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Geospatial Assessment of Invasive Plants on Reclaimed Mines in Alabama

Dawn Lemke, Callie J. Schweitzer, Wubishet Tadesse, Yong Wang, and Jennifer A. Brown*

Throughout the world, the invasion of nonnative plants is an increasing threat to native biodiversity and ecosystem sustainability. Invasion is especially prevalent in areas affected by land transformation and disturbance. Surface mines are a major land transformation, and thus may promote the establishment and persistence of invasive plant communities. Using the Shale Hills region of Alabama as a case study, we assessed the use of landscape characteristics in predicting the probability of occurrence of six invasive plant species: sericea lespedeza, Japanese honeysuckle, Chinese privet, autumn-olive, royal paulownia, and sawtooth oak. Models were generated for invasive species occurrence using logistic regression and maximum entropy methods. The predicted probabilities of species occurrence were applied to the mined landscape to assess the probable prevalence of each species across the landscape. Japanese honeysuckle had the highest probable prevalence on the landscape (48% of the area), with royal paulownia having the lowest (less than 1%). Overall, 67% of the landscape was predicted to have at least one invasive plant species, with 20% of the landscape predicted to have two or more species, and 3% of the landscape predicted to have three or more species. Japanese honeysuckle, sericea lespedeza, privet, and autumn-olive showed higher occurrence on the reclaimed sites than across the broader region. We found that geospatial modeling of these invasive plants at this scale offered potential for management, both for identifying habitat types at risk and areas that need management attention. However, the most immediate action for reducing the prevalence of invasive plants on reclaimed mines is to remove invasive plants from the reclamation planting list. Three (sericea lespedeza, autumn-olive, and sawtooth oak) out of the six most common invasive plants in this study were planted as part of reclamation activities.

Nomenclature: Autumn-olive, *Elaeagnus umbellata* Thunb.; Chinese privet, *Ligustrum sinense* Lour.; Japanese honeysuckle, *Lonicera japonica* Thunb.; royal paulownia, *Paulownia tomentosa* (Thunb.) Sieb. & Zucc. ex Steud.; sawtooth oak, *Quercus acutissima* Carruthers; sericea lespedeza, *Lespedeza cuneata* (Dumont) G. Don.

Key words: Invasive plants, logistic regression, maximum entropy, remote sensing, spatial analysis.

Nonnative plants are becoming an increasing threat to native biodiversity and ecosystem functions through invasion of both natural and managed systems (Ricciardi 2007; Vitousek et al. 1997). Land transformation and anthropogenic disturbance often facilitate the establishment and persistence of invasive plant communities (Alston and Richardson 2006; Vitousek et al. 1997). Surface mining is a major form of land transformation and has been estimated to have affected over 2.4 million hectares of terrestrial habitat in the United States since 1930 (Zeleznik and Skousen 1996). These mines are major sources of disturbance to the landscape, and thus may be a major source of invasive plants to the surrounding forest.

Since the introduction of the Surface Mine Reclamation Act (SMCRA) in 1977, all of the land transformed by surface coal mining in the United States is required to be reclaimed, with efforts aimed at improving the quality of the land by restoring the premining land use and its capability to produce vegetation. The SMCRA mandates that mined land be reclaimed and restored to its original use or a use of higher value. Land value is often measured through financial productivity (i.e., crop yield) and thus reclamation efforts rarely result in ecosystems that approximate premined characteristics.

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Management Implications

Geospatial modeling of the invasive plants studied, at this project scale, is useful and offers the potential for management both in terms of identifying habitat types most at risk and identifying areas that need management attention. At an individual species level we did not determine the need for strong active management for Japanese honeysuckle (ubiquitous), or royal paulownia (very low prevalence), both volunteer species. The only species not planted for which we suggest active management is Chinese privet. This species is considered to be the second most abundant invasive plant in the South and possibly the most detrimental. We would suggest that privet is of management concern in the Shale Hills region (SHR) given its potential distribution, and that as forest regenerates that it would be advisable to manage for privet, particularly in the depressions and low-lying areas that are more hydric and closer to water. The most immediate action for reducing the prevalence of invasive plants on reclaimed mines would be to remove invasive plants from the reclamation planting list. Three out of the six most common invasive plants have been planted as part of reclamation activities. For the planted species, sericea lespedeza was the most prevalent; however, it may be competitively excluded as forest reestablishes. For the management of this species, increased canopy cover with a diverse forest structure seems to be the best long-term approach, but the best management practice to assist in eliminating this species from the reclaimed sites would be to remove it from allowable seeding mixtures. Autumn-olive, also planted, is not at high densities throughout the larger region; it is very likely that removal of current infestation and no future planting activity would be very worthwhile and possible lead to eradication in the SHR.

