INVASIVE EXOTIC PLANTS OF THE ENO RIVER WATERSHED

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ABSTRACT

Invasive exotic species are an international threat to biodiversity. Management of invasive species is divided into three approaches: prevention of introduction outside of native range; eradication of invasions; and containment and control strategies. Prevention is unfortunately limited by accurate predictions and border control measures which are difficult to implement. Similarly, eradication is made difficult due to the fast acting and aggressive behavior of many invasive species, some of which are naturalized for many years before control measures are implemented. This leaves containment and control as management strategies for many managers today. Land protection groups in the United States including non-profit land trusts and governmental agencies – local to national -- address invasive species on nearly all protected lands. I have consulted with the Eno River Association of Durham and Orange counties in North Carolina to address the management of three invasive plant species of concern: tree of heaven (*Ailanthus altissima*), Chinese privet (*Ligustrum sinense*), and multiflora rose (*Rosa multiflora*). After assembling an observational data set of these three species, I used Maxent, a maximum entropy based machine-learning software, to model the potential distribution of each species within the Eno River watershed. Distributions of all three species were best predicted by soil type and distance to rivers. Properties of the Eno River State Park master plan -- a land protection priority list for the Eno River Association and the Eno River State Park -- were analyzed and ranked for the total area and the percent coverage of invasive plants from the modeled distributions.
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INTRODUCTION

Invasive exotic species are a major threat to biodiversity (Pimm et al. 1995, Wilcove et al. 1998). Whether by intentional introduction or accidental escape, many invasive species significantly alter the communities they enter by out-competing native species for resources and changing the physical environment by altering soil chemistry, water balance, or other features. Not only that, but the rate of invasions rises globally as humans travel more extensively around the planet and with greater frequency. Invasives are both a conservation concern and an economic concern causing direct and indirect negative impacts on agriculture, forestry, and industry (Pimentel et al. 2001). Damage estimates range from $100 million per year due to extensive loss of ecosystem services and risk to public health (Andersen et al. 2004) to $28 billion per year in agricultural losses due to invasive weeds (Pimentel et al. 2001). The collective impact of invasive species is widespread and extensive, with Baker (2001) estimating that invasives cause aggregate losses of $125 billion per year. Here I will address invasive species management from the perspective of a not-for-profit land protection organization.

Invasive species management includes three approaches: prevention before an outbreak occurs; containment or control of spread; and eradication from an area of interest (Radosevich et al. 2007 p. 259). Prevention is by far the most effective and therefore preferable of the three methods. Unfortunately, it is also the most difficult because it requires predictions of invasiveness of species as well as knowledge of where an introduction will take place. However, this information is rarely available at the time of introduction. In many cases, invasive plants are controlled and contained in an effort to eradicate even though eradication is often not feasible.

Not all exotic species exhibit invasive behaviors. How then does one know which exotic species are or will become invasive? Although not a diagnostic list, invasive species almost always share three traits: (1) adaptability to new environments; (2) competitive advantage in utilizing available resources; and (3) a high capacity for reproduction with many invasive species being able to propagate by more than one method (i.e. seed, vegetative structures such as roots or stems, etc.).

In addition to researching the biological invasibility, environmental and community invasibility is also of key importance to predicting and understanding species spread (Radosevich et al. 2007 p.101). Research on predicting the invasibility of habitat is inconclusive (summary by Radosevich et al. 2007 p.89). Despite best efforts, most invasive species are identified only after the problem is large enough to warrant attention and when the invasion is so large that eradication becomes very challenging. This common scenario elects containment and control as the primary method of managing invasive species in most cases.

Although few, if any, plant communities are immune to non-native invasions, when managing for native species, it is useful to understand what habitat types may be more or less susceptible. Riparian areas, as an example habitat type, may have a higher relative environmental invasibility due to a higher rate of disturbance through flooding and water-borne dispersal of seeds and propagules (Radosevich et al. 2007, Richardson et al. 2007). Additionally, riparian areas can serve as corridors that facilitate species spread that is less common in closed habitat or ecosystems (Stohlgren et al. 1998, Radosevich et al. 2007 p. 30). Similar to other wetland ecosystems, they also have a high proportion of biodiversity and relatively high available resources. Different areas report different
results on the effects of biodiversity. High biodiversity is generally thought to protect against competing species; however, Stohlgren et al. (1999) predict a strong positive relationship between plant diversity and plant invasion in areas of highest productivity. Research has shown that wetland areas of high diversity were not impervious to invasive plant colonization (Planty-Tabacchi et al. 1996, DeMeester and Richter 2010).

Invasive spread is of special concern for land protection organizations who are dedicated to conserving biologically sensitive and ecologically important areas such as riparian areas. Notably, rivers and streams have been recognized as areas of greatest concern for decreasing biodiversity worldwide (IUCN 2008); these ecosystems are also one of four main types of corridors which facilitate the dispersal of organisms across the landscape (Myers and Bazely 2003). As With (2004) explains, invasive spread is facilitated by connected and spatially correlated areas of disturbance allowing for spread at lower levels of disturbance. Alternately, more significant disturbance is generally required to facilitate invasive spread if disturbed areas are distributed at random and in small patches. Most often, habitat corridors are promoted in conservation of endangered species, but in the case of invasive species, corridors such as rivers, roads, and trails can be an additional challenge to protected areas management.

