non-native species richness based on models of disturbance variables; Table 1). The single variables of tree removal and deer densities had little influence, with R^2 values ranging 0% to 5%. For the eastern half of the U.S., the three variables combined had R^2 values of 11% and 14%, depending on the regressor (for predictions of withheld observations of non-native species richness; 1581 unique species or subspecies in 2431 U.S. counties; Table 1). Although there was not a consensus of most influen-

Table 1. Most important variables, importance value, and R2 (predictions of withheld samples) for random forests, cubist, and extreme gradient boosting models of non-native plant richness in eastern forests and the eastern United States.

random forests			cubist			extreme gradient boosting		
	value	R^2		value	R^2		value	R^2
eastern forests all variables								
wildfire area	100	0.23	wildfire area	100	0.30	wildfire area	100	0.15
deer density	9		tree removals	11		deer density	19	
tree removals	0		deer density	0		tree removals	0	
eastern forests single variables								
wildfire area		0.18	wildfire area		0.31	wildfire area		0.15
tree removals		0.00	tree removals		0.05	tree removals		0.00
deer density		0.01	deer density		0.01	deer density		0.01
eastern U.S. all variables								
deer density	100	0.14	wildfire area	100	0.14	deer density	100	0.11
wildfire area	91		tree removals	100		wildfire area	68	
tree removals	0		deer density	0		tree removals	0	
eastern U.S. single variables								
deer density		0.01	deer density		0.02	deer density		0.01
wildfire area		0.01	wildfire area		0.08	wildfire area		0.02
tree removals		0.00	tree removals		0.03	tree removals		0.00

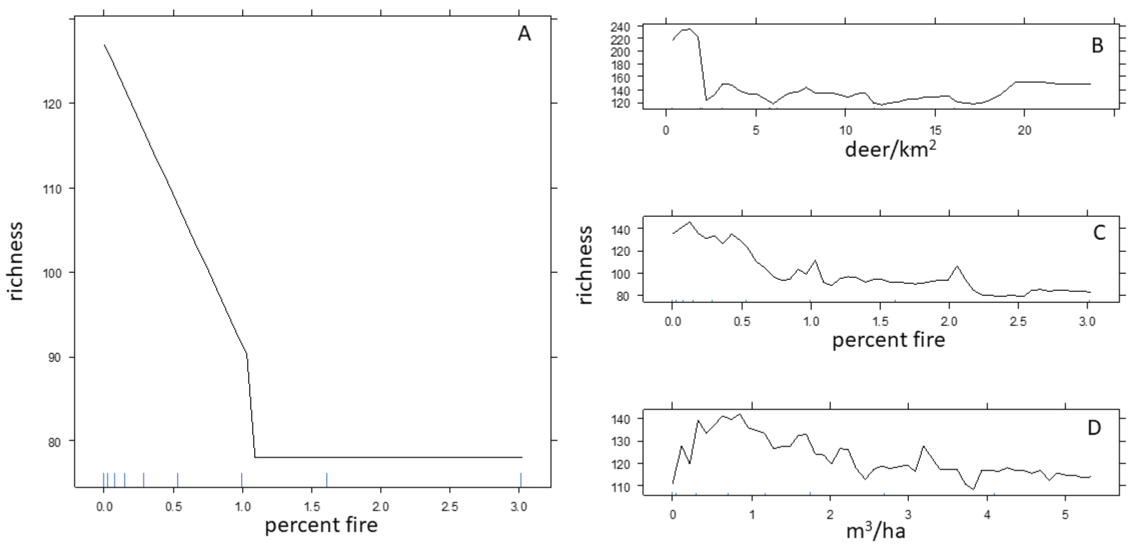

Figure 7. Partial plots that display the strongest modeled relationship in eastern forests between non-native plant richness and percentage wildfire area (A), and in the eastern United States between non-native plant richness and deer density (B), percentage wildfire area (C), and tree removals (D). Additional x-axis tick marks indicate the deciles of the predictor distributions.

tial variables by the three regressors, the percentage wildfire area variable alone generated the strongest yet slight relationship (R^2 value = 8%, with the cubist regressor).