Land reclamation on abandoned mine land under SMCRA has focused on reducing acid mine drainage and eliminating dangerous high-walls and hazards to the public. The Appalachian region has focused on forestry, pasture, and wildlife habitat. Current initiatives in improving land reclamation in the Appalachian region include the Appalachian Region Reforestation Initiative, aimed at restoring forest productivity by applying the forestry reclamation approach to reduce soil compaction, improve drainage, and improve plant growth media (Zipper et al. 2011).

Legislation mandates evaluation of land reclamation success after a relatively short time period (Holl and Cairns 2002). This encourages reclamation approaches that address the short-term concerns of providing erosion control and minimizing acid mine drainage, but not long-term concerns of restoration of ecosystem services. Goals for short-term and long-term recovery of highly disturbed sites often conflict (Holl 2002); for example, planting aggressive nonnative ground cover species to minimize short-term erosion may also slow long-term recovery. There is currently a push towards more diverse and ecologically sustainable reclamation (Zipper et al. 2011). Even though there is a transition to a more ecologically stable restoration approach, the legacy of nonnative plants will remain. Thus understanding the distribution across the landscape is an important component of invasive plant management and an applicable tool for evaluating the incidence of, and the potential for, invasion.

Techniques such as species distribution modeling offer opportunities for providing information on invasions of nonnative species and can be used to assess broader vegetation characteristics. To date, various statistical methods have been used to integrate individual species occurrence data with environmental spatial data to predict site suitability for alien plant species. These have included logistic regression (Collingham et al. 2000), fuzzy envelope models (Robertson et al. 2004), genetic algorithms (Underwood et al. 2004), maximum entropy (Hoffman et al. 2008), and general additive models (Dullinger et al. 2009). These models differ in the underlying algorithms and in their requirement of species-presence–only data or for both presence and true absence data. The strength of a habitat model is influenced by the correlation of species distribution to input parameters (Hoffman et al. 2010) and the number of observation points. Input parameters are often landscape-level digital information that provide a representation of environmental heterogeneity of the landscape, including climate; habitat diversity; landscape characteristics; habitat patch size and shape; connectivity; regional and local diversity of biota; vegetation structure; and the intensity, frequency, and magnitude of disturbance (Kumar et al. 2006; Stohlgren et al. 1999; With and Crist 1995), all of which vary across spatial and temporal scales (Kumar et al. 2006; Pickett and Cadenasso, 1995). Collectively, these factors result in interlaced patterns of species distribution at multiple spatial and temporal scales (Wagner and Fortin 2005).

Other research on habitat associations of invasive plants on mines have shown that the invasive plant community was predominantly associated with forest structure and composition. At an individual species level, forest structure and composition also dominated habitat associations; however, soil characteristics were also integrated (Lemke et al. 2012). This study builds on previous research of Lemke and others (2012) to assess the uses of digital geospatial data at multiple resolutions and develop non–field-based models for assessment of nonnative invasive plants on reclaimed mines. Both traditional statistics and machine learning techniques are used to model invasive probabilities across the mined landscape of the Shale Hills region (SHR) of Alabama.

Materials and Methods

Study Area. This study was conducted in the Shale Hills region (SHR) of the southern Cumberland Plateau in the

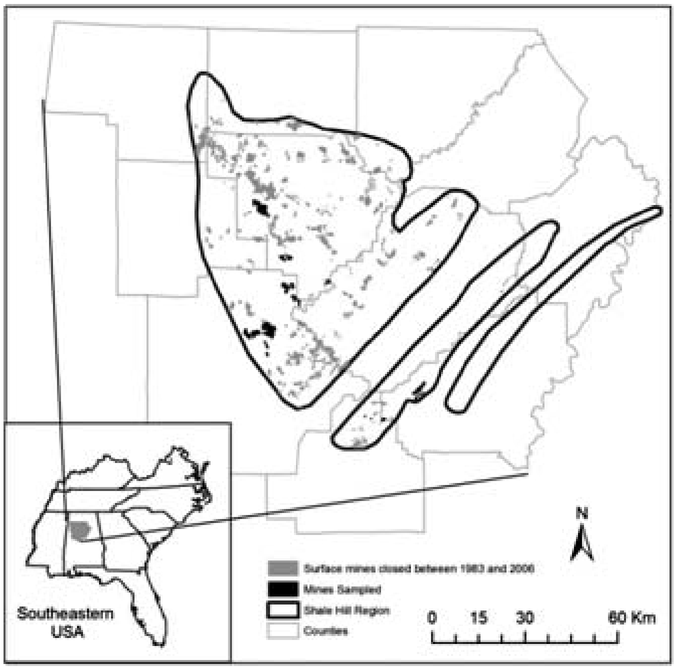

Figure 1. Study area location map, Shale Hills region, Alabama.