Effective management requires significant resources (i.e. equipment, funding, etc.) and useful decision support tools to determine which species to focus on and where to allocate limited resources for maximum effect. Importantly, invasive species management does not end when unwanted species are removed. Reintroductions are common and virulent, even in restored areas that have species-rich native communities (DeMeester and Richter 2010). This is also true in “designer” restorations where native species are planted to ensure community structure (Cole 1999). For all of these reasons, understanding the extent of invasive species and predicting the areas at highest risk of invasion is necessary to make successful management plans that consider the necessary immediate and long-term resources.

My research predicts the extent of invasive plants in the Eno River watershed, part of the Upper Neuse River Basin of North Carolina and identifies future land protection properties with the largest potential invasive species distributions. The Eno River Association (ERA) is the primary land protection organization in the watershed and my client for this research; they have worked to protect the river, its watershed (402 km²) and lands since 1966. Managing these properties requires significant stewardship and maintenance. One significant part of this responsibility is invasive species management. Three species account for the majority of invasive control and removal work for the ERA: tree of heaven (Ailanthus altissima), Chinese privet (Ligustrum sinense), and multiflora rose (Rosa multiflora). These species have been targeted primarily because they can be controlled through manual removal or simple herbicide treatments by volunteers with relative success. To model these species, I inventoried a conservation area owned and managed by the ERA at the headwaters of the Eno River. I have combined additional species presence data from the Eno River State Park made available by Dr. Julie Reynolds’ citizen science invasive plant monitoring program.
Research Questions:
- Where are the invasive species of interest at the Confluence Natural Area?
- Can the patterns of these invasive species across the Eno watershed be predicted using property monitoring methods employed by land trusts?
- Can data collected during invasive species monitoring facilitate future land protection?

Study Area:

The Eno River watershed (402 km$^2$) is at the headwaters of the Neuse River basin in North Carolina. The Confluence Natural Area (36.136904, -79.159412), owned by the Eno River Association (ERA), is 0.73 km$^2$ in northern Orange County, North Carolina and was the primary site for invasive plants surveying. Previously, this land was two tracts used for non-industrial timber harvest and agriculture; the bottomlands that make up much of these adjacent properties have mature mixed hardwood forests and substantial riparian corridors. Invasive plants were also surveyed in portions of the Eno River State Park (36.056667N, -78.981111W) which is approximately 16 kilometers downstream from the Confluence Natural Area (Figure 1).

Figure 1. Protected areas of the Eno River watershed
Invasive exotic plants:

Below is some background information on the invasive exotic plant species surveyed for this study. This is not an exhaustive list of the invasive plants found in the Eno River watershed; however, these are the three species which the ERA actively manages. Both the ERA and Eno River State Park manage these species primarily by manual removal with supplemental herbicide treatment. All three species respond well to glyphosate treatments: 50% solution should be used with the hack and squirt application method of tree trunks and unfelled large individuals; a 25% solution is best for the cut and paint method of larger cut stems and trunks.

*Ailanthus altissima* (Tree of heaven)

This tree was first introduced into the United States from China in 1784 as an ornamental garden plant, and has now spread across almost the entire nation, save only the northern Great Plains (Patternson 1976, CISEH 2010). *A. altissima* is shade intolerant and although it prefers well drained soils, this species has the ability to grow in poor soil conditions (University of Georgia- CISEH 2010).

Most often, *A. altissima* is found along roadsides, in riparian areas and other disturbed sites (Hunter 1996). This species grows very quickly and is capable of forming dense monoculture stands by clonal and sexual reproduction. Each mature tree can produce up to one million seeds (Weber 2003) that are easily dispersed by wind along corridors including roadsides and rivers. In addition, this species releases a phytotoxic compound into the soil which causes mortality in other plant species (Heisey 1996). This allows *A. altissima* to poison other competing plants while simultaneously growing and reproducing rapidly, resulting in dense thickets that crowd out native plants. Pulling young trees is very easy, even manually; larger trees should be treated with herbicide either by cutting and painting the stumps or by the hack and squirt method of killing standing trees. Weber (2003) also suggests girdling growing trees.

*Ligustrum sinense* (Chinese privet)

Another native of eastern China, this evergreen species was first introduced into the United States through horticulture as an ornamental plant in 1952. *L. sinense* primarily occupies the southeastern US with some spread reported in Massachusetts, Texas, and Oklahoma (invasive atlas 2009).

It is common to find *L. sinense* in bottomland areas, along edges both natural and manmade (Haragan 1996), and in woodland interiors (Morris *et al.* 2002). As with many invasive plants, *L. sinense* is an aggressive reproducer with fruits that are distributed by birds and other wildlife; this species can also spread vegetatively by roots and damaged plants sprout vigorously. Small individuals should be removed manually or with a weed wrench; larger plants, greater than approximately one inch should be cut and treated with herbicide (Weber 2003).

