Spatial Distribution of Four Exotic Plants in Relation to Physical Environmental Factors with Analysis using GIS

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Abstract

The spatial distributions of four plant species native to Asia, yet considered invasive in southwestern Virginia, were studied in order to produce predictive habitat maps. The study took place in the mountains to the north of Blacksburg, VA, on National Forest lands. A random GPS survey of each of the four species, *Microstegium vimineum*, *Lonicera japonica*, *Rosa multiflora* and *Elaeagnus umbellate*, was used in combination with a series of Geographic Information System (GIS) layers representing environmental variables (Elevation, Aspect, Roads, Trails, Streams, & Normalized Difference Moisture Index) to produce logistic regression models. After field-validating the models, the models were ranked according to usefulness, with the *E. umbellate* model proving most accurate. It is hoped that such GIS models will allow forest managers to more productively search for invasive species within their jurisdiction, by indicating sites more likely to provide habitat suitable to the invasive species described by the model.

A non-GIS search for correlations between the study species' presence and field-collected discrete environmental variables was also included. Both Disturbance and Canopy Cover were considered for their effect upon *Microstegium vimineum*, *Lonicera japonica*, *Rosa multiflora* and *Elaeagnus umbellate* presence. Using Pearson's Correlation with the Canopy Cover data, and Chi-squared Correlation with the Disturbance data, only *R. multiflora* and *E. umbellate* showed significant correlation to decreasing canopy cover.

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A Description of Terms

There are two main, artificial (not based on genetic relationship) categories into which all plants may be divided: *native* and *exotic*. For any given area there exist plants that first arrived in the area under natural circumstances (Sauer 1988), either evolving in place or being carried there by wild animals, wind, or water; these plants are considered *native*. *Exotic* plants are defined as all the plants in an area which are not native (they may also be referred to as non-native or alien) (Heffernan 1998). *Exotic* plants are transferred to new areas through human-related phenomena. Exotics can be further subdivided into various classes which can include *invasive* and *non-invasive*. *Invasive* plants are those that spread excessively, reducing diversity and generally negatively altering the natural landscape (Goodwin et al. 1999; Higgins et al. 1999; Gabbard and Fowler 2006; Hallett 2006).

Chapter 1: Introduction

Within the context of the global distribution and spread of plant species, humans have always played an active role. However, after the advancement of boating technology within the last six hundred years and the far-reaching advances of British colonialism, the exchange and redistribution of plants around the world has accelerated greatly (Mack 2003). Prior to transportation via human action, plants spread only by the natural means available to them, and only if the propagule was, at the end of the trip, still viable (Lockwood et al. 2007).

Over the centuries, plants have been purposefully introduced for a variety of reasons. European colonists often carried essential medicinal and crop plants with them to their new homes, some of which would escape into the wild, while still other species were intentionally released to improve a new environment (for a given value of 'improve') (Bright 1998; Lockwood et al. 2007). The intercontinental routes of diffusion, along which such introductory vectors travel, have only increased in frequency with the introduction of mechanized travel: the sailing ship landing at an exotic port would have brought new species a few times a year; an airplane might now land at the same destination many time a day (Lockwood et al. 2007). The increased frequency of vectors also means an increased frequency of accidental introductions, which can have a surprising effect on the local environment (Bright 1998; 2006; Lockwood et al. 2007).

In fact, introduced species make up the bulk of the United States food industry (Pimentel et al. 2004), though not all introduced species are possessed of a beneficial nature. For example, Thomas, Ellison, and Tomley (2006) concluded that the general release of a certain plant pathogen in Australia may provide relief from Lantana, a plant cultivated ornamentally in the past and now "considered one of the world's most problematic weed" (p. 35). It is estimated that the United States spends 25 billion dollars per year on damages caused by exotic plants alone; however, only 9.6 billion dollars per year is spent in the US trying to control those plants (Pimentel, Zuniga, and Morrison 2004).

In an effort to stem the spread of invasive plant species into the United States of America and control those already occupying the territory, Executive Order 13112 was placed in effect by then US President William J. Clinton. This order charges federal agencies dealing with exotic species to do so in a carefully controlled manner, and includes duties for the identification, detection, and management of populations falling within their jurisdictions (Clinton 1999). The objectives of this Executive Order lie readily within the USDA Forest Service's mission "…to sustain the health, diversity, and productivity of the nation's forests and grasslands to meet the needs of present and future generations" (USDA 2008). Invasive plants in the realm managed by the USDA Forest Service can easily disrupt that mission, as they are defined in the executive order as able "…to cause economic or environmental harm or harm to human health" (Clinton 1999).

Current conservation efforts on the part of forest managers are based on the idea that the initial spread of exotic plant species occurs from visitor access areas, and limiting this initial foothold (Leung and Marion 1999). To support these efforts, trails have been examined in detail for their role in exotic species distribution (Benniger-Truax et al. 1992; Tyser and Worley 1992; Campbell and Gibson 2001; Potito and Beatty 2005; Gabbard and Fowler 2006). Results of such studies have been mixed in the degree to which trails and roads affect exotic species' spread.

Dispersal agents of exotic plants include humans, animals, wind and water (Daubenmire 1974; Kellman 1980). Determining the factors that influence the dispersal and distribution of exotic plants requires an understanding of the relationships among plants and their environment. Thus, the field of autecology and its principle precepts, which seek to determine the environmental requirements of individual plants, should not be underappreciated in the search for those factors effecting the distribution of exotic plants. Various authors have described the many effects of local environmental characteristics on plant distribution and health (Moskalenko et al. 1961; Pavlova 1961; Preobrazhenskaya 1961; Viktorov et al. 1964; Daubenmire 1974; Smith and Burkhart 1976; Kellman 1980; Meiners et al. 1984; Howard and Mitchell 1985; Avery and Burkhart 1994; Kruckeberg 2002). The fact that the immediate environment can have a direct effect on a species' presence or absence in any area can lead to the identification of the preferred habitat of that species, if its particular environmental requirements or preferences are known.

Only a few, recent studies have considered the spatial distribution of exotic, invasive plant species using GIS as a means of analysis (Franklin 1995; Higgins et al. 1999; Price and Tinant 2000; Rew et al. 2005; Ruiz et al. 2006). So considered, patterns of distribution, and thus a species' autecology, may be discerned. By modeling the autecology of an invasive species, and applying that model across a region similar to the study area, areas most likely to support the invasive plant in question may be identified- a bottom-up approach to determining an invasive species' biogeography. Thus, areas considered to be the likely habitat of an invasive species may be given a higher priority for sampling by the management agency responsible for finding and mapping such populations.

Thesis Goal & Objectives

The goal of this thesis was to use GIS to create models predicting habitat of high risk for four common invasive plant species (*Microstegium vimineum*, *Lonicera japonica*, *Rosa multiflora*, and *Elaeagnus umbellate*) found in recreational park areas of the Appalachians in southwest Virginia. It is a goal which supports Executive Order 13112 and the Management Plans which the Order spawned, namely the detection of populations of invasive species for later control (Clinton 1999).

To operationalize this goal, three main objectives were attained. From study sites located in Jefferson National Forest and Mountain Lake Wilderness, current positions of species presence and absence were found through field sampling. Models were then created to simulate the relationship between the environmental variables selected for analysis and georeferenced sample site positions. Finally, the models were validated through further field sampling the following year, and ranked by usefulness.

Significance

This study will not only further knowledge of the autecology and the distribution of certain exotic plant species in southwest Virginia, but also leads to useful models depicting areas with a high likelihood of supporting invasive plants within the Appalachians.

Although some information of a species' preferred habitat may already be known, any new habitat study only adds to that available information base. Through the regression variable selection methods employed during this project, only the environmental variables most important (of those offered for selection and analysis) to recorded plant species' positions were used in the subsequent models. Such significant variables may be used in other, future studies of the plant species represented here.

Predictive models of exotic plant species' likely habitat allow forestry management personnel advanced knowledge of areas in danger of invasion (if suitable propagation materials were in evidence), allowing sufficient time to plan management strategies. The Forest Site Quality Index (FSQI), which utilizes topographic and other environmental variables and was originally created without a modern GIS, has similarly been used by forest managers for decades to indicate forest productivity and to help facilitate proper management (Smith and Burkhart 1976; Meiners et al. 1984; Avery and Burkhart 1994). GIS and geographic positioning systems (GPS) are even now being used to determine site-specific management practices to be applied within fields of crop plants to maximize yield while minimizing expenses (Ruiz et al. 2006).

The use of GIS specifically in this project yields a more comprehensive understanding of the selected exotic species' spatial distributions than traditional field study alone by utilizing pre-existing data layers and a holistic approach to spatial analysis. The only information gathered in the field are species' positional information, existence of study species, and information not readily available as a continuous data set (existence of disturbance; percent canopy cover), allowing addition or removal of variables of suspected importance within the GIS software. Map layers such as stream networks and digital elevation models are often available from institutional, government, and private sources, and can be integrated into GIS models with field-collected data as the need arises. Pre-GIS studies examining correlations between a species and its local habitat variables have relied on direct measurement of each suspected significant variable (Daubenmire 1974), and variables identified as likely statistically significant needed to be tested in field experiments- an extended process (Kellman 1980). The complex sampling mentioned by Daubenmire is, in this project, not needed, as such measurements are already compiled in the data layers provided by other sources; nor is the predetermination of likely variables to sample required, as variable layers may be added into the GIS as they are found or needed. Kellman's dilemma is similarly neutralized as the project is not based solely on observational data, but on georeferenced species' positions and similarly referenced data layers which mimic the environment; using this technique allows the initial information collection and analysis to be carried out in a simplified GIS environment and only uses the field to test the model's results. Finally, any data produced by this project can later be incorporated into subsequent studies of the area, because the data are in an easily retrievable and transferable format.

Chapter 2: Literature Review

Concepts described in the following Literature Review introduce the theoretic base for this study. An introduction to the basic ideas of ecology applied to plant habitats and non-native plant habitats is followed by an explanation of how exotic plants respond to habitats, the basis of the following research. The importance of immediate environmental habitats is then discussed in the context of various habitat variables, the effects of artificial habitats, and disturbance, most of which were included in this study. Trails and roads are discussed as they relate to the positions of habitats; trails and roads become very important during the second stage of the initial data collection, described in greater detail later.

Ecological Basics

Individual plant species have specific resource requirements provided by the habitats in which they reside (Gleason and Cronquist 1964). Similarly, habitats lacking those requirements will lack those species. That local environmental factors directly relate to the presence of a species is the basic principle of autecology (Daubenmire 1974; Kellman 1980). Wheat could be maliciously introduced to the Arctic Circle in a vain attempt to displace native vegetation, but it would not flourish, being ill-adapted to the environment (light availability, temperature, and water availability being important limiting factors here).

However, when exotic species are introduced to a new habitat, there exists the possibility that they will develop invasive traits not displayed in their native habitats: spreading throughout their new environment and endangering the species naturally found therein. The development of invasive traits in a new and alien habitat is generally revealing of the plant's innate ability to reproduce in a favorable environment (Gleason and Cronquist 1964) coupled with the relative removal of pests (Kellman 1980) and other co-evolved relationships (Hallett 2006) found in the plant's native range. Newly invaded areas tend to occur in the same climate type as the immigrant plant's native habitat (Daehler et al. 2004; Hallett 2006) or general geographic range (Goodwin et al. 1999), and the environmental requirements will be the same as well. Invasive and potentially invasive species existing within the Appalachians will conform to these basic autecological rules. The areas such species should be able to invade can be identified through models created from the present spatial distributions of these species correlated with environmental mesohabitats.