southeastern United States (Figure 1). The southern Cumberland Plateau has a temperate climate characterized by long, moderately hot summers and short, mild winters (Smalley 1979). Annual precipitation averages approximately 1,400 mm (55 in) and is distributed throughout the year (Smalley 1979). Topography is rugged, complex, and characterized by extensive hills, not mountains or a plateau. Strongly sloping land predominates, and the area is mostly forested. In this area, dissection has largely removed the parent soil's sandstone cap and exposed the underlying shale. Coal mining, both shaft and strip, has been a major industry (Smalley 1979). Like much of the forests in the eastern United States, the native deciduous hardwood and mixed pine hardwood ecosystems of the southern Cumberland Plateau have undergone a long history of land use change (McGrath et al. 2004; Wear and Greis 2002) though surface mining, forestry, agriculture, and urbanization. Our target area included reclaimed surface mines that have had time for vegetation to reestablish, defined as those permitted after 1983 that were closed before 2006.The final phase of restoration is planting of the permanent vegetation; mines considered in this study were planted at a rate of 1200 to 1700 pines per hectare (500 to 700 pines per acre), with 1111 trees per hectare (450 trees per acre) considered successful (Skelly and Loy Engineers 1979).

Species of Interest. Mine lands were surveyed for species as defined by the U.S. Forest Service (USFS) to be invasive to forest in the southern region (Miller et al. 2010). This paper specifically focuses on common invasive species (more than 50 occurrences across the sampled landscape). Six species were considered common: sericea lespedeza (*Lespedeza cuneata* (Dumont) G. Don), Japanese honeysuckle (*Lonicera japonica* Thunb.), Chinese privet (*Ligustrum sinense* Lour.), autumn-olive (*Elaeagnus umbellata* Thunb.), royal paulownia (*Paulownia tomentosa* (Thunb.) Sieb. & Zucc. ex Steud.), and sawtooth oak (*Quercus acutissima* Carruthers). All six species were introduced to the region from Asia in the 19th century as ornamentals or for commercial use (Miller et al. 2010, 2012) and are now found through the majority of the eastern and southern United States (USDA 2011). They share several traits that have facilitated their widespread distribution, including multiple reproductive modes and human use (Table 1). Three of the species—sericea lespedeza, autumn-olive, and sawtooth oak—have been, and continue to be, planted as part of reclamation activities (R. Johnson, personal communication).

Site Selection. Sites were selected using stratified spatial balanced sampling (Stevens and Olsen 2004). Sampling was stratified by mine age: $>$ 20 yr, 10 to 20 yr, and $<$ 10 yr, with 36 transects located across the reclaimed mined landscape of the SHR. Transects were arranged in a figure-eight pattern (crossing at right angles in the middle of the transect) covering 0.8 km (2624 ft; 100 m (328 ft) on each side of the figure eight). Sampling was carried out in the spring of 2011. Occurrence of invasive plants was assessed for every 6 m (19.7 ft) of the transect. Forbs and vines were assessed on the main transect, whereas trees and shrubs were assessed on the main transect and 3 to 9 m (9.8 ft to 29.5 ft) and 9 to 15 m (29.5 ft to 49.2 ft) on either side of the main transect. Vegetation sampling for herbaceous plants, forbs, and vines was carried out at 129 plots within each transect (beginning and end points are the same and the four points in the middle were assessed as one due to overlap), and shrubs and trees were sampled at 645 plots per transect. A total of 4,644 (36 transects by 129 plots per transect) plots were assessed for herbs, vines, and forbs and 23,220 (36 transects by 645 plots per transect) plots were assessed for trees and shrubs.

Geospatial Data. Mine boundaries were obtained from Alabama Surface Mining Commission and verified with georeferenced aerial photography of 2009 obtained from the U.S. Department of Agriculture, Natural Resources Conservation Service (USDA NRCS), National Cartography and Geospatial Center. The time since mine closure was determined by the permit release or forfeit date (forfeited permits often did not undergo full reclamation, with natural reestablishment of plant communities), and grouped into three age classes (1983 to 1990, 1991 to 2000, and 2001 to 2006). Environmental and topographic variables were represented by slope, aspect (northness), solar radiation, curvature, and distance from water. These variables were selected based on their biological importance

Table 1. Summary of invasive species (Miller et al. 2010, 2011; USDA 2011; R. Johnson, personal communication).