Partial plots displayed overall negative relationships between non-native species richness and the three variables (Figure 7). In eastern forests, the strongest relationship was between non-native plant richness and percentage wildfire area; the relationship was negative for a small percentage of area (≤1%) and after that threshold, the relationship levelled to a flat line of about 80 non-native species, with no numerical response regardless of percent wildfire area. Non-native species richness increased with tree removals at very low values for tree removal and with deer densities at very high values for deer densities in the eastern U.S.

4 Discussion

This comprehensive approach to determine whether non-native plant species richness is associated with wildfire, tree removals, and deer densities in the entire eastern U.S. and eastern forests helped support stand studies that found limited relationship between non-native species richness and disturbances. Of the three variables, wildfire had the strongest association with non-native species richness in eastern forests (up to R^2 = 31% for the cubist regressor), but non-native species richness decreased as percentage fire area increased up to a small percentage of area (≤1%) and then the relationship did not change, regardless of the percentage area of fire. Fire in the eastern U.S. and tree removals and deer densities in eastern forests and the eastern U.S. had negligible associations (R^2 = 0% to 8%) with the number of non-native species. Therefore, non-native species richness does not appear to increase with wildfire, tree removals, and deer densities at landscapes scales in the eastern U.S. These overall, multi-regional results corresponded with Moles et al. (2012), who determined through a global meta-analysis that disturbance was a weak predictor of invasion.

Considering wildfire is only one of many disturbances, wildfire area had a relatively strong association with non-native species richness in eastern forests. The modelled fire variable specifically was wildfire and not prescribed burns because Alba et al. (2015) found that wildfires favoured non-native plants, while prescribed fire effects were neutral in temperate forests and grasslands. Additionally, prescribed burns are most common in the southeastern U.S. where non-native plant species richness is low. Wildfires may be relatively comparable to prescribed burns in the eastern U.S. due to less extreme fire weather than in other locations. In these models, wildfire generally had a neutral relationship with non-native plant richness, but with a beneficial negative relationship at low percentage areas, similar to prescribed burns. Because such a small areal extent affected by wildfire may not be influential in reducing non-native invasive plant spread, the correlation may simply be a coincident reflection of spatial patterns in non-native species richness rather than a biologically meaningful relationship. In any event, non-native species richness does not appear to increase with wildfire area at landscapes scales in the eastern U.S.

Fire is one mechanism for controlling some plant species increases. Fire directly removes fire-sensitive plant species and favours plants that respond to fire, such as by germination after fire or smoke exposure or by greater survival, growth, and reproduction under open conditions (Zouhar et al. 2008). Fire promotes biotic resistance to invasion through increasing competitiveness for growing space by native fire-dependent species in regions that historically had frequent surface fire regimes. Prior to disruption of historical land use and disturbances by Euro-American settlement, most of the eastern U.S. experienced frequent surface fire. Fire frequency increases with the amount of herbaceous vegetation, and fires particularly were frequent in both in the southeastern and central interior regions, which at least historically were grasslands or open forests with an understory of grassland plants (Hanberry et al. 2020). Fires along with high herbaceous plant richness, and perhaps greater herbicide applications than other regions, may be providing protection from invasion to the southeastern and central interior U.S. Alternatively, these less-populated regions may have fewer recorded non-native plant species than other regions due to relatively reduced number of point sources of propagules, which often are spread deliberately through human agency.