Importance of Habitat: Old & New

In an exotic plant's native range, there are many factors that may keep its population in check. Competition for resources between species and between individuals is only one aspect of population control (Kellman 1980; Keddy 2001) in any environment. Hallett (2006) argues that invasiveness or noninvasiveness in displaced exotic plant species occurs only after the disassociation with coevolved factors found within the plant's native range. Such factors include coevolved relationships with mutualists, microorganisms, and allelopathic chemicals (Hallett 2006). Dissociation with pests occurring in the native range can allow continued, vigorous growth in the new habitat (Kellman 1980).

There is currently no known, completely accurate method for predicting whether or not an exotic species will become aggressively invasive, out-competing native flora for habitat and resources, if introduced to a new area (Daehler et al. 2004;

Hallett 2006). Many exotic immigrant species do not react in such a fashion, but exotics can and often do spread through natural areas in a way alarming to conservationists and preservationists who wish to keep natural areas "natural." Numerous factors relating to the large-scale spread of such exotics have been proposed from study results, of which anthropogenic (human-induced) disturbance seems to be commonly cited, but of which biogeographic factors must still be taken into account.

Importance of Local Factors

Geoedaphic ("reciprocal interactions of topography [landforms], lithology, and soils with floras and vegetation") (Kruckeberg 2002, p. 320) landscape features of mountains have been shown to have a great influence on local climates (hereafter referred to as mesoclimates), and in effect, the spatial distribution of plant species adapted to these climates (Kruckeberg 2002). Some geoedaphic features are interrelated; exposure to sun, wind, and precipitation all interact in complex ways to mold an area's mesoclimate.

Topographic factors have been shown to directly affect plant growth with variations occurring along resource gradients (Keddy 2001); although such gradients are not specifically studied in this project, certain topographic factors (aspect and elevation) have been included. Aspect, the compass direction occurring along the greatest slope of a mountain face, has a large effect on species composition (Howard and Mitchell 1985). Solar insolation plays a great role in moisture loss, and aspects incurring more sunlight tend to be drier (Wathen 1977; Lipscomb and Nilsen 1990). The Virginia Appalachian region shows a distinct variation in forest type with aspect (and consequently moisture); south and southwest aspects are normally xeric and yield oak-pine forests, whereas most other aspects support oaks and other hardwoods (Delcourt and Delcourt 2000). Aspect, along with site position on a slope and percent slope, have been used to determine soil available moisture indexes for vegetation research and forestry applications (Smith and Burkhart 1976; Meiners et al. 1984). Elevation is known to have an effect on vegetation type, with such populations experiencing lower temperatures, higher winds, and more extreme precipitation as elevation increases (Kruckeberg 2002). In his study published in 1981, Robert Leffler correlated such a decrease in temperature range with increase of elevation at selected Appalachian mountaintops, as well as mentioning the presence of high winds in such locations (Leffler 1981). This change in climate with elevation allows tree species more commonly found in boreal forests to survive at higher elevations (Constantz 2004).

Light availability has been noted as a very important factor in influencing the spread of exotics, as exotic species are most often found in high light conditions (Parendes and Jones 2000; Hawbaker and Radeloff 2004) such as those found along most trails and roads. For example, Gabbard and Fowler (2006) examined a single species of grass (*Bothriochloa ischaemum*) and found a positive trend toward its distribution along roads, but not along streams or trails. Only later did the researchers mention that this particular species is never found "under tree canopies" as were both the streams and trails sampled, rendering population limitation results more in favor of light limitations than were the study's original intent (Gabbard and Fowler 2006).

In the context of invasive, exotic species, a large amount of research has been devoted to the study of habitat altered by human action; such research is generally grouped under the subject of 'disturbance.' Disturbed areas are generally considered prime habitat for exotic species colonization. Roads and trails are commonly such areas of habitat created by disturbance (Benniger-Truax et al. 1992; Parendes and Jones 2000; Harrison et al. 2002; Watkins et al. 2003; Potito and Beatty 2005; Wangen et al. 2006), whether degree of disturbance (Rentch et al. 2005), creation of more edge via fragmentation (breaking once-continuous habitat into smaller, discontinuous habitats) (With 2002), or a combination of factors relating to light and litter levels (Watkins et al. 2003) was considered a more important factor in creating habitat conducive to exotic species. A study in Theodore Roosevelt National Park found that the number of exotic plant species sited along disturbed transects were greater or equal to the number found along undisturbed transects (Larson et al. 2001). Conversely, a study in Glacier National Park concluded that anthropogenic disturbance was not a viable factor in the spread of exotics into grassland areas, having found exotics in areas not grazed by cattle (Tyser and Worley 1992). Still, it is generally understood that disturbance, as a factor by itself, plays some role in the invasive potential of exotic plants (Hallett 2006).

Natural disturbances such as fire and high winds create a constant turnover of succession in the Appalachians. Both burned vegetation and windthrown trees alter the soil nutrients in the immediate area and facilitate light penetration by opening gaps in the canopy (Constantz 2004). As previously mentioned, areas exposed to high light availability are often colonized by exotic plants.

Effects of Trails on Exotic Plant Spatial Distribution

Although the purpose of this research is to examine various environmental factors in an effort to determine the autecology of four exotic species, the existence of trails and roads in, near, or surrounding the study region requires an apropos detailing of their effects on the spatial distribution of exotic plants. The role of trails in shaping the distribution of exotic species is a diverse and complex one that can vary among sites. In the context of landscape ecology theory, trails can function as both corridors and boundaries (Forman and Godron 1986; Puth and Wilson 2001) depending on whether species are positively or negatively influenced by the environment found along trails (Benniger-Truax et al. 1992; With 2002). A good example of this dichotomous function of trails, specifically in relation to horse trails, is the finding that "the density of graminoids is higher along trail corridors than in the forest interior, while the density of vines is lower" (p. 30) (Campbell and Gibson 2001).

Anthropogenic disturbances in the form of trail and road building seem to affect the patterns of exotic distribution more so than natural disturbances (Rew et al. 2006), wherein the initial disturbance has the greatest effect on natural habitat (Potito and Beatty 2005). The gist of the idea is that since disturbance corridors create habitat conducive to exotics (Benniger-Truax et al. 1992; Parendes and Jones 2000; Watkins et al. 2003), they will gain a foothold on such edges and then spread into natural areas, as various invasion models describe (Tyser and Worley 1992; Harrison et al. 2002). Strangely enough, most studies have found that although various human activities along trails, such as horseback riding (Tyser and Worley 1992; Campbell and Gibson 2001), can enhance the probability of the introduction and spread of exotics along trails, exotics often do very little spreading into natural habitats (Campbell and Gibson 2001). Exotic plant species tend to keep within a general zone of influence which has been found to be approximately 1m for a footpath (Potito and Beatty 2005), about 15m for roads (Watkins et al. 2003; Hawbaker and Radeloff 2004), and 120m for "improved roads" (Hawbaker and Radeloff 2004). Even so, at least one study has described species spreading outwards from trails into natural habitat (Benniger-Truax et al. 1992).

Considering the Literature Review

Reviewing the various factors considered to be of importance in influencing plant distribution, several conclusions are possible. Several of the factors seem interrelated, as the use of elevation and aspect data in site quality and moisture indices would indicate (Smith and Burkhart 1976; Meiners et al. 1984); at the same time, both elevation and aspect influence light availability and moisture in mountain habitats (Kruckeberg 2002). Light availability in turn is also influenced by the presence of roads and trails, both of which limit overhead forest canopy since the formation of either necessitates the removal of trees, a process classified as a disturbance. While it might be possible to use only a few of these habitat variables to infer the remaining, this study used a minimum of physical, environmental factors in the following analyses. It was hoped that the selected factors would explain the distribution of the invasive species chosen for the study.

Chapter 3: Study Area & Species

Study Sites

Two study areas were selected on National Forest land within areas of Jefferson National Forest and Mountain Lake Wilderness in Montgomery and Giles counties in southwest Virginia (Figure 1). This region was formerly known as the 'oak-chestnut region,' prior to the introduction of chestnut blight and the subsequent decimation of the American chestnut populations. Now known as the Appalachian Oak Forest Region, it is composed of six main forest habitat types, which can be summarized as mixed oak-pine forests with various mixtures of other hardwoods (Delcourt and Delcourt 2000). This area of the state is classified as the Ridge and Valley physiographic region and is typified by limestone valleys interspersed between sandstone ridges (Dietrich 1970; Constantz 2004). Both study sites are situated between two mountain ridges and were selected in order to capture a broad range of possible hillside aspects for use in the analysis.

The first study area is situated in the valley between Brush Mountain and Sinking Creek Mountain – an area that includes Pandapas Pond Recreation Area and the area west of the pond. Here is located a popular trail system, with mix-use recreation, and is frequented by hikers, bikers, and equestrians. The elevation range of this study area is from ~ 560 to 880 meters above sea level.

The second study area is located between Salt Pond Mountain and Johns Creek Mountain, which lies to the west of the town of Captain, VA. The area is home to a few trail systems, including a section of the Appalachian Trail. Elevations at this site range from around 600 to 1360 meters. The greater elevations found here will produce greater variations in the study species' recorded spatial distributions.

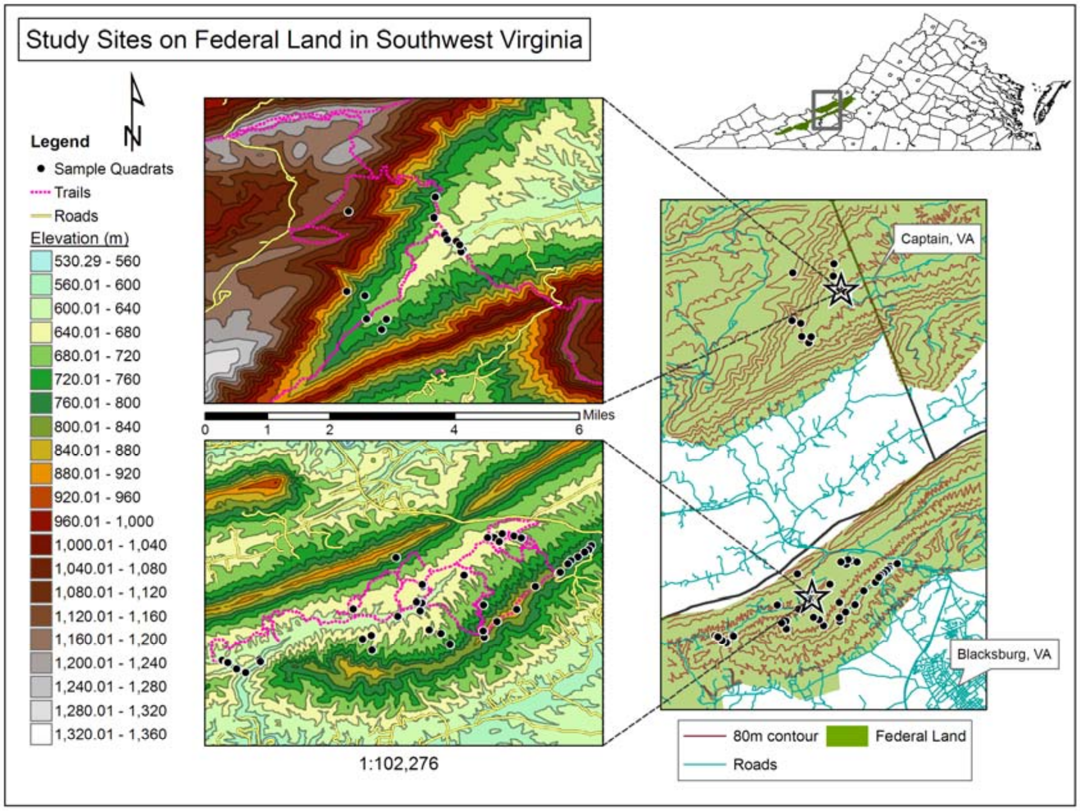

Figure 1 *Maps of the two study sites: Mountain Lake Wilderness (above) and Jefferson National Forest (below); inset regional map on right shown with contour intervals of 80 meters; the two individual study site maps shown with contour intervals of 40 meters and at 1:102,276 scale.*

Species Descriptions

The four exotic species chosen for this study (*Microstegium vimineum*, *Lonicera japonica*, *Rosa multiflora*, and *Elaeagnus umbellate*) were selected to encompass a variety of plant growth forms found within the study area (Table 1); both annuals and perennials are represented, as are a grass, a vine, and two shrubs (one of which often occurs as a small tree). Each represents plants displaying different mechanisms for survival and presumably requiring different habitats. The decision to use the four species selected for this thesis was based upon their perceived frequent occurrence in the study areas, and the relative ease of their correct identification compared to other invasive plants considered for this study. The Virginia Department of Conservation and Recreation's exotic invasive plant advisory list classifies each of the following species as "highly invasive" and able to survive varied habitat similar, but not limited to, study area conditions (2003).