*Rosa multiflora* (Multiflora rose)

A native of Japan and Korea, this plant was introduced into the United States in the early 1800s as an ornamental garden plant (Patterson 1976). In the 1900s, this thorny, deciduous shrub was widely spread across grazing lands for use as a living fence and as wildlife forage (Invasive Atlas 2009). This species has since escaped across most of the...
eastern and western United States with the western plains and Rocky Mountain states unaffected.

*R. multiflora* occurs most often in forests, along forest edges, and in grasslands (Weber 2003); it is also found along roadsides and other disturbed, open areas as well as wetlands (Dreyer 1996). Although this plant will tolerate wet and shady conditions, it thrives in open areas with well-drained soils. Invasive characteristics of *R. multiflora* include: abundant fruiting; ability to reproduce by seed which is well dispersed by birds and layering or rooting of arching stems; and ability to form tall, dense, and impenetrable thickets that suppress other vegetation. Solitary plants can occupy dense clumps up to 10m in diameter (Patterson1976). More typically, multiple *R. multiflora* grow together in dense stands.

*R. multiflora* is easily pulled manually (when small) or with a weed wrench. When cut, stems should be cut near the ground and all stumps should be treated with herbicide to avoid resprouting (Weber 2003).
METHODS

Data

All three invasive plant species were surveyed at the Confluence Natural Area during the winter of 2009-2010. Surveying during the dormant “leaf off” season aided in identifying the two shrub species: *Rosa multiflora* by its characteristic branching shape and *Ligustrum sinense* because it is one of few evergreen plants in the deciduous forests of this region. *Ailanthus altissima* had been targeted during summer and autumn workdays and was marked by cuts in the bark of each tree. These individuals were also identified by their distinctive branch shape and bark texture. Data were collected via handheld GPS (Trimble GeoXT 2005; ArcPad 6.0.3). Stem counts within a 2 m radius were recorded as single presence points. Additional data were collected in the lower watershed in the Eno River State Park during the summer of 2008 as part of the Duke University Plant Stalkers citizen science program (http://www.science-writing.org/citizenscience.html). Geospatial data modification and derivation was performed using ArcGIS software (v. 9.3, ESRI, Redlands, CA).

The data collection method mimics small-scale protected area inventorying and monitoring which is generally opportunistic -- mapping when plants are found -- and lacking in sampling design. Although this is not the preferred data collection method for statistical analysis, many land managers who are dealing directly with invasive species generally do not have the time or other resources to collect data this way. Instead, at best, land trusts and other land protection organizations monitor annually to track changes in spread and control using chemical and manual methods when possible. To aid in this endeavor, I have modeled species distributions with the two combined datasets collected from Eno River watershed.

Environmental variables

A total of six environmental predictor variables were included in the models. Three represent the topography of the physical landscape; the other three approximate the environmental invasibility. All downloaded data were processed in the North Carolina State Plane (ft) projection and clipped to the extent of the Eno River watershed. A 20 ft digital elevation model (DEM) was downloaded from the North Carolina Floodplain Mapping Program (NCFMP, http://www.ncfloodmaps.com). Generally, more readily available 30m DEMs are used in landscape scale habitat analyses; however, the 20 ft DEM was used for this analysis to analyze the watershed topography at a finer scale. The elevation layer was transformed into three indirect variables -- slope, aspect (azimuth), and topographic convergence index (TCI) which is a measure of relative wetness derived from relativized slope position. TCI was derived using the Topography Tools toolbox for ArcGIS (Dilts 2009). Sorenson and Seibert (2007) suggest that upslope area is affected by the resolution of the DEM for calculating TCI, and they recommend using a finer DEM and interpolating when one is not available. Although slope, aspect, and TCI have no physiological influence on species’ survival, these topography characteristics have been shown to be predictive in other species distribution models and were thus chosen for these invasive species models (Guisan and Zimmermann 2000).

Central and eastern North Carolina both have such minimal topography that the influence of slope at the watershed scale is unlikely to be very strong. Aspect provides a proxy for available sunlight and solar radiation and is also linked to the scale of analysis...
and diversity of topography. In the Eno River watershed the differences in aspect at the 20ft resolution are expected to explain a small portion of invasive species distribution probabilities. The topographic convergence index, also called the wetness index, derives the relative wetness of each gridcell from the slope and the upslope contributing area to the cell; both are calculated from the DEM (Bevin and Kirby 1979). Additionally, the TCI is well suited for analysis at the watershed scale (Urban 2000) where the groundwater is driven by changes in topography, unlike flat areas that have recharge-driven groundwater (Haitjema and Mitchell-Bruker 2005). The TCI variable was also chosen for inclusion in distribution modeling because of the perceived association between the species of interest and wetter, bottomland areas.

I chose three additional geospatial datasets to represent the biophysical environment: soils data from the soil survey geographic database (SSURGO) of the Natural Resources Conservation Service (NRCS); hydrography from the North Carolina Center for Geographic Information and Analysis in conjunction with the North Carolina Division of Water Quality; and landcover from the North Carolina land use/landcover dataset from 1996 (30m). All GIS data were resampled to 20ft grid to match the finer resolution DEM. Resampling does not improve the resolution of these data; however it does allow for analyses at the finer resolution. All dataset sources and dates are summarized in Table 1 below.