Scientific name	*Lespedeza cuneata*	*Lonicera japonica*	*Ligustrum sinense*	*Elaeagnus umbellata*	*Paulownia tomentosa*	*Quercus acutissima*
Common name	Sericea lespedeza	Japanese honeysuckle	Chinese privet	Autumn-olive	Royal paulownia	Sawtooth oak
Area of origin	Japan	Japan	China/ Europe	Japan/China	China	Asia
% of plots	53%	30%	1%	2%	0.5%	< 0.5%
Planted for reclamation	1970s to now	No	No	1970s to now		1970s to now
Estimated date of entry in to United States	1899	1882	1852	1830	1844	1862
Reproductive mode	Vegetatively and seed	Vegetatively and seed	Vegetatively and seed	Vegetatively and seed	Vegetatively and seed	seed
Shade tolerance	Low	High	High	Moderate	High	
Cold tolerance	Moderate	Moderate	Moderate	High	Moderate	
Human use	Pasture, erosion control, mining reclamation	Ornamental, creating wildlife habitat	Ornamental	Erosion control, mining reclamation, creating wildlife habitat	Ornamental, timber	Ornamental, creating wildlife habitat

suggested by other studies (Bartuszevige et al. 2006; Gutierrez et al. 2005; Lemke et al. 2011; Lockwood et al. 2007). They were derived from a 10-m digital elevation model (DEM) (Gesch et al. 2002). The DEM was used to generate slope (degrees), aspect (degrees), solar radiation (Wh m^{-2}), and curvature using ArcGIS Spatial Analyst tools (ESRI 10.0, Redlands, CA). Aspect was transformed into a linear north–south gradient (northness) by performing cosine transformation (Guisan et al. 1999). Solar radiation was calculated as the annual watt-hours per square meter given no cloud cover (ESRI10.0). Curvature is a measure of shape of the landscape, whether it is flat, convex, or concave. In ArcGIS, "curvature" assesses surrounding cells to calculate a curvature, with increasing positive scores representing increasing concavity (ESRI10.0).

Streams and water bodies may affect the distribution and establishment of plant species by influencing moisture availability. Riparian areas have been shown to contain more invasive plant species than nearby upland areas (Stohlgren et al. 2002). Therefore distance from water was included in the model. Considerable landscape alteration (due to mining activities) has occurred, therefore streams and water bodies were digitized from 2009 georeferenced aerial photography and not taken from available geospatial data sets to increase accuracy. Climate and elevation data were not integrated into these models. Since only few counties were sampled, variation in climate and elevation is small and as such is not likely to be important.

A number of anthropogenic variables related to land cover and roads were calculated. Land cover data were taken from the national land cover data available for 1992, 2001, and 2006 (Fry et al. 2011; Homer et al. 2004; Vogelmann et al. 2001). Percentage of forest within 100 m (328 ft) of each plot was calculated using Neighborhood Statistics (ESRI). Open area and distance to forest edge was assessed from 2009 georeferenced aerial photography. Public road files are available from U.S. Census Bureau and Alabama Department of Transportation, but due to the large numbers of access roads additional roads were digitized from 2009 1-m (3.3 ft) aerial photography obtained from USDA NRCS, National Cartography and Geospatial Center.

Color infrared imagery for 2009 and Landsat Thematic Mapper imagery of 1987, 1991, 1998, 2004, and 2011 were used to derive Normalized Difference Vegetation Index (NDVI) (Rouse et al. 1974). The NDVI is a simple indicator used to analyze remote sensing measurements to assess whether the target being observed contains live green vegetation or not. From the geospatial data we obtained a total of 18 landscape variables.