Table 1 *Lifecycle and form of each study species.*

Species	**Lifecycle**	**Form**
Microstegium vimineum	Annual	Grass
Lonicera japonica	Perennial	Vine
Rosa multiflora	Perennial	Shrub
Elaeagnus umbellate	Perennial	Shrub

The grass, *Microstegium vimineum* (Figure 2) or Japanese stiltgrass, is a ubiquitous invasive found today throughout the region. A native to Asia, Japanese stiltgrass was first found in the United States in Tennessee in 1919 (Gibson et al. 2002; Swearingen and Adams 2008), and was thought to have arrived as packing material for fine china (Howard 2005). This species spreads excessively, displacing native vegetation, and its consumption is avoided by white-tailed deer (2004; Swearingen and Adams 2008) and livestock (Howard 2005). *M. vimineum* is a warm season (C_4) grass that has adapted to low light conditions (Winter et al. 1982; Tu 2000; Rhoads and Block 2002; Howard 2005). An annual, it reproduces by seed which is then disseminated by animals, water, and humans (Tu 2000; Rhoads and Block 2002; Howard 2005; Miller and Miller 2005). There is some evidence that this species alters both physical and chemical soil properties (Kourtev et al. 1998; Tu 2000). According to the Virginia Department of Conservation and Recreation (2003), *M. vimineum* is limited primarily by xeric conditions.

The vine, *Lonicera japonica* (Figure 3) or Japanese honeysuckle, is another Asian import, common throughout Virginia and identified in 37 other US states

(USDA and NRCS 2007). Although the details of this species' introduction to the United States is uncertain, it became known in horticultural circles in 1806 (Pelczar 1995). Vines are by nature epiphytic (using nearby plants for support), and can block light to the plants they cover (Daubenmire 1974), eventually killing their support; *L. japonica* can also girdle nearby plants, essentially strangling them (2005; Bravo 2005). *L. japonica* is semi-evergreen and spreads by rhizomes and seed, the latter of which can be carried by animals (Miller and Miller 2005). *L. japonica* seems to be limited by poorly-drained soils, and climates with low precipitation and harsh winters (Munger 2002; 2005).

Rosa multiflora (Figure 4) is a shrub considered banned or noxious in 12 states, including West Virginia (USDA and NRCS 2007), and has been found in both Montgomery and Giles counties in the past (Associates 2007). Initially introduced from Asia in 1866 as ornamental rose rootstock, this rose has since been planted as a 'living fence,' to control erosion, and as cover for wildlife, only to escape into the wild (Munger 2002; Bergmann and Swearingen 2005). Besides it previously mentioned beneficial aspects, it can quickly form impenetrable masses of vegetation, reducing available farmland, and irritating cattle (Munger 2002; Bergmann and Swearingen 2005). This species spreads by runners and animal-carried seed (Munger 2002; Bergmann and Swearingen 2005; Miller and Miller 2005). *R. multiflora* has yet to be found growing under very dry conditions or in standing water (Munger 2002).

Elaeagnus umbellate (Figure 5) or autumn olive, is an Asian shrub (or small tree) found throughout Virginia (2003). Introduced to the United States in the early 19^{th} century (Munger 2003), *E. umbellate* provides edible fruit for wildlife, is "often planted in reclamation areas" (Miller and Miller 2005) since it can colonize nutrient-poor soils due to the atmospheric nitrogen-fixing actinomycetes bacteria symbiotically living within its root nodules, and has been planted as windbreaks (Munger 2003). *E. umbellate* foliage also provides cover to wildlife (Munger 2003). Plants are easily spread by birds who have previously eaten the fruit (Miller and Miller 2005). The single most important factor limiting *E. umbellate* growth in any particular environment could be considered its absence in that area (Munger 2003).

Figure 2 *Population of* Microstegium vimineum *found on Brush Mountain.*

Figure 3 *Trailing* s*tem and opposite leaves of* Lonicera japonica.

Figure 4 *Image of* Rosa multiflora *depicting entangled growth habit.*

Figure 5 *Image of* Elaeagnus umbellate *showing twigs, leaves, and fruit.*

Chapter 4: Methods Overview

Hypothetical Questions

The project goal of deriving each species' autecology using GIS focuses on eight primary environmental variables; only six of these variables are considered in the context of producing regression equation models due to the availability of sympathetic GIS data layers. The spatial correlates of exotic plant species were sought in reference to the: 1) aspect of slope, 2) relative site moisture, 3) elevation, 4) proximity to streams, 5) proximity to trails, 6) proximity to roads, 7) estimated density of the canopy, and 8) presence of disturbance. The last two variables, canopy density above each quadrat and presence of disturbance, were examined separately from the proceeding six, as both are discrete data sets.

Field Data Collection

Preliminary field data collection took place during the summer of 2007. At this time all study species were actively growing and readily identifiable. First, in order to determine sampling locations, sample points were randomly produced across the two study areas using the raster GIS program *IDRISI® Andes* using the stratified random sampler function. However, after visiting the selected sites in the field and finding very few invasive species, I chose to focus instead on areas with a higher probability of invasive distribution, as described in the literature (Benniger-Truax et al. 1992; Tyser and Worley 1992; Parendes and Jones 2000; Campbell and Gibson 2001; Harrison et al. 2002; Watkins et al. 2003; Hawbaker and Radeloff 2004; Potito and Beatty 2005; Rentch et al. 2005; Wangen et al. 2006). I then generated random sample points within a 15 meter buffer of trails and roads. Data collected at the randomly generated points under both conditions within the study areas have been utilized in this project. In addition, in the interest of time and ease of access, populations of the study species found while traveling to the randomly produced points were also collected in a random, non-methodical manner as pertinent data and their locations georeferenced for later analysis. Together, data collected randomly and data collected while in transit to randomly generated points yielded a total of 61 quadrats (26 of which contained at least one study species).

Random [x, y] points generated in Idrisi were uploaded in a Trimble GeoXT GPS unit. I navigated to these points in the field using the GPS and a Trimble Hurricane L1 external antenna. At each georeferenced point, species presence and species density (percent coverage of quadrat by species) were collected in a 10 meter quadrat (corresponding to a single raster cell of the DEM data for the area provided at 1/3 arc second) for each species present (Table 2). Additionally, the percent canopy cover above the quadrat (Table 3) was recorded for an estimate of light intensity. Due to the emphasis upon the role of anthropogenic and natural disturbances in exotic plant spatial distribution by other researchers, evidence of disturbance (i.e. fallen trees, mounds of gravel, burned areas, trails, roads, streams, campgrounds, fire breaks, and utility corridors) within quadrats was also recorded (Table 3).

Table 2 *Sample data dictionary entry recorded for each species' presence at every quadrat.*

Species name	Input	Default
Present	Yes/No	No
% Plant cover	#%	0%

Table 3 *Sample data dictionary entry recorded only once at each quadrat.*

Quadrat	Input	Default
% Canopy	#%	*none*
Disturbance	Yes/No	No

GIS Database Construction

Layers included in the GIS database and available for analysis consisted of derived variables from existing datasets, as well as the field-collected, georeferenced positional layers indicating species presence (Table 4). With the exception of the field-collected species data (representing a 10 meter quadrat on the ground, but stored as vector point data), all final GIS database layers are raster layers. To reduce the chance of error, all analysis occurred using the NAD 1983 datum because this was the original format used by the majority of the datasets acquired for this research. Initial GPS data collection during the summer of 2007 used the WGS84 datum (the datum used by most GPS units (Wilson 1995; Cusick 2003; 2006)), which were then converted to NAD83 using the ArcMap transformation NAD_1983_To_WGS_1984_1; all subsequent GPS fieldwork used NAD 1983.

Table 4 *Variables used to construct the GIS Database.*

Variable	Original Dataset	Original Resolution	Final Resolution	Type
Elevation	DEM	10 meters	10 meters	Independent
sin (aspect)	DEM	10 meters	10 meters	Independent
cos (aspect)	DEM	10 meters	10 meters	Independent
RoadsOF	Travel Route polylines	*Vector*	10 meters	Independent
RoadsS	Travel Route polylines	*Vector*	10 meters	Independent
Trails	Travel Route polylines	*Vector*	10 meters	Independent
Streams	US Census Tiger files	*Vector*	10 meters	Independent
NDMI	Landsat TM	30 meters	10 meters	Independent
Species Presence	*Field Collection*	*Stored as Point*	10 meter^2 Quadrat	Dependent

Using a digital elevation model (DEM) layer available from the USGS Seamless Database (USGS) covering the aerial extent of both study areas, the topographical variables used in this study (aspect and elevation) were derived using ArcMap (Figure 6). The aspect raster layer was further modified to produce “**sin** (aspect)” and “**cos** (aspect)” layers, which transformed the circular aspect data into information suitable for use in a regression analysis (Beers et al. 1966). Both sin (sine) and cos (cosine) were applied to aspect in order for every unique aspect to be represented; applying only one trigonometric function (cosine or sine) to aspect would have resulted in similar series of numbers representing very different aspects (in degrees).