As summarized by Radosevich et al. (2007), effects of invasion at the landscape or regional scale are best predicted by traits of the invasive species as well as ecological factors such as resources, disturbance, etc. To that end, I have chosen environmental layers that approximate these landscape features: general species composition/diversity (landcover), nutrient availability (soil type), and vector of spread (distance to rivers). A common vector of spread recognized for its influence in plant invasions is distance to roads. This variable is not in this analysis due to strong bias of occurrence points. The data collected at the Confluence Natural Area are not sampled on or near roads while the data from the state park are collected primarily along walking trails. Without plant demography data, I was unable to include propagule pressure which is also linked to predicting invasibility of landscapes. Climatic variables are often included in species distribution modeling; however, in this case, the study size is too small for climate data to be informative or discriminatory between samples.

Each of the environmental variables was sampled at each species occurrence point from within the ArcInfo GIS environment. Sampling of the environmental variables at all data points was done with bilinear interpolation to address expected spatial alignment errors in the environmental rasters (Phillips et al. 2006). Bilinear interpolation combines mixed values in instances where samples fall on the boundary of two type classes and also help address inherent errors expected from disparate data sources.
<table>
<thead>
<tr>
<th>Environmental Variable</th>
<th>Data Resource</th>
<th>Date of Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>soils</td>
<td>SSURGO- Natural Resources Conservation Service</td>
<td>1977</td>
</tr>
<tr>
<td>land cover</td>
<td>NC Statewide Land use/land cover 1996</td>
<td>1993-1995</td>
</tr>
<tr>
<td>distance to rivers</td>
<td>NC hydrography 1:24,000, NC Center for Geographic Information and Analysis in conjunction with NC Division of Water Quality</td>
<td>1997-present</td>
</tr>
<tr>
<td>elevation</td>
<td>20ft DEM, NC Floodplain mapping project</td>
<td>2001</td>
</tr>
<tr>
<td>slope</td>
<td>Derived from DEM</td>
<td>2001</td>
</tr>
<tr>
<td>aspect</td>
<td>Derived from DEM</td>
<td>2001</td>
</tr>
<tr>
<td>tci</td>
<td>Derived from DEM</td>
<td>2001</td>
</tr>
</tbody>
</table>

**Species Distribution Modeling**

Species distribution modeling has been a major component of much research in ecology. New understanding from species models has informed conservation, protected areas planning, and invasive species management (Elith et al. 2006). As a general approach, species distribution modeling allows limited understanding, and sometimes minimal data, to make robust predictions about the extent and possible range of a given species.

More conventional methods of species distribution modeling such as logistic regression (or generalized linear modeling) were not appropriate in this circumstance. The primary reason for this was the lack of absence data necessary for a discriminatory method such as logistic regression. Many other studies have used pseudo-absences, or random samples of the not-surveyed study area; however, in the case of invasive species modeling, assumptions about where a plant is absent are difficult to interpret and perhaps inappropriate. For many invasive plants like the three examples studied here, their potential distributions cover a wide range of habitats. Therefore, absence or pseudo-absence data may be better described as not-present-yet which greatly confuses a model designed to maximally separate presence and non-presence. Further, these models include categorical variables (soil type and land cover), which are not suitable for logistic regression and other distance measured models (Phillips et al. 2006). To accommodate these features of the data, I have chosen to model invasive plant species distributions with Maxent software instead.

**Maxent:**

Maxent is a maximum entropy based software developed to model species distributions using presence-only data (Phillips et al. 2006). More specifically, Maxent uses the maximum likelihood distribution of species determined by presence points contrasted against a random sampling of the study area’s range of habitats. Predicted distributions for each variable are overlain to describe the likelihood of habitat using.
samples compared against random background rather than juxtaposed against absence
data. The background points are used to assess the availability and range of habitats in the
study area and were sampled by the program from raster grids of environmental predictor
variables.

For this application, 75% of each species’ data points were randomly sampled by
Maxent for use as test data, reserving the other 25% of data points for model evaluation.
Ten replicate models were completed for each species with bootstrapping such that the
training data were sampled with replacement (the number of samples equaled the total
number of presence points). Replication of species distribution models results in an
average model output plus one standard deviation.

Maxent provides internal model evaluation by habitat area, similar to the receiver
operator curve (ROC) often used with logistic regression. Maxent is able to present
sensitivity (true positive rate) but, without absence data, specificity (true negative rate) is
defined as a fractional predicted area (Phillips et al. 2006). Overall model correctness is
presented as the area under the curve (AUC) on a scale 0-1 (a perfect model equals 1).
The ROC shapes and AUCs of the three models presented here were compared for model
predictability (Pearce and Ferrier 2000).

The continuous logistic output created by Maxent for each of the three species
distribution models was tuned for maximum sensitivity and specificity to identify model
cutoff values. The median maximum sensitivity plus specificity value was calculated
from the 10 replicate models per species: the smallest total predicted area that maximizes
the true positive rate is chosen. Cutoff values were used to create a binary habitat/non-
habitat raster grid for displaying predicted species ranges where values greater than the
cutoff were classified as presence or habitat and values below the cutoff were classified
as absence or non-habitat. Model accuracy was evaluated by checking the distributions
for fit to the data. Species presence points were overlain on the habitat maps and
omissions from the predicted habitat were tallied then divided by the total number of data
points per species for an omission error per model.