Data Analysis. Pearson's correlations between each of the environmental and anthropogenic variables were assessed using SAS (version 9.2, SAS Institute, Cary, NC) to identify less-correlated ($r^2 < 0.50$) variables for further analysis. The variable retained was selected on biological relevance and ease calculation. Invasive species occurrence data were assessed using logistic regression and MaxEnt modeling approaches. Logistic regression is a generalized linear model that is used to investigate the relationship between a categorical outcome and a set of explanatory variables or for prediction of the probability of occurrence of an event by fitting data to a linearization of the logistic curve, using the absence and presence data (Hosmer and Lemeshow 2000). It makes use of several predictor variables that may be either numerical or categorical. Logistic regression makes no assumptions about the distribution of the independent variables. Logistic regression was conducted using SAS (SAS Institute). Data were resampled to give balance data with at least a 20% occurrence for each species (Oommen et al. 2010). MaxEnt (Phillips et al. 2006) is based on a maximum entropy probability distribution, the distribution whose entropy is at least as great as that of all other members of a specified class of distributions. MaxEnt estimates the probability distribution that is most spread out subject to constraints such as the environmental characteristics at known locations of the species. The MaxEnt model only uses occurrence data. A combination of modeling techniques was used to increase confidence in the result. One of the major differences between the two modeling methods is the use of absence and presence data in logistic regression and presence only in MaxEnt. To assess models the data were split with 70% to training and 30% for testing. One hundred replications were run for the MaxEnt and logistic regression models to obtain the average importance, area under the curve (AUC), and type II error. For descriptive purposes, variable importance and direction of variables were tabulated. For logistic regression, variable importance was calculated using the Wald chi-square statistic, dropping the intercept Wald chi-square and standardizing the remainder to 100. Prediction accuracy was assessed using AUC and type II error. We used the following classes of AUC to assess model performance: 0.50 to 0.75 = fair, 0.75 to 0.92 = good, 0.92 to 0.97 = very good, and 0.97 to 1.00 = excellent (Hosmer and Lemeshow 2000). Type II error was assessed based on a threshold value determined by maximizing specificity plus sensitivity (Manel et al. 2002). Due to variation in species occurrence across the study area, benchmark type II errors were defined as if data were randomly assigned, and a decrease of more than 25% was considered a useful model (Hair et al. 2006; Manel et al. 2002).

Geospatial data were applied in models to assess potential distribution of each species across the study area. Maps were generated by reclassifying the continuous output to binary using the maximized specificity and sensitivity threshold. For each species, the logistic regression and MaxEnt maps were combined to give estimates of the proportion of the landscape that had low potential (not predicted by either model), moderate potential (predicted by one model), and high potential (predicted by both models). These maps were then combined to give an estimate of invasive species diversity across the landscape.

Results and Discussion

Overall elevation of the study area ranged from 103 to 230 m, with an average slope of 9%. The average distance to a road (including service roads) was 92 m and the average distance to water was 240 m. The surrounding area (100-m radius) of any point was, on average, 42% forested (Table 2). Pearson's correlation was used to remove the highly correlated variables of open area, proportion of forest within a 100-m area, and NDVI of 1991 and 2004. Variable reduction through correlation assessment identified 13 variables to be used for model development.

We found robust models for five of the six species, all with comparable AUC and decreases in type II error rates between the MaxEnt and logistic regression models (Table 3). We did not find a robust model for sericea lespedeza (AUC < 0.70). Of all the geospatial variables used, distance to forest, distance to roads, and NDVI of 1987 and 2011, supplied the highest contribution to the models. Distance to forest was significant (logistic regression) or important (MaxEnt), in 11 out of the 12 models (Table 3). This suggests that landscape disturbance and habitat characteristics (amount of forest) are greatly influencing the distribution of invasive species in the area at the scale of these models. One caveat to note is that these models are of habitat characteristics that may be influencing the distribution within the climatic and elevational range of this study area and not broad-scale distribution models.

Although we were assessing the distribution of species invasive to the forested areas, there was one species that was not associated with forest: sericea lespedeza. Sericea lespedeza is a planted species and was especially prevalent in the open areas. It had the weakest models with logistic regression test, with an AUC of 0.70, and MaxEnt test AUC of 0.69 and decrease in type II errors of 0.45 and 0.36, respectively (Table 3). Sericea lespedeza was predicted to increase on sites that had more recently been reclaimed, had a greater distance from an established forest, were closer to roads, had less forest in 1990, and a lower NDVI in 1998 and 2011 (Table 3). The result suggests that the most recently disturbed areas are dominated by sericea lespedeza and that this species may be competitively excluded as forest reestablishes. The models generated for sericea lespedeza were not strong, suggesting there may be other factors that need to be considered in determining distribution. Previous work by the lead author related to local habitat characteristics on reclaimed mines in the region showed higher prevalence of sericea lespedeza in open or pine areas with little or no midstory (Lemke et al. 2012). Sericea lespedeza has been planted since 1970 as part of reclamation plans; this still continues today (R. Johnson, personal communication), and it may be the effect of this planting that we are failing to capture. For the management of this species where the species already exists,

Table 2. Summary of geospatial variables measured at each plot.