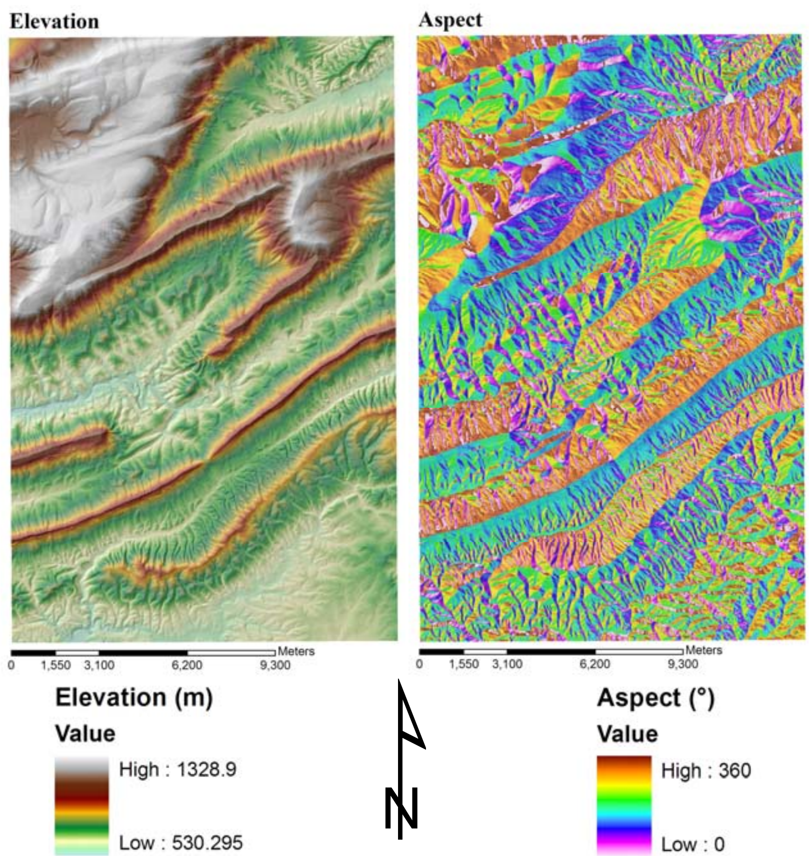

Figure 6 *DEM-derived layers used in this study. Left to right: Elevation and Aspect.*

Layers containing roads and hiking trails were added from the George Washington and Jefferson National Forests GIS Data Homepage (USDA), which provides and updates information layers as they become available. Misclassifications of roads and trails identified by direct observation were corrected. As with the aspect raster layer, the roads vector layer also required preprocessing into suitable files for subsequent analysis. Preprocessing resulted in two road layers: roads open year-round and forestry roads. These two layers were grouped to produce one layer (RoadsOF), and roads subjective to state, county, or city maintenance were used to produce the other layer (RoadsS). These two categories were chosen to provide some distinction between levels of road use; RoadsOF are used for recreation and access through the National Forest areas, while RoadsS indicate normal use roads (including, but not limited to, access to homes and businesses, highways). Within the RoadsOF layer, Route 601 was removed from the dataset after it proved difficult to access using the vehicle utilized during this study; also, most land surrounding Route 601 is private property, and was thus inaccessible for sampling or model validation.

The streams layer was produced by merging the pertinent US Census TIGER files from Montgomery, Giles, and Craig counties (Census 2006; Census 2006; Census 2006) using ArcMap. No further alterations were made to the stream data. The streams dataset was included after determining that streams and the valleys they occupy are a major landscape feature, capable of influencing at least the distribution of *M. vimineum*, citing its use of waterways for seed dispersal (Tu 2000; Rhoads and Block 2002; Howard 2005; Miller and Miller 2005).

Individual raster layers indicating distances to the trails, roads (of both ‘OF’ and ‘S’ designation), and streams were created to be used in the GIS analysis, and were produced using both the linear feature layers themselves and the DEM covering the study areas. To indicate some semblance of overland distance from each linear feature to any given cell, a trigonometric cost raster (Equation 1) was applied to the percent slope raster derived from the DEM.

Equation 1 Ground Distance Estimation Formula

Cell Resolution ÷ Cosine (Degree Slope) = Ground Distance Across Cell

Where:

Cell Resolution = DEM Resolution = 10 meters

Degree Slope = Percent Slope ÷ (180/π)

180 ÷ π = 57.29578

Resulting in:

10m ÷ Cosine (Percent Slope ÷ 57.29578) = Ground Distance Across Cell

Ten meters was the resolution of the original DEM used for both the derived slope raster and the template for the rasters indicating distances to linear features. Ten meters multiplied by the cosine of the slope angle (in degrees) will produce an approximate distance along the slope for every cell in the raster layer. As the DEM-derived slope raster was measured in radians, the cost layer equation also needed to convert these slope values to degrees by dividing them by 180 ÷ π (or the value 57.29578, as used in the equation). This cost raster combined with a distance query applied to the linear features described previously resulted in a final Distance Raster for each linear feature indicating the least number of meters from each feature for every raster cell (Figure 7).

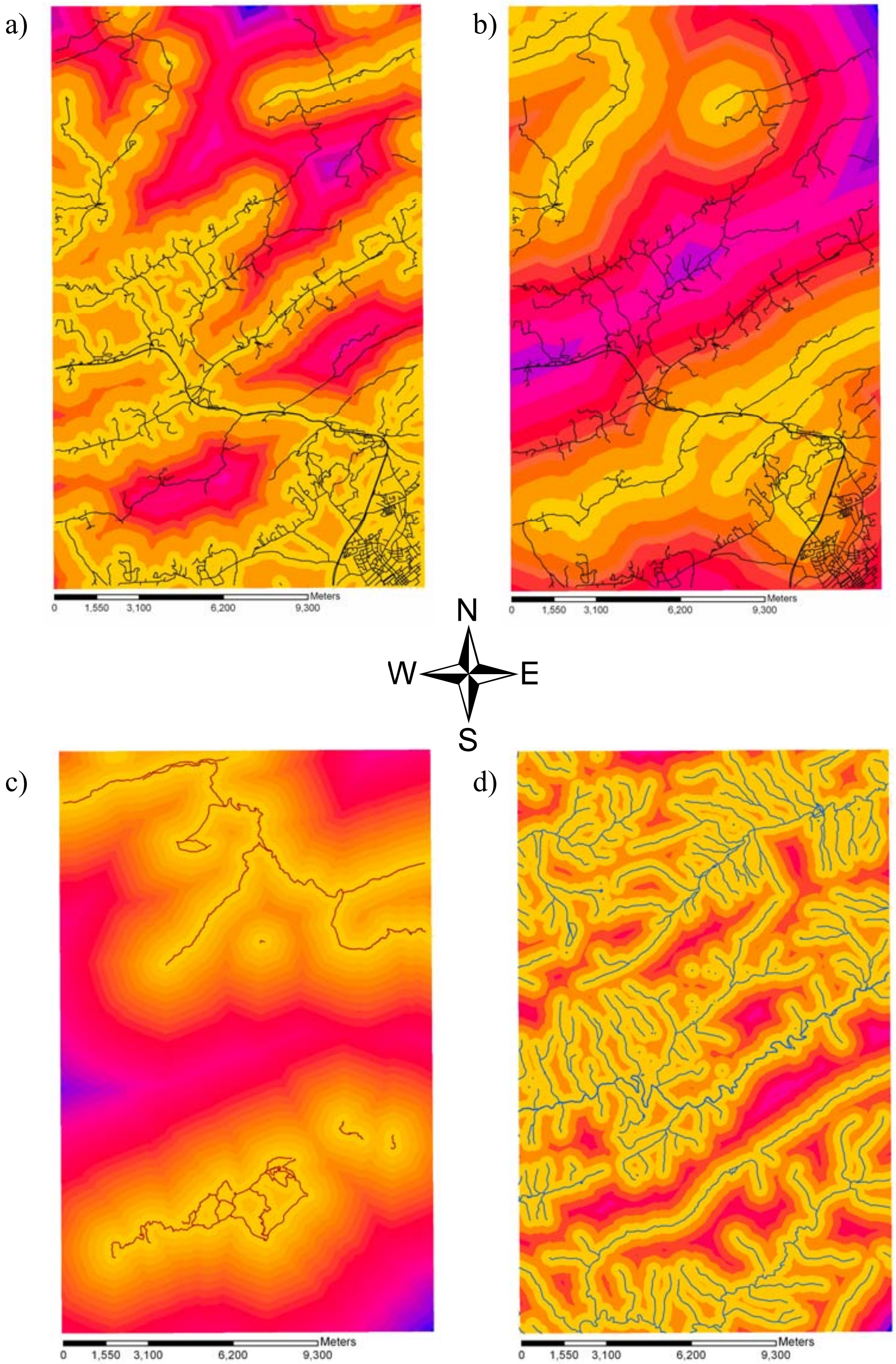

Figure 7 *Clockwise from upper-left: a) RoadsS, b) RoadsOF, c) Streams, and d) Trails. GIS distance layers shown with their originating vector layers superimposed. The distance raster has been shown using a 3000m graduation. The removed Route 601 can be seen in the top two images as the only line not surrounded by the graduated distance buffer in either image.*

A Landsat TM image (Figure 8) covering the extent of the study area (Path 17, Row 34) was acquired from the VT Forestry Department, who in turn acquired it from GLOVIS (USGS 2000). A Normalized Difference Moisture Index (NDMI) (Equation 2) was produced from bands 4 (near infrared) and 5 (mid infrared) of the Landsat image, as described by Price and Tinant (2000) and Wilson and Sader (2002).

Equation 2 *Derivation of NDMI from Landsat TM bands.*

$$\text{NDMI} = \frac{\text{Band 4} - \text{Band 5}}{\text{Band 4} + \text{Band 5}}$$

From this index, a soil moisture layer was derived (Figure 9) (Price and Tinant 2000). Values expressed range from -1 (dry) to +1 (moist). Landsat imagery has a 30 meter resolution, three times that of the other raster layers; the *IDRISI Andes* **WINDOW** operation was used to extract an area the extent of the DEM-derived raster layers from an image which had already been processed using the *IDRISI Andes* **EXPAND** operation, which increased the original resolution to 10 meters, through pixel duplication (Tables 4, Figure 8). Histograms of the two images confirmed that the mean values and standard deviations of each image's values were the same; the extracted NDMI image contained a subset of the raster cell values found in the original image (Table 5).