Maxent provides an estimated percent contribution to model fit for each predictor
variable. When some variables are correlated -- as they are in this dataset -- it can be
difficult to interpret individual contribution. Maxent provides a jackknife test where the
total model gain (including each variable in turn) is compared to the model gain of all
other variables (excluding the tested variable). More commonly, variable explanation is
determined successively which indicates a lack of independence for variable valuation.
Gain describes the amount of unique information not redundant in other variables. Being
closely related to deviance of discriminatory functions, gain is used as a measure of
likelihood of the training data. Beginning with zero, gain increases toward an asymptote.
Variables that are correlated and removed result in little loss of model gain. This measure
represents the improvement of the model fit to the training data points as opposed to a
random selection of available habitat. Each model was analyzed for the most predictive
variable that may be used as an indicator of invasive plant habitat.

Maximum entropy modeling has been shown to be effective in modeling species
distributions, especially in cases where only presence data are available (Phillips et al.
2006). Maxent models are generative and not discriminatory meaning they do not
contrast species presence against absence or pseudo-absence. Further, maxent is not
limited to modeling linear relationships which are rare in nature. Instead, because
variables are predicted individually and overlain, disparate relationships (e.g. threshold, Gaussian, etc.) are possible for each variable giving a more complete and holistic representation of the study area than a restrictive linear model can (Phillips et al. 2006). Areas where invasive species are not found cannot be ruled out as non-habitat. It may in fact only be non-habitat that will be invaded in the near-term future. Modeling invasive species with presence-only data avoids the assumptions of habitat uniqueness and discernibility (inherent in presence/absence comparison analyses such as logistic regression) that are not suitable to the study of invasive species at the parcel and landscape scales.

GIS Analysis

Areas that were predicted by each species distribution model were further analyzed for application in the Eno River watershed land protection. Species richness was calculated across the watershed to identify areas with characteristics common to all three species. Predicted distributions were also analyzed for soil types to understand which types are associated with these invasive species. The majority and minority soil types were summarized by species as well as the variety of soil types found within predicted distributions. These summarizations were repeated within a 100ft buffer of the stream network as an approximation of the floodplain and riparian zone. Lastly, invasive species distributions were compared within the properties remaining in the Eno River State Park master plan that both the ERA and the North Carolina State Division of Parks and Recreation use as a prioritized list for future land protection. By comparing the relative likelihood of invasive species spread, all master plan properties were ranked to guide these land protection organizations in making protection and management decisions for future and currently owned properties.
RESULTS

Model cutoff or threshold values were similar among species, ranging from 0.26 for *L. sinense* to 0.32 for *R. multiflora* (Table 2). These values identify the smallest total predicted area that maximizes the true positive rate. All three models had high corresponding AUC values (*A. altissima* = 0.936; *L. sinense* = 0.903; and *R. multiflora* = 0.871, Table 2) indicating high model correctness. Although *A. altissima* had the highest AUC, this species also had the highest omission error of 15% while both of the shrub species had omission errors of 6% (Table 2).

<table>
<thead>
<tr>
<th></th>
<th><em>A. altissima</em></th>
<th><em>L. sinense</em></th>
<th><em>R. multiflora</em></th>
</tr>
</thead>
<tbody>
<tr>
<td>AUC (0-1)</td>
<td>0.936</td>
<td>0.903</td>
<td>0.871</td>
</tr>
<tr>
<td>Cutoff (0-1)</td>
<td>0.304</td>
<td>0.260</td>
<td>0.320</td>
</tr>
<tr>
<td>omission error (%)</td>
<td>15</td>
<td>6</td>
<td>6</td>
</tr>
</tbody>
</table>

Comparison of species distribution models with ROC curve allows for a single measure of model performance that is independent of chosen thresholds (Phillips et al. 2006). Each of the three models had different ROC shapes despite similar AUC values. If AUC is the same or similar, then the models have similar performance (Phillips et al. 2006); however, curves with the most even shape are considered the most accurate (Pearce and Ferrier 2000). The *A. altissima* model is the most restrictive model and misses some divergent data points (omission error 15%); however it includes the lowest relative non-habitat of the three models. Both shrub species models are truer to the data and therefore have lower omission errors but they also include greater amounts of non-habitat as seen in the right-leaning ROC curves. Model iteration agreement is reflected in the first standard deviation of the ROC curve such that wider standard deviation indicates less model agreement (Figures 2-4). *L. sinense* had the best consistency among model iterations; with low omission error, high consistency among model iterations and high AUC, this model is the best of the three.
Figure 2. ROC for bootstrapped *A. altissima* distribution model.
Red: average ROC; Blue: 1 standard deviation; Black: random model (50:50).

Figure 3. ROC for bootstrapped *L. sinense* distribution model.
Red: average ROC; Blue: 1 standard deviation; Black: random model (50:50).
All three models predicted likelihood ranges within 3 km$^2$ of each other. The area predicted to be potentially invasible by both *A. altissima* and *L. sinense* is 32 km$^2$ and 35.8 km$^2$ for *R. multiflora* (Table 3, Figures 6, 8, and 10). There is considerable overlap in potential ranges of these species within the Eno River watershed. A total of 23 km$^2$ are predicted to be invaded by any two of the three invasive species with approximately 8 km$^2$ invaded by all three species of interest (Table 4, Figure 12).