Code	Description	Mean ± SD	Range	Unit	Source
Age	Date of bond release or forfeit	1995 ± 6	1983 to 2006	yr	Alabama Surface Mining Commission
Northness	transformed into a linear north–south gradient, cosine transformation	0.03 ± 0.71	−1 to 1		USGS 10 m DEM[a]
Curvature	shape of the landscape, whether it is flat, convex, or concave (increasing positive scores representing increasing concavity)	0.04 ± 1.46	−14.8 to 1 6.5		USGS 10 m DEM
Slope	Slope	8.9 ± 6.6	0.3 to 55	degrees	USGS 10 m DEM
Solar	Solar radiation given no cloud cover	246 ± 10	131 to 254	Wh m^{-2}	USGS 10 m DEM
Dist River	Distance to water	240 ± 132	0 to 660	m	2009 aerial photo
Open100	Proportion of open land within 100 m of plot	0.39 ± 0.34	0 to 1		2009 aerial photo
Dist Forest	Distance to forest	73.3 ± 88.1	0 to 360	m	2009 aerial photo
Dist Roads	Distance to roads	92.2 ± 71.6	0 to 352	m	2009 aerial photo
Forest06	Proportion of forest within 100 m of plot in 2006	0.42 ± 0.36	0 to 1		USGS LULC
Forest00	Proportion of forest within 100 m of plot in 2001	0.46 ± 0.36	0 to 1		USGS LULC
Forest90	Proportion of forest within 100 m of plot in 1992	0.78 0.29	0 to 1		USGS LULC
NDVI2009	NDVI in 2009	0.19 0.05	−0.05 to 0.31		2009 aerial photo
NDVI1987	NDVI in 1987	0.43 0.25	−0.12 to 0.74		Landsat
NDVI1991	NDVI in 1991	0.34 0.21	−0.05 to 0.71		Landsat
NDVI1998	NDVI in 1998	0.23 0.11	−0.05 to 0.6		Landsat
NDVI2004	NDVI in 2004	0.41 0.17	−0.03 to 0.73		Landsat
NDVI2011	NDVI in 2011	0.43 0.11	0 to 0.66		Landsat

[a] Abbreviations: USGS, U.S. Geological Survey; DEM, digital elevation model; LULC, land use/land cover; NDVI, Normalized Difference Vegetation Index.

increased canopy cover with a diverse forest structure would be an effective long-term approach. However, the best management practice to assist in eliminating this species from the reclaimed sites would be to remove it from allowable seeding mixtures.

The models generated for Japanese honeysuckle were considered acceptable with a logistic regression test AUC of 0.75 and a MaxEnt test AUC 0.73, and high decrease in test type II errors at 0.70 for logistic regression and 0.66 for MaxEnt (Table 3). Two variables, distance to forest and NDVI of 2011, dominated both models, with combined relative importance of over 60% of each model (Table 3). Sericea lespedeza and Japanese honeysuckle utilized opposing habitats in the landscape and were ubiquitous across the area. Japanese honeysuckle was more likely to be close to, or within, forest, and with a higher NDVI in 2011 (Table 3). This suggests that it is primarily in forested environments. Our finding agrees with other studies that have found Japanese honeysuckle to have high shade tolerance and lower competitive abilities in open or high-light environments (Miller et al. 2010; Lemke et al. 2012). Japanese honeysuckle has been widely planted for deer and cattle forage (Dickson et al. 1978; Patterson 1976) and is now considered naturalized in upland and lowland forests as well as in forest-edge habitats of the southeastern United States (Patterson 1976; Yates et al. 2004). It is not as detrimental as some of the other nonnative species, but it has been shown to impact even-aged pine regeneration when established at very high densities (Cain 1991). Given the prevalence of Japanese honeysuckle throughout the southern states, there may be scant management efficacy for its removal from the SHR.

Table 3. Summary statistics of the logistic regression and maximum entropy (MaxEnt) models from 100 resamples for six dominant invasive plant species. Variable contribution and direction of relationship are given along with the average contribution of each variable to all species. See Table 2 for descriptions of codes.