Table 5 *Histogram data regarding the NDMI layers before and after pixel duplication, and extraction, while disregarding background pixels.*

Image	Minimum	Maximum	Mean	Std. Dev.	N
30m NDMI	-1.00	1.00	0.11	2.11	36,722,126
Expanded 10m NDMI	-1.00	1.00	0.11	2.11	330,499,134
Extracted 10m NDMI	-0.47	0.88	0.15	1.30	2,962,148

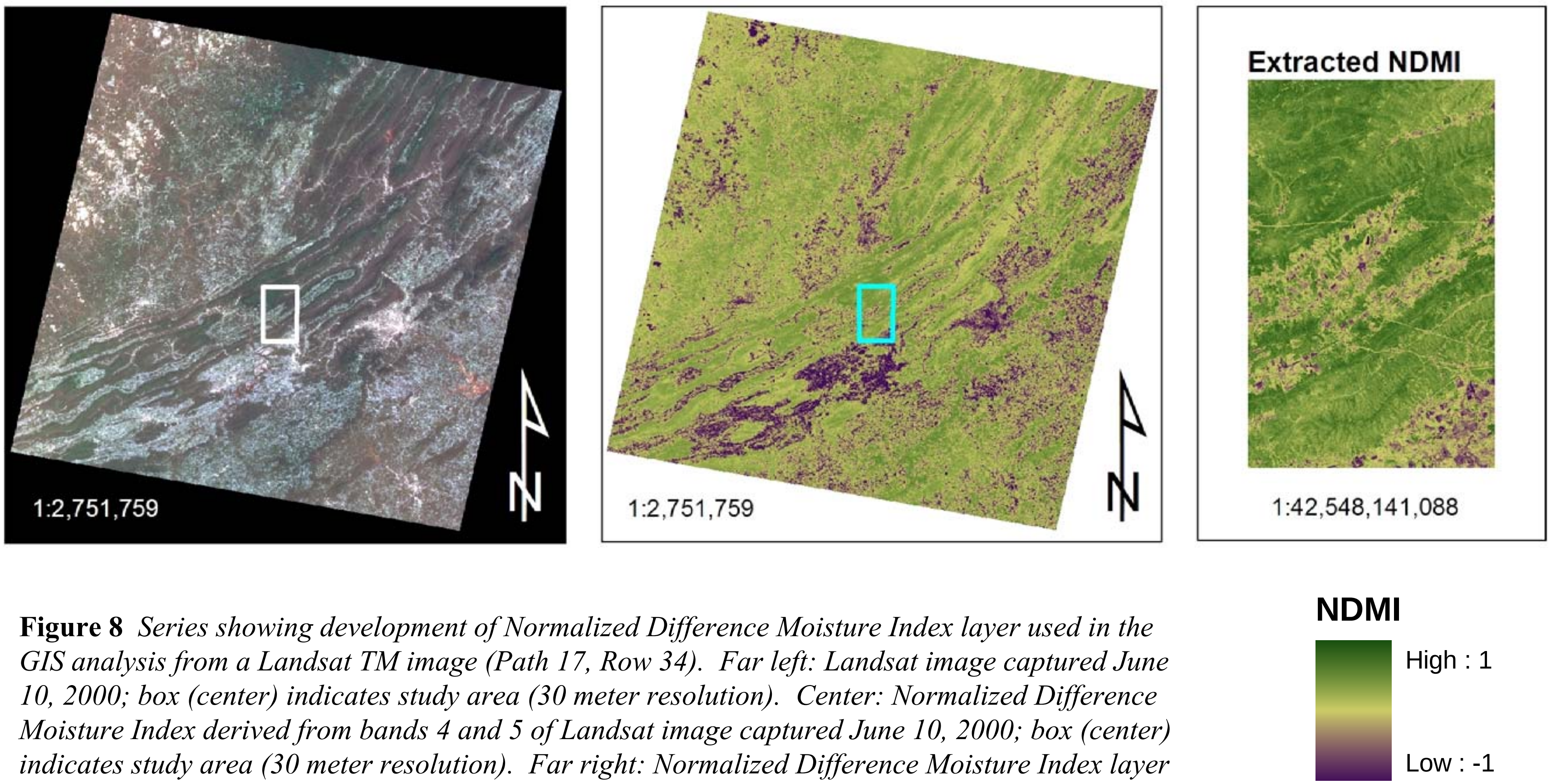

Figure 8 *Series showing development of Normalized Difference Moisture Index layer used in the GIS analysis from a Landsat TM image (Path 17, Row 34). Far left: Landsat image captured June 10, 2000; box (center) indicates study area (30 meter resolution). Center: Normalized Difference Moisture Index derived from bands 4 and 5 of Landsat image captured June 10, 2000; box (center) indicates study area (30 meter resolution). Far right: Normalized Difference Moisture Index layer extracted from the full image and after pixel duplication (10 meter resolution).*

GIS-based Statistical Analysis

The statistical analysis chosen for modeling each of the invasive species' habitat was logistic regression, given that the dependent variable in each case was binary (species presence or absence) and the independent environmental variables continuous; logistic regression is also useful when using independent variables which may not fit the assumptions of other statistical analyses (Franklin 1995; Hintze 1999). *IDRISI Andes* notes that the use of the Logistic Regression operation (**LOGISTICREG)** applied to continuous geographic variables like those used in this study could result in falsely significant relationships due to the autocorrelation of cells (all possible individual sample areas) in a geographic raster image. Autocorrelation is a basic concept of geography: two nearby places will be more similar than two distant places (Odland 1988). To remedy this concern, a mask was applied to all layers of GIS data during the use of **LOGISTICREG** to filter out all but those cells within which sample quadrats lay; in essence, the analysis proceeded as though independent samples were taken.

Combinations of significant variables to be used in each species' logistic regression model (Table 6) were selected using NCSS 2007, which utilizes McHenry's Select Algorithm to find an optimal combination of variables resulting in the highest R^2 available. Using this method, the variable subset chosen for logistic regression occurs at the point of stabilization of the R^2 values; the cutoff value for the change in R^2 values was arbitrarily set to 0.009.

Table 6 *Variables selected for each species to be used in subsequent regression analyses.*

Model	R^2	Variables Selected
M. vinimeum	0.2164	Trails Cos (Aspect) NDMI RoadsOF
L. japonica	0.1263	Streams Cos (Aspect) Sin (Aspect) RoadsOF RoadsS
R. multiflora	0.2300	Streams Trails Cos (Aspect) RoadsOF
E. umbellate	0.5500	Streams Cos (Aspect) Sin (Aspect) NDMI

Values for each layer were stretched from 0 to 100 to standardize the variable coefficients resulting from the logistic regressions and make them instantly comparable. *IDRISI*'s **LOGISTICREG** operation was run once for each species upon all 61 quadrats; each species was labeled either present or absent in each quadrat.

Describing the Models Produced

Regression equations resulting from *IDRISI*'s **LOGISTICREG** operation on the presence/absence species data produce a probability of presence ranging between 0 and 1. In addition to an equation, **LOGISTICREG** outputs several regression statistics, two of which will be discussed within the context of each equation: the classification table (particularly the initial and adjusted cutoff values) and the Relative Operating Characteristic (ROC).

A classification table identifies both the predicted and observed occurrences of 'presence-' or 'absence-' classified cells, given a cutoff value defining the two categories; initially, this value is the predicted 0.5 probability. A second, adjusted classification table in which the total number of 'presence' values is matched to the initial number of 'presence' values used in the regression is also produced. With the formulation of a new classification table, a new cutoff value of predicted probability is produced to indicate the point of presence/absence classification under the new conditions.

ROC is a technique which compares a probability map (values range: 0 to 1) to an image representing actual data (values: 0 or 1) of the same area. It produces a measure of fit: a random fit is indicated by an ROC value of 0.5; a perfect fit is indicated by a value of 1.0; a value between 0.5 and 1.0 indicates some fit.

Process of Model Validation

To validate the models produced by each logistic regression equation, as applied to the study area, areas of high likelihood described by each model were selected and field verified for species presence or absence. To select these areas, a mask was first created to remove areas of standing water and known private property, and areas of false positive results relating to edge effect (areas at the edge of the sampling area, where layers did not quite overlap). After removing these inappropriate sampling areas, the remaining raster cells were ranked in descending order of habitat likelihood, and the top fifty cells indicating most likely habitat selected. The top fifty raster cells indicating high probability habitat were selected as it was hypothesized that if the models were to be proved true, these high likelihood cells were the most likely positions at which each study species would be found. These points were exported to the Trimble GPS unit and an attempt was made to locate each point in the field; some areas, although located, could not be sampled due to the existence of dense vegetation, uncertain terrain, or previously unidentified private property. Due to positional uncertainty in the field (sometimes greater than 5 meters), "top fifty" points were not always correctly identified, but were located in the general vicinity of the area of predicted high probability habitat.

Similarly to the initial data collection, a number of quadrats containing the species but not selected as a "top fifty" point were collected near such a point or in between such points. It must be noted that extra data collected at sites of species presence found near the actively sought quadrats should not be considered inclusive of all such populations near an actively sought area; collected extra data points were recorded sporadically and randomly in areas noticed to contain a species. Such information was collected in order to indicate presence of a species near or in an area considered of high habitat probability.

Canopy & Disturbance Analysis

Both estimated canopy cover (percent) above each quadrat and disturbance presence (1) or absence (0) at each quadrat were recorded to examine the possible influence of these variables on the four study species. For the purposes of this study, no distinction is made between anthropogenic and non-anthropogenic forms of disturbance; if disturbance occurred in a quadrat, it was so noted. The concept of 'disturbance' can take several forms (i.e. presence of trails and roads, windthrown trees, fallen trees, upturned trees, and evidence of fire), each resulting in the loss of canopy or changes to the forest floor. Although originating from different mechanisms, disturbances will create similar habitat types that can be examined as such.

Since continuous data sets were not available for the canopy cover or disturbance variables, neither was included in the GIS-based logistic regression models. Lacking independent variable raster layers of these two environmental characteristics excluded their use in applying a logistic equation toward a predictive habitat map. Instead, they are later presented using descriptive statistics to examine any patterns which may be described.

Chapter 5: Results

The initial species surveys to determine areas where study plant species were and were not located was only the first of three main thesis objectives planned in order to develop probable habitat models for each species. These surveys were carried out through field data collection over the first summer of research, in 2007. The data collected is shown in the two following tables, along with summaries of each environmental variable (sans disturbance), by species: quadrats with species found present (Table 7) and quadrats with species found absent (Table 8).

Table 7 Initial Quadrats with Species Present

#	Species	Variable	Minimum	Maximum	Mean	Standard Deviation
15	*M. vinimeum*	% Canopy Cover	5.00	90.00	44.33	24.49
		Elevation (m)	624.88	857.46	727.10	90.99
		cos (aspect)	-0.99	0.67	-0.22	0.60
		sin (aspect)	-0.99	0.96	-0.01	0.81
		NDMI	0.13	0.23	0.19	0.03
		Stream Distance (m)	100.04	7155.77	2480.59	2303.27
		Trail Distance (m)	0.00	8618.44	1181.26	2338.42
		RoadsS Distance (m)	100.07	23625.28	8353.22	7944.00
		RoadsOF Distance (m)	0.00	7634.21	1478.93	2046.69
#	**Species**	**Variable**	**Minimum**	**Maximum**	**Mean**	**Standard Deviation**
4	*L. japonica*	% Canopy Cover	0.00	90.00	43.75	36.83
		Elevation (m)	598.63	659.64	626.91	28.74
		cos (aspect)	-1.00	0.98	0.32	0.89
		sin (aspect)	-0.07	0.79	0.41	0.41
		NDMI	0.08	0.20	0.15	0.05
		Stream Distance (m)	304.35	724.60	545.89	207.22
		Trail Distance (m)	0.00	6052.41	1899.47	2809.40
		RoadsS Distance (m)	4757.17	22463.91	13150.28	7827.26
		RoadsOF Distance (m)	0.00	1653.29	515.24	764.76
#	**Species**	**Variable**	**Minimum**	**Maximum**	**Mean**	**Standard Deviation**
11	*R. multiflora*	% Canopy Cover	0.00	60.00	17.73	22.51
		Elevation (m)	590.49	850.18	674.38	88.09
		cos (aspect)	-0.75	1.00	0.16	0.69
		sin (aspect)	-1.00	0.95	0.05	0.77
		NDMI	0.01	0.23	0.14	0.07
		Stream Distance (m)	100.48	3905.62	1064.33	1256.35
		Trail Distance (m)	0.00	13233.71	3930.93	5163.87
		RoadsS Distance (m)	1386.07	19557.70	8874.16	6253.81
		RoadsOF Distance (m)	0.00	2378.51	516.73	789.24
#	**Species**	**Variable**	**Minimum**	**Maximum**	**Mean**	**Standard Deviation**
9	*E. umbellate*	% Canopy Cover	0.00	40.00	9.44	17.40
		Elevation (m)	589.97	658.15	612.81	26.43
		cos (aspect)	-0.75	1.00	0.26	0.68
		sin (aspect)	0.03	1.00	0.65	0.34
		NDMI	0.01	0.23	0.10	0.06
		Stream Distance (m)	100.48	712.53	303.24	190.44
		Trail Distance (m)	0.00	7319.03	3473.93	2829.05
		RoadsS Distance (m)	4128.89	16308.45	10621.33	4233.88
		RoadsOF Distance (m)	100.12	1740.52	412.65	518.84