<table>
<thead>
<tr>
<th>area</th>
<th>A. altissima</th>
<th>L. sinense</th>
<th>R. multiflora</th>
</tr>
</thead>
<tbody>
<tr>
<td>km$^2$</td>
<td>32.8</td>
<td>32</td>
<td>35.8</td>
</tr>
<tr>
<td>acres</td>
<td>8109</td>
<td>7904</td>
<td>8856</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>species richness</th>
<th>area</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>km$^2$</td>
<td>30</td>
<td>23</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>acres</td>
<td>7393</td>
<td>5605</td>
<td>2088</td>
<td></td>
</tr>
</tbody>
</table>

Habitat of all three invasive species is best described by soils, distance to rivers, and land cover (Table 5). Both *A. altissima* and *L. sinense* are best described by soils (~40-50%) and distance to rivers (33-36%; Table 5), a correlated variable. For *R. multiflora*, the opposite is true with distance to rivers contributing roughly half of the model explanation and soils only 20%. Together, soils and distance to rivers describe approximately 70-80% of variable deviance for all three species. Both *L. sinense* and *R.
multiflora are also influenced (>10%) by land cover. See Figures 7, 9, and 11 for variable contribution comparisons from Maxent jackknife output per model.

There are a total of 71 soil types within the Eno River watershed. L. sinense is the species least associated with soil type (range of 45 soil types), followed by R. multiflora (28), and A. altissima (23) (Table 6). All three habitat models identified potentially invaded areas as those with a majority of Georgeville silt loam (6-10% slope). Within the 100ft stream buffer, both L. sinense and R. multiflora contained a majority of Chewacla and Wehadkee soils (0-2%) slopes (Table 6). The same variety of soils was present for each species within the 100ft buffer with the exception of L. sinense which was reduced to 41 soil types. Invasive species results within the Eno River State Park master plan properties are found in the management recommendation below.

<table>
<thead>
<tr>
<th>predictor variable</th>
<th>A. altissima</th>
<th>L. sinense</th>
<th>R. multiflora</th>
</tr>
</thead>
<tbody>
<tr>
<td>soils</td>
<td>49.5</td>
<td>42.6</td>
<td>20.6</td>
</tr>
<tr>
<td>distance to rivers</td>
<td>33.4</td>
<td>36</td>
<td>48.5</td>
</tr>
<tr>
<td>land cover</td>
<td>5.5</td>
<td>14</td>
<td>20</td>
</tr>
<tr>
<td>aspect</td>
<td>8.5</td>
<td>5.2</td>
<td>6.3</td>
</tr>
<tr>
<td>tci</td>
<td>1.8</td>
<td>1.4</td>
<td>3.9</td>
</tr>
<tr>
<td>slope</td>
<td>1.3</td>
<td>0.8</td>
<td>0.7</td>
</tr>
</tbody>
</table>

Table 6. Soils associated with invasive species of the Eno River watershed

<table>
<thead>
<tr>
<th>Total watershed</th>
<th>A. altissima</th>
<th>L. sinense</th>
<th>R. multiflora</th>
</tr>
</thead>
<tbody>
<tr>
<td>majority</td>
<td>Georgeville silt loam (6-10% slope)</td>
<td>Georgeville silt loam (6-10% slope)</td>
<td>Georgeville silt loam (6-10% slope)</td>
</tr>
<tr>
<td>minority</td>
<td>Congaree silt loam (0-2% slope)</td>
<td>Altavista silt loam (0-2% slope)</td>
<td>Wehadkee silt loam (0-2% slope)</td>
</tr>
<tr>
<td>variety of soils</td>
<td>23</td>
<td>45</td>
<td>28</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>100ft river buffer</th>
<th>A. altissima</th>
<th>L. sinense</th>
<th>R. multiflora</th>
</tr>
</thead>
<tbody>
<tr>
<td>majority</td>
<td>Georgeville silt loam (6-10% slope)</td>
<td>Chewacla/Wehadkee (0-2% slope)</td>
<td>Chewacla/Wehadkee (0-2% slope)</td>
</tr>
<tr>
<td>minority</td>
<td>Congaree silt loam (0-2% slope)</td>
<td>White Store loam (2-6% slope)</td>
<td>Wehadkee silt loam (0-2% slope)</td>
</tr>
<tr>
<td>variety of soils</td>
<td>23</td>
<td>41</td>
<td>28</td>
</tr>
</tbody>
</table>
DISCUSSION

All three models identify areas along or in close proximity to streams as the most likely habitat to be invaded in the watershed. This is partly attributable to bias in the data collection; areas surveyed for invasives were primarily riparian areas and immediately surrounding property. It is apparent in the literature that *A. altissima*, *L. sinense*, and *R. multiflora* also invade and spread intensively along roadsides, in open fields, and other areas of disturbance (Weber 2003, Hunter 1996, Haragan 1996, and Dreyer 1996). For a more complete model of predicted invasion, roadside areas and field edges should also be considered; however, the focus of both the ERA and the ERSP is to protect and preserve the riparian areas of the Eno River so these models were trained to riparian areas (distance to rivers, wetness, etc). With this limitation, Maxent was an appropriate choice because additive modeling emphasizes the contribution of all environmental variables rather than the average (Philips *et al.* 2006). Additional presence data would likely improve the models, in particular data that are less biased toward streams and park trails. Including additional vectors of spread would also provide a more holistic view of the invasive plant distributions. It should be noted that overall species distribution models tend to be biased toward inclusion of non-habitat resulting in inflated models (Loiselle *et al.* 2003) and Maxent is not immune to this tendency. However, for the purposes of these maps, and the resolution they are analyzed in, all three models can be considered fairly strong predictive models for these invasive plant species.