Tree removals and deer densities did not have any relationship with non-native species richness according to this comprehensive approach. Both tree removals and deer browsing remove established vegetation, allowing propagules that are present to establish. One study in the eastern U.S. showed that the interaction between canopy disturbance and propagule pressure was most important for determining forest invasibility relative to other potential factors (Eschtruth and Battles 2009), but based on another study in the eastern U.S., tree removals primarily increased non-native plant species that were not invasive and also increased native species (Belote et al. 2008). For 23 sites in the eastern U.S., Averill et al. (2018) determined that deer indirectly increased the proportion of non-native plants by their negative influence on native plants, but in other meta-analyses, Levine et al. (2004) and Parker et al. (2006) determined that native vegetation coexisted better than non-native vegetation with native herbivores.

Non-native species richness, wildfires, tree removals, and deer densities are non-stationary in time and space, so that associations, or lack thereof, may not be stable. One aspect of disturbance is whether frequency and severity are within the historical range of variation that ecosystems can tolerate and may require for maintenance (Moles et al. 2012). Under historical disturbances, native species persisted but did not expand and increase because both disturbances and biotic interactions maintained ecosystems (Hanberry 2021b). However, in the U.S., many ecosystems have departed from pre-Euro-American states; therefore, departure in disturbance to new land use disturbance may be appropriate for the newly assembled ecosystem, which also encompasses non-native species. Non-native species richness has been increasing since Euro-American settlement and the non-native species that seemingly are benign now may become more abundant as propagule pressure exceeds a critical threshold or conditions such as climate changes. Surface fires were common until changes led to fire exclusion by approximately the 1920s (Hanberry 2021b); fires may become more frequent and severe due to fuel accumulation during recent decades. Deforestation occurred by the 1920s, in conjunction with Euro-American settlement, and for example, pine plantations, with attendant frequent tree removals, have become consistently more abundant since the 1950s (Hanberry 2021c). Deer densities equally decreased with Euro-American settlement and likely have returned to relatively equivalent to historical densities during recent decades (Hanberry and Hanberry 2020).

As opposed to number of non-native species, invasiveness and impact may be better registered by non-native plant cover or other relevant abundance metric, and accordingly, the amount of growing space taken from native plants (Pearson et al. 2016). Some non-native species may realize widespread distributions, but not achieve great enough local abundance to have measurable effects on native species, even cumulatively in combination with other minor non-native species. If disturbances spread one invasive plant that dominates growing space at the expense of native species, that may be more harmful than lack of association between disturbances and numerous non-native plants. Or alternatively, if these disturbances at high severities ultimately reduce rather than promote native plant cover, then biotic resistance may be lowered. Indeed, Averill et al. (2018) determined that white-tailed deer did not increase non-native plant richness or cover but increased the relative cover of non-native plants indirectly by reducing native cover in the eastern U.S.

Varying effects at different severities and scales may in part explain why disturbances overall may be relatively weak predictors of non-native species richness and cover. The influence of fire, tree removals, and herbivory disturbances on non-native plants may depend on the ecological context, which in this case is at landscape scales. The extent of disturbance affects resource availability, and these disturbances may have only localized influences that do not scale up to landscapes.

Rather than diffuse disturbances, concentrated source points of invasive species likely are more critical invasion pathways (Moles et al. 2012). Greater numbers of non-native species indicate conditions, such as proximity to source points or disturbances, that promote ability of non-native species to establish populations, and consequently an increased probability that some species will be invasive, or impact native species or systems. Colautti et al. (2006) recommended that propagule pressure, rather than complex processes with varying severities, be considered the primary factor for invasion. Source points, such as human population densities and horticultural locations, supply a stream of propagules until reaching the critical number of individuals for sustained spread (Crooks 2005; Simberloff 2009).

4.1 Limitations, future research needs, and management implications

Modulating considerations include the accuracy of the measured variables, even though the data were the best available information at county scales, patterns overall appeared reasonable, and sample sizes were relatively large. Survey effort for non-native species is unknown, but likely to be imbalanced and biased. However, with a different dataset, Allen and Bradley (2016) documented similar species richness patterns. The wildfire data likely have some omissions, although wildfire patterns approximate prescribed burn patterns in the eastern U.S. Deer densities are the best available reports from state wildlife agencies, and densities in some counties may be not accurate, even though relative densities appear to be accurate at landscape scales (Hanberry and Hanberry 2020).