Table 8 Initial Quadrats with Species Absent

#	Species	Variable	Minimum	Maximum	Mean	Standard Deviation
46	*M. vinimeum*	% Canopy Cover	0.00	100.00	46.41	30.73
		Elevation (m)	589.97	1106.42	710.47	97.98
		cos (aspect)	-1.00	1.00	-0.01	0.69
		sin (aspect)	-1.00	1.00	0.07	0.73
		NDMI	0.01	0.23	0.17	0.05
		Stream Distance (m)	0.00	9779.09	2878.02	2912.30
		Trail Distance (m)	0.00	13233.71	3219.62	3580.23
		RoadsS Distance (m)	142.28	26501.94	12106.72	7345.32
		RoadsOF Distance (m)	0.00	27436.98	5775.56	7600.07
#	**Species**	**Variable**	**Minimum**	**Maximum**	**Mean**	**Standard Deviation**
57	*L. japonica*	% Canopy Cover	0.00	100.00	46.05	28.92
		Elevation (m)	589.97	1106.42	720.71	95.96
		cos (aspect)	-1.00	1.00	-0.09	0.66
		sin (aspect)	-1.00	1.00	0.02	0.76
		NDMI	0.01	0.23	0.17	0.05
		Stream Distance (m)	0.00	9779.09	2937.09	2791.00
		Trail Distance (m)	0.00	13233.71	2775.85	3468.78
		RoadsS Distance (m)	100.07	26501.94	11045.73	7642.03
		RoadsOF Distance (m)	0.00	27436.98	5014.01	7057.56
#	**Species**	**Variable**	**Minimum**	**Maximum**	**Mean**	**Standard Deviation**
50	*R. multiflora*	% Canopy Cover	0.00	100.00	52.10	26.80
		Elevation (m)	589.97	1106.42	723.40	96.02
		cos (aspect)	-1.00	0.99	-0.11	0.67
		sin (aspect)	-1.00	1.00	0.05	0.75
		NDMI	0.07	0.23	0.18	0.04
		Stream Distance (m)	0.00	9779.09	3157.80	2865.79
		Trail Distance (m)	0.00	9553.14	2451.63	2906.64
		RoadsS Distance (m)	100.07	26501.94	11691.83	7835.16
		RoadsOF Distance (m)	0.00	27436.98	5643.51	7317.16
#	**Species**	**Variable**	**Minimum**	**Maximum**	**Mean**	**Standard Deviation**
52	*E. umbellate*	% Canopy Cover	0.00	100.00	52.21	26.00
		Elevation (m)	624.88	1106.42	732.17	92.48
		cos (aspect)	-1.00	0.99	-0.12	0.66
		sin (aspect)	-1.00	1.00	-0.06	0.75
		NDMI	0.10	0.23	0.19	0.03
		Stream Distance (m)	0.00	9779.09	3209.01	2774.72
		Trail Distance (m)	0.00	13233.71	2587.62	3515.54
		RoadsS Distance (m)	100.07	26501.94	11281.07	8073.24
		RoadsOF Distance (m)	0.00	27436.98	5464.34	7233.87

Logistically Regressed Models

The creation of the logistic regression models from the initially collected species presence data and the available environmental variables was the second objective of this thesis. The variables used in each regression were selected to produce a combination yielding a high R^2 value that was stable when compared to other possible variable combinations. One of the regression statistics used to describe each model indicates the accuracy of the model for a given cutoff value of present or absent when compared to the initial data, while the ROC produces a value that describes how well the logistic regression model describes the provided data.

It must be reiterated that the layers RoadsOF, RoadsS, Streams, and Trails indicate an approximate overland distance from those linear features. For example, a negative coefficient preceding the layer 'Trails' indicates an affinity to trails (the physical feature) by the species represented in the model.

Microstegium vimineum data produced a regression equation from 15 quadrats at which it was found to be present and 46 quadrats at which it was found to be absent.

Predicted *M. vimineum* presence =

-18.4120 - 0.146790 (Trails) - 0.018418 (cos (aspect))

+ 0.432774 (NDMI) - 0.330831 (RoadsOF)

The initial *M. vimineum* classification table indicated that 46.67% of the observed 'present' cells were predicted correctly (initial classification cutoff value is always 0.5 probability). This percentage rose to 60% in the adjusted classification table, and the new cutoff was calculated to be the 0.4651 probability value. The ROC was 0.85; the equation does not fit the initially observed "reality" perfectly, but the regression is closer to 'perfect' (ROC = 1.0) than to 'random' (ROC = 0.5).

Lonicera japonica data produced a regression equation from 4 quadrats at which it was found to be present and 57 quadrats at which it was found to be absent.

Predicted *L. japonica* presence =

9.9343 - 0.256618 (Streams) + 0.021541 (cos (aspect))

- 0.522027 (RoadsOF) + 0.050374 (RoadsS)

+ 0.012591 (sin (aspect))

The initial classification table observed no positions at which *Lonicera japonica* was both predicted and observed to occur. This changed to an 50% accuracy for presence prediction when the category cutoff value was lowered to 0.3212 in the adjusted classification table. ROC for this equation indicated a good fit at 0.90.

Rosa multiflora data produced a regression equation from 11 quadrats at which it was found to be present and 50 quadrats at which it was found to be absent.

Predicted *R. multiflora* presence =

10.8704 - 0.158195 (Streams) + 0.089387 (Trails)

+ 0.008168 (cos (aspect)) - 0.567318 (RoadsOF)

The percentage of correctly predicted incidents of presence in the initial classification table of *R. multiflora* was found to be 63.64%, while that of the adjusted classification table was 72.73% if the category cutoff value was lowered to only 0.4540. The ROC for this equation was found to be 0.88.

E. umbellate data produced a regression equation from 9 quadrats at which it was found to be present and 52 quadrats at which it was found to be absent.

Predicted *E. umbellate* presence =

63.8320 - 0.743439 (Streams) + 0.026430 (cos (aspect))

- 0.771317 (NDMI) + 0.062919 (sin (aspect))

Both the initial and adjusted *E. umbellate* classification tables give an accurate ‘presence’ prediction value of 88.89%. In the adjusted table, the classification cutoff value is actually raised to 0.5496. The ROC value for the *E. umbellate* regression equation was an amazing 0.99, or nearly a perfect fit to the initially observed data.

Validation Results

The third objective to reaching the goal of good habitat prediction models was the field validation of each model over the second summer of thesis research in 2008. The method used here to validate or invalidate any habitat probability model was to compare the number of quadrats found containing the study species of interest while using the habitat probability model to the number found the previous summer at randomly selected locations (Table 9). If the model is used successfully to find study species populations, it should be considered valid; if the sampling while using the model yields no greater chance of finding species presence than random sampling, the model should be considered invalid.

Table 9 *Accuracy of locating study species though randomly predicted, computer-generated locations. Data collected Summer 2007. 'All Random' includes both 'Initial Random' and '15m Buffer Random,' the previous referring to those quadrats produced initially and scattered across both study areas, the latter referring to those quadrats produced randomly within a 15 meter buffer of roads and trails. The total 61 quadrats used in all logistic regressions used these 38 quadrats, as well as 23 other quadrats collected in the field while in transit.*

Number of Quadrats:	38		15		23	
Species	**All Random**	Accuracy	**Initial Random**	Accuracy	**15m Buffer Random**	Accuracy
M. vimineum	7	0.184	0	0.000	7	0.304
L. japonica	1	0.026	0	0.000	1	0.043
R. multiflora	1	0.026	0	0.000	1	0.043
E. umbellate	1	0.026	0	0.000	1	0.043

Utilizing the habitat model produced from the logistic regression, *M. vimineum* was found in 25 of the 68 locations at which validation information was taken; 45 of those recorded points were being actively sought as "top fifty" points (the remaining five points were inaccessible). Fifteen of the "top fifty" points, although containing no *M. vimineum* themselves, were within 70 meters of an identified population. Quadrats containing *M. vimineum* existed in a wide range of modeled probable habitat values (see Table 10) as low as 0.0009 and up to 0.9055. Compared to the 18.4% success rate of locating *M. vimineum* at randomly generated points, the use of the *M. vimineum* probable habitat model produced a 36.7% success rate (presence at 25 quadrats of 68 recorded validation quadrat sites).

Table 10 *The number of validation quadrats of* M. vimineum *presence by the model probability values at which they were found.*

Recorded Quadrats of Presence	Probability Range
2	1.0-.90
7	.90-.80
5	.80-.70
1	.70-.60
2	.60-.50
1	.50-.40
1	.40-.30
1	.30-.20
2	.20-.10
3	.10-0.0

The *L. japonica* habitat model was slightly less successful at indicating areas of the species' presence at the time of model validation. Of 42 recorded validation quadrats, 7 contained *L. japonica*, producing a success rate of 16.6%. Thirty-seven of the recorded sites were of the actively sought "top fifty" points, according to the model, but only two of those contained *L. japonica* (the remaining 5 quadrats being those sporadically collected at identified populations near actively sought quadrats). Eight of the quadrats containing no *L. japonica* were found to be within 70 meters of an identified population. Model values at sites where the species was found to be present (Table 11) were more constrained than were the values at *M. vimineum* sites. The initial success rate of finding *L. japonica* at computer generated, random locations was 2.6%, lower than the success rate of finding *L. japonica* populations while using the model.

Table 11 *The number of validation quadrats of* L. japonica *presence by the model probability values at which they were found.*

Recorded Quadrats of Presence	Probability Range
-	1.0-.90
-	.90-.80
-	.80-.70
2	.70-.60
1	.60-.50
2	.50-.40
1	.40-.30
-	.30-.20
1	.20-.10
-	.10-0.0

R. multiflora was found in 7 quadrats of the 13 quadrats at which validation data was recorded (Table 12). None of the positions considered of highest habitat probability that were also accessible to sampling contained *R. multiflora*, nor were any found nearby those sites. The lack of a species at a position considered of high habitat probability should not invalidate such a habitat model, as other authors have recognized the difficulty in labeling areas which *could* support a species which has *not yet* arrived as misclassified or inaccurate solely due to absence of the species at the time of data collection (Price and Tinant 2000; Gillham et al. 2004). Still, the area atop Salt Pond Mountain, to the west of Mountain Lake which was predicted to be of very high habitat probability occurred in an area of loose, moss covered stone and at an intersection of roads which were deemed unlikely, at the time of validation data collection, to support a large shrub like *R. multiflora*. Despite such uncertainty, compared to the 2.6% success rate using randomly generated locations, the *R. multiflora* habitat model successfully encompassed the seven populations recorded of the species at validation, producing a validation success rate of 53.8%.