It is interesting to note that there was very little contribution from the topographic variables. This may be due to the little diversity in elevation, aspect, or slope at the 20ft resolution of the analysis. TCI, or relative wetness, was not a strong explanatory variable as was expected. Instead, variable contribution was dominated by soils and distance to rivers for all three models. The soil type that constitutes the majority of predicted habitat for all three species (Georgeville silt loam 6-10% slope) is a non-hydric soil considered moderately permeable with rapid surface runoff (Soil Survey Staff NRCS). This soil type is extensive in the gently sloping piedmont uplands of the southeastern United States and is typically forested in mixed hardwoods and pines (Soil Survey Staff NRCS). The association with rivers for these species distribution models suggests that the soil categorization is a product of the resolution of analysis. Although the models overwhelmingly predict riparian zones, the soil majority categorization may be confounded by pixel resolution such that the more restricted hydric soils of the river floodplains are outnumbered and not reflected in these summary statistics. Analysis of an approximate floodplain area 100ft from streams revealed that the two shrub species were more common in frequently flooded loam soils in this partial range. The Maxent models found similar results to the literature: these invasive species can tolerate a range of conditions exemplified here by soils ranging from frequently flooded riparian soils to well-drained upland soils.

Potential *R. multiflora* presence can be best predicted by nearness to rivers which can allow for quick estimations of time and funding needed for management in the Eno River watershed. Surveys of future land protection projects should focus on these areas with the guidance of distribution maps made here. This single variable, distance to rivers (one primary vector of spread), is not the most explanatory variable for *A. altissima* or *L. sinense* which are better guided by the distribution maps which are largely driven by soil.
type. All three species can also be anticipated with greater confidence in areas near known invasions.

MANAGEMENT RECOMMENDATIONS

The models described above have several possible applications. First, they can guide invasive plant management on ERA properties for survey of predicted areas of vulnerability and providing a framework for more general monitoring beyond the traditional focus of property boundaries. Second, these models can be applied to guide future land protection in the watershed by examining areas predicted as potential habitat within properties of interest. I have applied the models to the remaining properties in the Eno River State Park master plan and indicated those properties most likely to have larger invasions both in size and percent cover. Both the state park and the ERA utilize this master plan as a land protection prioritization guide. Third, these species models can inform the land management practiced on neighboring lands adjacent to current and future protected areas, for example, private land owners, many of whom greatly value their borders with the state park and ERA protected lands. This would be mainly done through outreach by the mentioned organizations.

Properties:

The current protected land in the Eno River State Park exceeds 16.6 km$^2$ (4,100 acres) with an additional 7.7 km$^2$ (1,900 acres) in the State Park master plan (Figure 1). The master plan focuses on acquiring properties that create a contiguous corridor of land adjacent to both sides of the Eno River. By securing the river frontage, the state park can allow for more complete protection of the riparian areas of the Eno River as well as provide more continuous open space for nature study, recreation, and wildlife. The master plan also includes several areas adjacent to the current park boundary extending away from the river and adding to the depth of the natural area buffer and wildlife habitat provided by the parkland (Figure 1).

In total, the master plan includes 153 properties which are not currently owned by the park or protected by the ERA. The species distribution models demonstrated here predict portions of nearly all of these properties as likely habitat for each of the three invasive species. Regardless of the method, all invasive plant control approaches require time and money to implement. Avoiding some of these costs by preventing further spread is the principal goal of annual monitoring of invasive species. In land management, preparing and planning for perpetual stewardship is no small task. Non-profit land trusts like the ERA must consider how conservation goals, mission statements, and budgetary limitations correspond with stewardship estimates. North Carolina State Parks and other agencies must make the same evaluations of anticipated stewardship costs. When buying property to implement the master plan, stewardship considerations are less important than the conservation and functional value or adjacency to the current park boundary; however, it is still a very important component to consider for annual and long-term budgeting. The invasive species models described here were used to evaluate the relative likelihood of invasion based on similar physical characteristics.

Two properties (H10B and H10A) rank in the top 5 of invasible acreage for all three species (Figure 5) with an additional three properties that rank for at least two species (Table 7). When analyzed by greatest percentage of each property invaded, a
single different property (G2) ranks in the top five for all three species with three other properties ranking for at least two species each (Table 7). None of the highest percentage invasible properties fall within the top five ranked properties for greatest area invasible suggesting they are smaller properties that have a high concentration of characteristics associated with these species’ invadability. As might be expected, the property with the largest potentially invasible area is also the largest property in total area. Similarly, the property with the largest percentage invasible is quite small which will allow for concentrated control measures (Figure 5). It is reasonable to anticipate greater stewardship costs with densely or widely invaded properties. I recommend that both the ERA and the Eno River State park consider how adjacent property management may be affected by invasives presence or spread into these areas when estimating stewardship costs for these land protection priorities.