Future research needs include meta-analyses or syntheses of wildfire effects and tree removal effects on non-native plant species richness in the eastern U.S., which appeared to have few studies for these disturbances relative to deer herbivory (Eschtruth and Battles 2009; Black et al. 2018), and other comprehensive landscape studies that help support or counter these results to develop a weight of evidence and regional variation. For multi-species, broad-scale models, different datasets at county scales are one option. It may be possible to locate or develop similar data at finer resolutions at least for smaller extents to model one forest type with consistent fire regimes, tree removals, and deer densities to determine regional effects, rather than overall effects for all eastern forests or all of the eastern U.S.

Furthermore, quantifying the relative importance of other factors but primarily propagule pressure is an important direction for future research. This research direction encompasses the relationship of non-native species to propagule pressure through pathways of source points such as accidental introductions at commerce entry points, deliberate introductions by horticulture, and introductions generally related to human population densities. In terms of measuring management success, it would be interesting to determine if the regions with fewer non-native species also had greater treatment intensity, through herbicide applications. Herbicide applications may be applied more routinely in regions with great percentage of crops (the central interior region) and pine plantations (the southeast region).

Concentration on reducing non-native species introductions rather than these disturbances is the most efficient management plan (Colautti et al. 2006), based on the lack of a link between number of non-native plants and wildfire, tree removals, and deer herbivory. Early intervention strategies ideally prevent non-native species from arriving at new locations and promote rapid detection and control after establishment but before spread (Epanchin-Niell et al. 2010). Invasions occur across international borders regulated by customs and border enforcement agencies and also a series of internal borders maintained by a variety of agencies, representing commerce, transportation, and natural resources. The benefit of a sequence of borders is multiple opportunities to detect and prevent entry, but different regulations, directives, and species lists mean that invasive species pass through borders, sometimes uncontested due to the management burden (Epanchin-Niell et al. 2010).

A management need is compilation of invasive species with a consistent approach into a list of non-native species that cause damage to ecosystems rather than only agricultural interests (i.e., noxious weed lists). Multiple lists of invasive species can serve different purposes. Invasive plants cause damage because they have spread successfully, at which point prevention of entry is not possible. A list of species that cause damage outside of international borders will be most useful for agencies that focus on critical prevention. Another list of invasive plant species that have already entered a country, partitioned within different internal borders, will aid rapid detection and response as the second line of defence. For management at local units, reducing the number of non-native species to primarily invasive species that become dominant components in ecosystems, rather than minor or transient constituents (Blackburn et al. 2011), will increase capacity both to identify and control invasive species on limited budgets with few trained personnel (Epanchin-Niell and Hastings 2010). Partnerships to coordinate efforts, rather than independent development of identification skills, and to share surveillance information will increase capacity to rapidly detect and treat invasive species (Westbrooks 2008).

5 Conclusions

Spatial patterns of non-native species richness overall were not associated with wildfire, tree removals, and deer densities at landscape scales in the eastern United States or eastern forests. Of the three variables, only wildfire had a relatively strong association with non-native species richness within eastern forests (up to R^2 = 31%), but non-native species decreased with a small area of fire and then did not change with increasing area of fire. The finding that these disturbances generally are not related to multi-regional patterns in non-native species richness may suggest these disturbances, in balance, neutralize pathways of non-native species introduction and spread by potentially promoting resistance of native species or deterring invasion of non-native species. Alternatively, these disturbances may have only localized influences that did not scale up to the multi-regional study extents of the eastern U.S. or eastern forests. Research and management implications include a greater focus on non-native species introductions, or propagule pressure, rather than these disturbances, based on the lack of an association between number of non-native plants and wildfire, tree removals, and deer herbivory.

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Declaration of Competing Interest

The author has no conflict of interest.

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