Table 12 *The number of validation quadrats of* R. multiflora *presence by the model probability values at which they were found.*

Recorded Quadrats of Presence	Probability Range
-	1.0-.90
-	.90-.80
2	.80-.70
4	.70-.60
-	.60-.50
1	.50-.40
-	.40-.30
-	.30-.20
-	.20-.10
-	.10-0.0

Validation of probable habitat sites for *E. umbellate* yielded an impressive 13 sites of recorded presence from 25 recorded positions. One "top fifty" position sought for predicted high probability habitat that did *not* include the species was found to be within 23 meters of at least one plant. The range of *E. umbellate* habitat model probability values recorded at validation sites of species presence was narrow compared to the other study species, and skewed toward the ranges of higher probabilities (Table 13). Compared to the 2.6% success rate of finding *E. umbellate* in the initially collected, randomly selected quadrat locations, the model used here for validation yielded a successfully predicted presence rate of 52%.

Table 13 *The number of validation quadrats of* E. umbellate *presence by the model probability values at which they were found.*

Recorded Quadrats of Presence	Probability Range
11	1.0-.90
1	.90-.80
-	.80-.70
1	.70-.60
-	.60-.50
-	.50-.40
-	.40-.30
-	.30-.20
-	.20-.10
-	.10-0.0

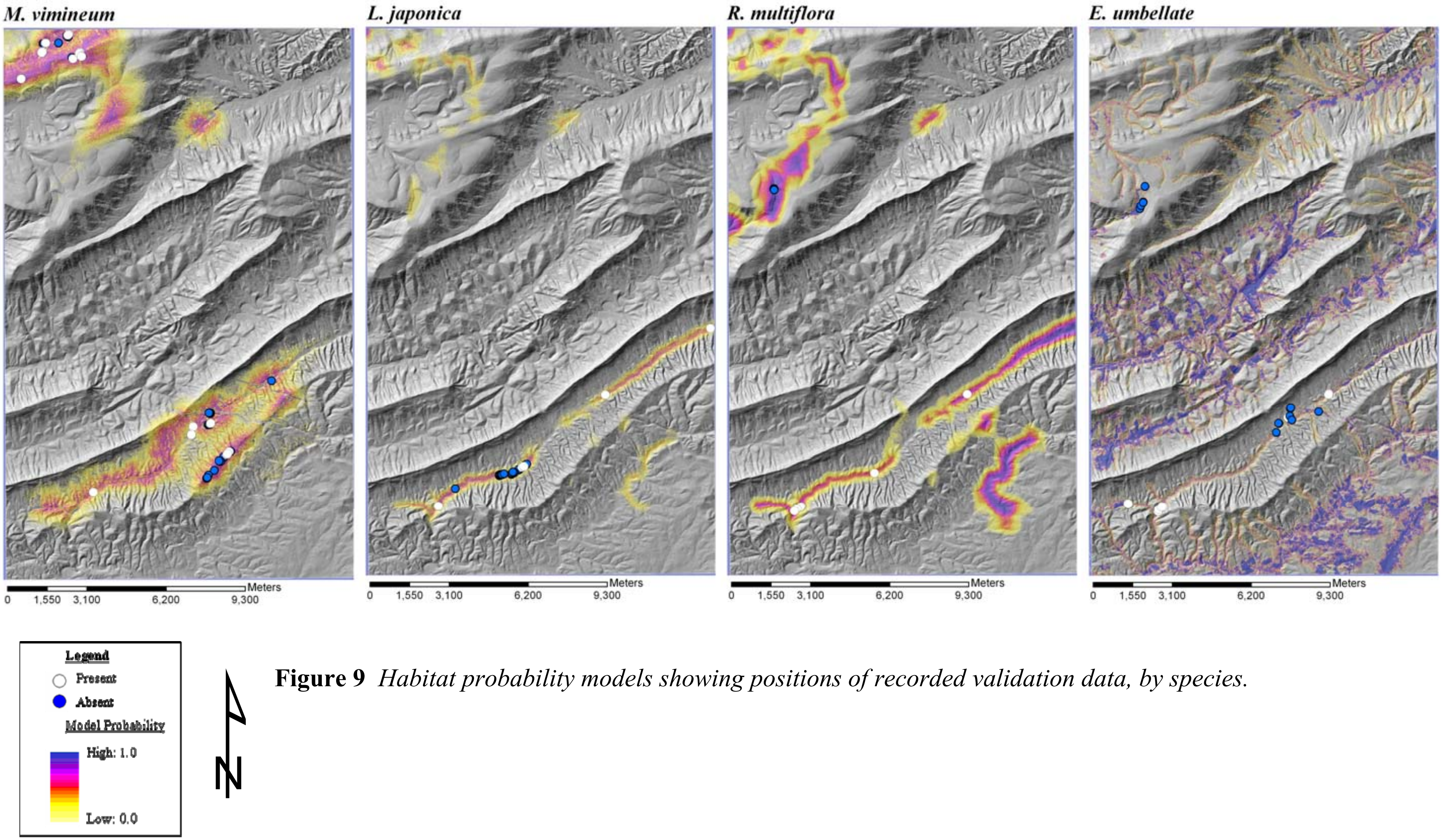

Figure 9 *Habitat probability models showing positions of recorded validation data, by species.*

Canopy & Disturbance Results

Due to the unavailability of continuous raster layers depicting canopy cover and disturbance across the study areas, these data could not be included in the previously described logistic regression habitat probability models. Instead, they are presented here using descriptive statistics to examine any patterns which may be described.

Table 14 *Descriptive statistics of estimated canopy cover data by species presence and absence; total range of canopy cover possible was 0 to 100%.*

Species	# of Quadrats	Occurance	Minimum	Maximum	Mean	Standard Deviation
M. vimineum	15	Present	5%	90%	44.33%	24.49
	46	Absent	0%	100%	46.41%	30.73
L. japonica	4	Present	0%	90%	43.75%	36.83
	57	Absent	0%	100%	46.05%	28.92
R. multiflora	11	Present	0%	60%	17.73%	22.51
	50	Absent	0%	100%	52.10%	26.80
E. umbellate	9	Present	0%	40%	9.44%	17.40
	52	Absent	0%	100%	52.21%	26.00

Table 14 (above) indicates that the study species were present in areas with less than total canopy cover, and that *E. umbellate* in particular was found in areas of little canopy (and therefore, sunny areas), followed by *R. multiflora*. *E. umbellate*'s average canopy cover value for presence was 9.44%, with a standard deviation of 17.4%, the lowest of either category for any of the species; *R. multiflora* had a mean of 17.73% cover, and a standard deviation of 22.5%. Both *M. vimineum* and *L. japonica* were possessed of canopy cover means near 44% with standard deviations of 24.4% and 36.8%, respectively; from these data, neither of these species shows a preference for a narrow range of canopy cover values. Also, the range of canopy cover values of both *M. vimineum* and *L. japonica* presence were not much different from the range of canopy cover values attached to their absence; again indicating a lack of canopy cover preference.

A Pearson's Correlation of species presence/absence versus canopy cover (Table 15) confirms the relationships described in Table 14: there is a significant negative correlation between both the rose and olive presence and canopy cover, when p = 0.05.

Table 15 *A Pearson's Correlation Report displaying correlations and significance levels of each Species' Occurrence to Canopy Cover*

	Pearson's Correlation	Significance Level
M. vinimeum	-0.03099	0.8125 > 0.05
L. japonica	-0.01973	0.8800 > 0.05
***R. multiflora* ***	-0.45736	0.00021 < 0.05
***E. umbellate* ***	-0.52493	0.00001 < 0.05

*Indicates significant correlation.

Concerning disturbance and species presence, for those quadrats with species present it is shown in Table 16 that more were disturbed than undisturbed. All species except for *E. umbellate* seem to have been found more often in disturbed quadrats. The larger number of quadrats recorded as containing some form of disturbance (41) compared to those recorded as not disturbed (20) could be explained by the decision to randomly select quadrat sites near roads and trails, both of which are considered forms of anthropogenic disturbance.

Table 16 *Disturbance totals by occurrence of species*

M. vimineum

	Disturbed	Undisturbed	Total
Present	12	3	15
Absent	29	17	46
Total	41	20	61

L. japonica

	Disturbed	Undisturbed	Total
Present	3	1	4
Absent	38	19	57
Total	41	20	61

R. multiflora

	Disturbed	Undisturbed	Total
Present	8	3	11
Absent	33	17	50
Total	41	20	61

E. umbellate

	Disturbed	Undisturbed	Total
Present	5	4	9
Absent	36	16	52
Total	41	20	61

However, the Chi-squared (χ^2) correlation (Table 17) report indicates that any apparent correlation observed between disturbance and species presence is not significantly different from that shown by two independent variables, when p = 0.05.

Table 17 *χ^2 Correlation Report displaying correlations and significance levels of each Species' Occurrence to Presence of Disturbance*

	χ2 Correlation	**Significance Level**
M. vinimeum	1.47584	0.224427 > 0.05
L. japonica	0.11779	0.731450 > 0.05
R. multiflora	0.18516	0.666972 > 0.05
E. umbellate	0.65107	0.419729 > 0.05

Results Summation & Ranking of the Modeled Habitats

It has been shown that the maps of model output developed through logistic regression (Figure 10) utilizing the selected environmental variables describe the locations of study species collected at the time of validation more accurately than a random sample. The frequency and habitat probability value of species populations recorded at the time of validation can be used to rank the usefulness of the individual species models. This is similar to other researchers' model validation methods, which sought to equate predicted map probability values with the proportion of observed occurrences (Rew et al. 2005), but instead only using the distribution of recorded quadrat occurrences at the time of validation to rank the models. Here, models with concentrations of occurrences at high probabilities are ranked above models with concentrations at low probabilities, while evenly distributed probability occurrences hold a rank in between. Thus, the best model is identified by species presence only in highly predicted areas; the mediocre model is identified by species presence evenly distributed throughout the range of predicted probabilities; the least rated model is that for which the indicated species was found only in low probability areas.

All *E. umbellate* validation populations occurred above the 0.60 probability, with the majority occurring above 0.90. During field validation, this model often produced high probability points immediately upon established populations. This model is the most highly rated.

The *M. vimineum* validation populations occurred in a fairly even distribution of probabilities, with a minor concentration between the values of 0.7 and 0.9. Occurrence in such a wide range of probable habitat values indicates the ubiquitous nature of *M. vimineum*. This model proved very useful, but the number of incidents occurring at very low probabilities make this model only the second highest rated.

The habitat model assigned the second lowest belongs to *R. multiflora*, which exhibits values between 0.77 and 0.42. The area considered to be of highest habitat probability, according to the model, showed no sign of *R. multiflora* establishment, nor did such establishment appear to be likely in the future due to the instability of the ground. Rather, it is supposed that there is at least one constraint to *R. multiflora* habitat which was not included in the environmental variables available for analysis that might limit the species in supposedly high probability areas; it is recommended that future studies include data pertaining to substrate characteristics, such as those available through the STATSGO or SSURGO databases. Only with the previous caution in mind is this *R. multiflora* habitat model recommended for use.

The lowest rated model is that describing the probable habitat of *L. japonica*, the majority of whose presence data at validation occurred below a probability of 0.54, which may also reflect the lack of high probability areas predicted to occur in the study area. The apparent success of this model is surprising since the original data collected to form the model contained a total of four quadrats at which *L.*

japonica was found to be present. Due to the small amount of presence data upon which this model is based and the relatively small number of presence sites found during the validation of the model, it is recommended that although this model may be used as it is, it should be further fortified with a greater number of *L. japonica* presence sites for greater model certainty.