<table>
<thead>
<tr>
<th>area invasible (km²)</th>
<th>A. altissima</th>
<th>L. sinense</th>
<th>R. multiflora</th>
</tr>
</thead>
<tbody>
<tr>
<td>H10B</td>
<td>H10B</td>
<td>H10B</td>
<td></td>
</tr>
<tr>
<td>I1</td>
<td>H10A</td>
<td>I1</td>
<td></td>
</tr>
<tr>
<td>I6</td>
<td>C2</td>
<td>I6</td>
<td></td>
</tr>
<tr>
<td>I4</td>
<td>B9</td>
<td>B9</td>
<td></td>
</tr>
<tr>
<td>H10A</td>
<td>C3A</td>
<td>H10A</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>greatest invasibility (%)</th>
<th>H5</th>
<th>H5</th>
<th>C5B</th>
</tr>
</thead>
<tbody>
<tr>
<td>F9</td>
<td></td>
<td>D12a</td>
<td>G2</td>
</tr>
<tr>
<td>H8</td>
<td>G2</td>
<td>H8</td>
<td></td>
</tr>
<tr>
<td>G2</td>
<td>D3</td>
<td></td>
<td>C7</td>
</tr>
<tr>
<td>F5B</td>
<td>28</td>
<td>D3</td>
<td></td>
</tr>
</tbody>
</table>

*properties highlighted in red are mapped in Figure 5 below

There are a total of 35 soil types in the state park master plan properties (Figure 14). Consultation of soils maps for areas within the 100 year floodplain or other near-stream areas is advised for guiding inventory, especially for the shrub species examined here.

The field of remote sensing and geospatial mapping is advancing all of the time and becoming increasingly available for land managers to utilize at low cost. Applications such as this invasive plant project show that sufficient free datasets are available to create better detailed, predictive maps of management concerns. These same methods could be repurposed to map rare or protected species with few modifications. That is, with monitoring data of rare or priority species, organizations could generate species distribution models to guide surveys for previously unmapped individuals or communities. Further, by mapping annual monitoring data, impacts of management can be tracked and evaluated for effectiveness.
Invasives Control:

Determining the method of invasive species control in natural ecosystems is less straightforward than in agriculture or other lands where weed invasion has direct negative impacts on the monetary value of the land (Radiosevich et al. 2007, p. 269). In the case of a local land trust managing species which have established populations across the country, a goal of total permanent eradication may not be feasible. That does not mean that local eradications are not beneficial or worth pursuing. In fact, this is one goal of many land managers who are dedicated to preservation of nature and native communities. To attain such goals, a combination of manual removal and herbicide application is often used. When using herbicide on woody shrub and tree species like those studied here, the plant may be cut entirely or only superficially, generally at the base of the main stem with herbicide applied to the cambium layer specifically. Alternatively, a foliar application may be used. Foliar spraying is not common practice for the ERA or Eno River State Park because herbicide drift and unintentional application is better controlled with direct application methods such as “hack and squirt” and “cut and paint”. Although these two methods may require more time, they do apply the active chemical more directly to the problem plant.

For chemical control of invasive plants, glyphosate has favorable characteristics for management: relatively low toxicity and irritation potential for the applier; non-bioaccumulation; relative immobility in the environment (Stensones and Garnett 1994);
and relatively rapid decomposition by soil microbes (Santos et al. 2009). Regardless of the method, it is most important to anticipate continued management for treated areas. DeMeester and Richter (2010) found that without continued maintenance, restored wetland sites were reinvaded within one year. Their study examined the overall effect of a different invasive plant, Microstegium vimineum (Japanese stilt grass). Their findings suggest that with reinvasion, wetland and riparian areas suffer a loss of native biodiversity. It is therefore advisable to prepare for additional monitoring and control resources beyond initial removals, and perhaps beyond recolonization of native flora. Total estimates of cost and resource needs can be guided by monitoring and modeling exercises such as those employed here.
ACKNOWLEDGEMENTS

Special thanks to Kurt Schlimme and the rest of the Eno River Association staff for their support this year. Also thank you to Prof. Julie Reynolds and Scott Spillias for Eno River State Park data access. Thanks to my advisor Prof. Dan Richter for his guidance in this process. This project would not have been possible without the support from my friends and family, thank you all.

CITED SOURCES


APPENDIX

A. Maxent

Figure 6. Potential Distribution of *Ailanthus altissima*

Figure 7. Maxent jackknife: *Ailanthus altissima*
Figure 8. Potential Distribution of *Ligustrum sinense*

Figure 9. Maxent jackknife: *Ligustrum sinense*
Figure 10. Potential Distribution of *Rosa multiflora*

Figure 11. Maxent jackknife: *Rosa multiflora*
Figure 12. Combined invasives distributions of the Eno River watershed
Figure 13. Invasive species richness of the Eno River State Park master plan future lands.
Figure 14. Soil types of the Eno River State Park master plan properties