	Autumn olive		Sericea lespedeza		Chinese privet		Japanese honeysuckle		Royal paulownia		Sawtooth oak	
Variable	M[a]	L	M	L	M	L	M	L	M	L	M	L
Test AUC	0.88	0.82	0.69	0.70	0.83	0.79	0.73	0.75	0.96	0.97	0.92	0.83
MaxSS threshold	0.31	−1.83	0.46	−0.09	0.32	−1.26	0.42	−0.88	0.11	−1.30	0.27	−1.06
MaxSS type II error	0.17	0.12	0.30	0.26	0.34	0.37	0.24	0.21	0.06	0.07	0.20	0.32
Random type II error	0.80	0.80	0.47	0.47	0.80	0.80	0.70	0.70	0.80	0.80	0.80	0.80
Decrease in type II error from random	0.78	0.85	0.36	0.45	0.58	0.54	0.66	0.70	0.93	0.91	0.75	0.60
Mine age	2	6*	5*	22*	−10	−15*	−2	−2*	17	12*	0	1
Curvature	1	1	0	0	∩1[b]	0	∩1	0	0	1	∩1	0
Dist Forest	−17*	−13*	7*	12*	−21*	−41*	−27*	−42*	−2*	2	−15*	−34*
Dist River	−12*	0	8*	4*	−21*	−24*	U3*	−3*	0	−1	∩1	3
Dist Roads	7*	14*	U4	−5*	−8*	−1	U5*	−5*	∩2	7	30*	36*
Forest06	13*	0	−5*	2*	∩9*	−8*	3*	−11*	4	1	∩18*	−4
Forest92	−3*	−9*	−10*	−11*	−1	0	2	3*	−1*	0	−1	−9
NDVI1987	−35*	−51*	U2*	−7*	∩10*	1	4*	0	−60*	−45*	∩25*	−3
NDVI1998	∩2*	2	∩26*	−28*	∩1	0	11*	7*	0	−3	0	−1
NDVI2009	1	1	∩2	−1	−1	1	1	4*	9	12*	3	4
NDVI2011	5	2	∩29*	−7*	∩12	−3	38*	22*	3	7	U1	−3
Northness	1	1	1	0	−3	−5*	1	0	U1	−5	∩2	1
Slope	1	0	1	1	∩2	1	∩2	−1	∩1	−4	−3	1

[a] Abbreviations: M, MaxEnt; L, logistic regression; AUC, area under curve; MaxSS, maximum sensitivity and specificity.

[b] ∩ and U are nonlinear relationships.

[*] For logistic regression, significance was measured at 0.05 level (represented with *); for MaxEnt, a measure of importance was used for each variable at 5% (represented with *).

The models generated for Chinese privet were good, with AUCs of 0.79 for logistic regression and 0.83 for MaxEnt, and decreases in type II errors of 0.54 for logistic regression and 0.58 for MaxEnt (Table 3). Privet was more likely to be found close to, or within forest, close to water, and on older reclaimed mines (Table 3). Chinese privet is considered the second most abundant invasive plant in the south and is most prevalent in the understory of bottomland hardwood forests (Merriam and Feil 2002). The authors suggest this to be of management concern in the SHR and that as forest regenerates it would be advisable to manage for privet, particularly in more hydric to mesic areas, closer to water.

The models generated for autumn-olive were good, with AUCs of 0.82 for logistic regression and 0.88 for MaxEnt, and decreases in type II errors of 0.85 for logistic regression and 0.78 for MaxEnt (Table 3). Autumn-olive was more likely to occur within or closer to forest, closer to rivers, but farther from roads, and with low NDVI in 1987 (Table 3). Once established, autumn-olive can develop intense shade, which suppresses native species and can cause serious problems for native species that flourish on nitrogen-poor

Table 4. Probable proportion of mined landscape invaded for six dominant invasive plant species.

Probability of occurrence	Autumn-olive	Sericea lespedeza	Chinese privet	Japanese honeysuckle	Royal paulownia	Sawtooth oak
Low	0.62	0.62	0.70	0.27	0.97	0.74
Moderate	0.25	0.21	0.23	0.25	0.03	0.21
High	0.14	0.17	0.07	0.48	< 0.01	0.05
Correlation between models	0.41	0.51	0.28	0.52	0.30	0.17

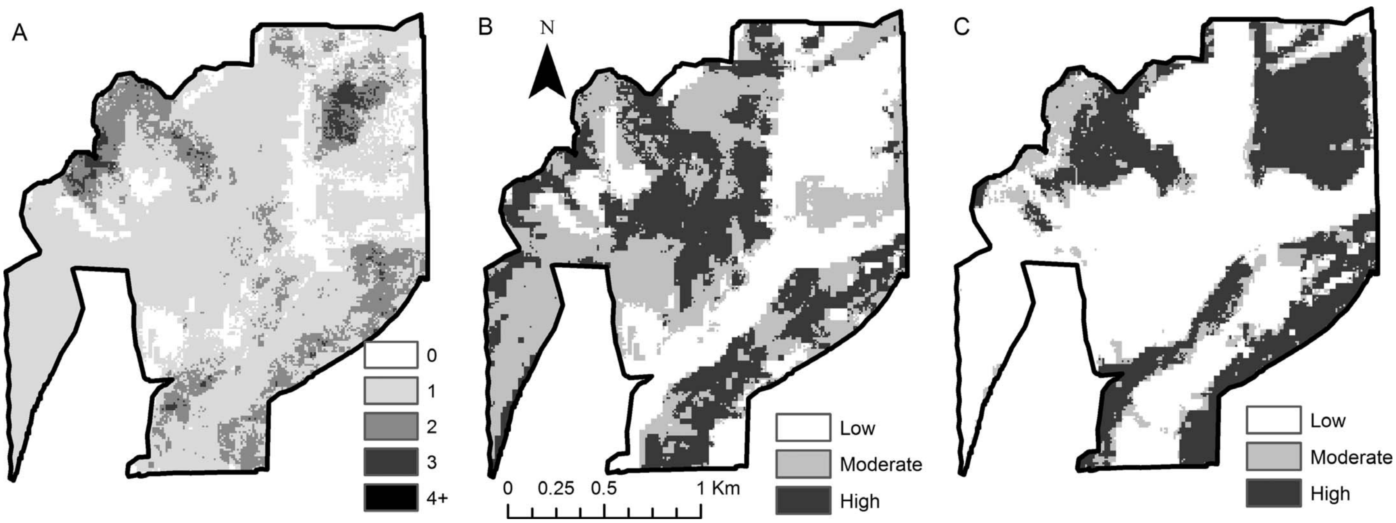

Figure 2. Example of mapping modeled invasive plant distribution on one reclaimed mine in the Shale Hills region, Alabama. (A) Combined geospatial species models to give probable number of invasive species. (B) Probable distribution of sericea lespedeza. (C) Probable distribution of Japanese honeysuckle.

soils (Sather and Eckardt 1987). It has been planted as part of reclamation in this area since the 1970s (R. Johnson, personal communication). In this study, the older mined areas had a higher occurrence of planting. However, the plants found were not only those planted, but volunteers that established around these plantings. As autumn-olive is not at high densities throughout the larger region (Miller et al. 2012) it is highly likely that removal of current infestation and no future planting activity would be worthwhile and could lead to eradication in the area.

The models generated for royal paulownia were very good, with test AUCs of 0.97 for logistic regression and 0.96 for MaxEnt and change in type II errors of 0.91 for logistic regression and 0.93 for MaxEnt (Table 3). Royal paulownia was more likely to be found with a low NDVI in 1987, in areas with historical disturbance. Royal paulownia occurrence was approximately even throughout the broader region and the SHR. Although some active management would be useful, this species is not of major concern.

The models generated for sawtooth oak were good, with AUCs of 0.83 for logistic regression and 0.92 for MaxEnt and decrease in type II errors of 0.60 for logistic regression and 0.75 for MaxEnt (Table 3). The greatest discrepancy between models was for sawtooth oak, where MaxEnt had an AUC of 0.09 higher and a 0.15 greater decrease in type II error rate than logistic regression. Sawtooth oak is a planted species and, as far as we could determine in the field, has not yet spread from the original plantings, thus the MaxEnt would likely do a better job of capturing its potential due to its current limited distribution. Sawtooth oak was more likely to be found within, or closer to, forests, and farther from roads (Table 3). It has been planted as part of reclamation in this area since the 1970s (R. Johnson, personal communication), for wildlife. Although sawtooth oak possesses many favourable traits, some studies have shown that it is not as hardy as native oaks and may not be as long-lived (Huntley and Hopkins 1979). During the course of the field work, we did not notice volunteer individuals; however, any non-native species is a risk and we would suggest that it be removed from the list of plants appropriate for reclamation.

All invasive species considered in this study occur on an average of $< 5\%$ of forested sites across the southern region (Miller et al. 2012). Japanese honeysuckle, autumn-olive, sericea lespedeza, and Chinese privet show had higher occurrence in the SHR than in the broader landscape, suggesting that mining or reclamation activities are likely influencing the increased occurrence of invasive plants. Models generated for each species were then applied to the mined landscape of the SHR to assess the probable occurrence of each species across the landscape. Japanese honeysuckle had the highest probable occurrence at 48% (73% moderate probable occurrence), with royal paulownia having the lowest at less than 1% (3% moderate probable occurrence) (Table 4). Overall, 33% of the landscape was predicted to have no invasive plants, with 47% predicted to have one invasive plant species, 17% to have two, and 3% to have three or more. An example of the mapped output is given in Figure 2. Sericea lespedeza and Japanese honeysuckle were found on opposing areas (see Figures 2B and 2C), with sericea lespedeza in the open and Japanese honeysuckle in forested areas.

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