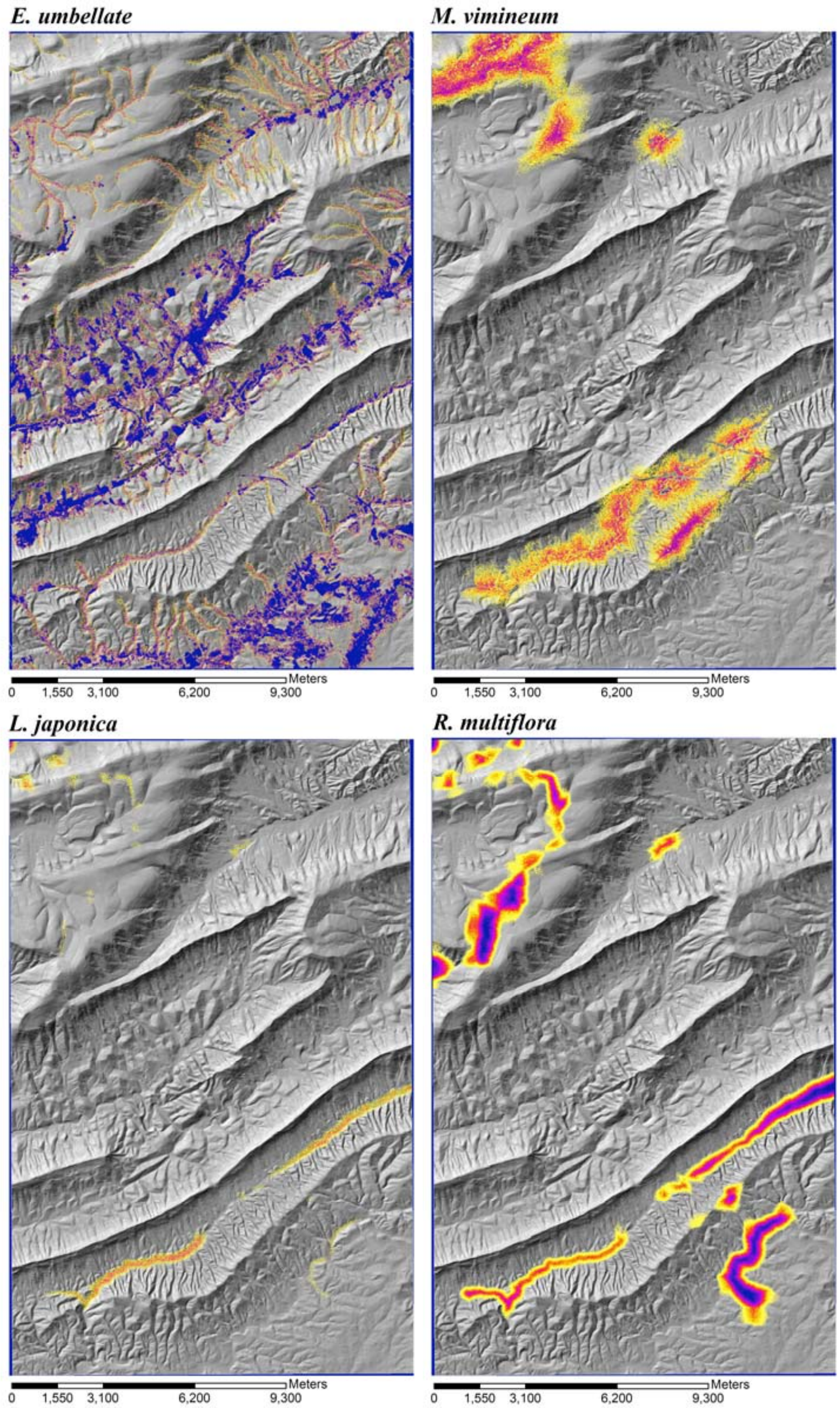

Figure 10 *Developed and validated model output for each species. Models are ranked in order of best to worst, clockwise from the upper left image:* E. umbellate*;* M. vimineum*;* R. multiflora; *and* L. japonica*.*

Chapter 6: Discussion & Conclusion

The final predictive habitat models were created over the course of a year through the process of reaching each of the three objectives set forth at the beginning of the study. Each stage of this process yielded information aside from the final models, which needs to be discussed in combination with the model results as pertinent information derived from the study. Collecting the initial species presence and absence data in the summer of 2007 yielded interesting site information; modeling in the lab provided some explanation of habitats and species autecology; the final habitat model validations in the summer of 2008 illustrated some of the problems inherent in predictive studies, as well as raising questions that could potentially be examined in further studies of the region.

Of interest during the initial data collection was the initial impression of site characteristics. For instance, at this time it was discovered that the most important factor in determining any species' presence at any point on the ground is the lack of rhododendron (specifically *Rhododendron maximum*) at that point, a rule borne true throughout the study. Rhododendron was found to present an impenetrable mass of vegetation difficult to travel through, and possessing of such characteristics that block out both light and GPS signals beneath their canopy; rhododendron surrounding a quadrat point generated in the lab made that point impossible to locate in the field, as well as ensuring the absence of any plant species besides the rhododendron. Later plant studies, as well as current forest management, could take this observation into account when searching for species besides rhododendron, by mapping all known rhododendron sites and then disregarding those positions. Rhododendron positions in the southern Appalachians have previously been determined by examining environmental characteristics which may limit their growth (Lipscomb and Nilsen 1990).

Among those observations concerning the study species, *Microstegium vimineum* was recurringly found to occupy sites that tend to remain damp but without standing water; atop Brush Mountain, there exist depressions filled with water at which *M. vimineum* is absent, yet nearby areas which apparently act as channels for water during periods of rain and which remain damp after the rain are densely populated by the C_4 grass. Also, areas of highly disturbed soil, such as those mounds of dirt and gravel found at the side of forest access roads, were found to be densely colonized. As such, current populations of *M. vimineum* should be taken into account when planning construction along these roads in order to avoid inadvertently spreading this invasive plant further; a recently published study from southern Ohio which included *M. vimineum* found that the plant found road sites to be good habitat and "that spread along the road axis was [likely] facilitated by movement of dormant seeds in road maintenance" (Christen and Matlack 2008).

Elaeagnus umbellate was observed most often in open canopy areas, probably due to the large vegetative form of the plant (large shrub or small tree). Large populations of this species were found in the area known as Boley Fields, and areas which constituted a gap in the canopy: under power lines and in fire breaks. If *E. umbellate* is consistently found in areas like fire breaks, it is possible that the species might use such pathways as migration routes, to spread from one area of likely habitat to another; such a hypothesis is supported by others' habitat invasibility studies which suggest that exotic invasive plant species passively flow through habitat to which they are suited, after the initial introduction of the species to a new area (Huebner and

Tobin 2006; Stohlgren et al. 2006). This reaction to suitable habitat by individuals of a species, a principle precept of autecology, can dictate the piecemeal spread of an entire population through the landscape over time.

After the observations made during the initial data collection objective, models were concocted from the presence/absence data and continuous raster layers representing environmental variables. It was determined at this point that the Elevation layer was not an important factor of habitat distribution for any of the study species at either of the study sites. During the initial investigation of the study sites and again during each successive data-gathering period, it was observed that the weather at the higher elevation study site was consistently harsher than weather at the lower elevation site, being noticeably colder, windier, and much closer to the cloud ceiling, the latter of which often enshrouded the mountain top. It is hypothesized that the differences in temperature, wind, and precipitation between the two sampling areas, imposed by the difference in elevation between the two sites, was not sufficient to significantly influence, positively or negatively, the distribution of any of the four exotic plant species examined.

Among the raster layers derived from linear features, each cell measured the approximate distance overland to the nearest road (state maintained or forest access), trail, or stream. The distinction between federal (RoadsOF) and state (RoadsS) road layers was created in an attempt to distinguish between the intensities of road use, but it would have been much appreciated if road type (gravel, paved, highway, etc.) or intensity of use information were included in the road and trail GIS data available for the area to produce more precise distinctions. With more time, road type and intensity of use data could be included in the GIS dataset, but the time allotted to complete this study was limited.

The variables selected for each model indicate some effect upon the distribution of each species, and may thus be considered of autecological value. Given the rather small sample size of quadrats with one or more study species present, that any produced useable models was surprising.

The *E. umbellate* model in particular was produced from a subset of environmental variables (Streams, **cos** (Aspect), **sin** (Aspect), and NDMI) that described nearly 55% of the species presence data (R^2=0.5500). The less than -0.7 coefficients describing both Streams (distance from the stream) and NDMI seem at first oxymoronic, but indicate a habitat preference for land near streams and yet generally dry.

The *M. vimineum* model (R^2=0.2164) variable coefficients indicate, besides influence by aspect, an affinity to both RoadsOF and Trails, and high soil moisture (NDMI). The greater than 0.4 coefficient describing NDMI is in agreement with the previously observed preference for moist habitats. It has previously been hypothesized that available soil moisture is of some importance to *M. vimineum*'s renowned reproductive capabilities (Gibson et al. 2002); the autecological preference to occupy moist habitat, thereby allowing consistent reproduction, would ensure multi-year population occupation of an area by this annual grass.

The *R. multiflora* model (R^2=0.2300) indicated affinities to RoadsOF and Streams, along with an effect by aspect, but a small positive coefficient (less than 0.09) describing Trails (preferring a greater distance from trail features). Although few in number, most *R. multiflora* plants were found near areas of past or present human habitation. It is known that *R. multiflora* was once purposefully planted by landowners; plants found today could simply be several generations removed from intended plantings, but still found near roads and surviving near available water sources.

The *L. japonica* model, produced of only four initial sites of species presence, unsurprisingly produced a model which could explain less than 13% of the initial species presence pattern inherent in the data (R^2=0.1263). This model described an affinity to RoadsOF and Streams, while exhibiting a minor dislike of RoadsS, and a very minor effect from aspect. That most of the variation in the initially collected data could be explained by one variable would indicate that other environmental factors besides those selected for analysis in this study are of importance and/or more samples need to be collected initially in any further research. Usually, four positive samples are not enough to construct a truly good model, and it is suggested that a much more extensive and systematic survey of *L. japonica* populations be conducted before logistic regression is used to produce a habitat probability model for this species.

The objective of model validation and the subsequent ranking of validated models related the worth of the predictive habitat equations produced from the preceding objective. Although all models were considered valid (model use generated more 'present' quadrats than a random quadrat site selection), those depicting *E. umbellate* and *M. vimineum* habitats were the most helpful during validation. The other two species' models, *R. multiflora* and *L. japonica*, though better than random, seemed insufficient for one reason or another which could be explained by the exclusion of an unconsidered, important environmental variable or an insufficient number of samples collected, either initially or during validation. By the very nature of the GIS-based analysis used in this research, one or both of these insufficiencies could be easily remedied in future studies by adding more environmental variables in the form of raster layers to those already available for analysis (in the case of the former) and ensuring a larger number of incidences of species presence (in the case of the latter). Due to the constraints imposed by time, a lack of funding, and a lack of field help, various methods used by other researchers to ensure a properly large sample size could not be implemented for this study, but should be taken into consideration in any similar future studies or continuations of the current study.

As it stands, this study was a success in developing predictive habitat models for invasive plant species that were better than randomly selecting sample points. The use of GIS analysis to examine the data proved to be a very good idea in that environmental data that was not directly measured in the field could be added or considered by the simple expediency of adding a new raster layer representing that data to the GIS; the only drawback being non-continuous environmental variables like Disturbance and Canopy Cover which may be important autecological variables but were not able to be added to the GIS analysis. At least two pieces of information regarding the habitat moisture requirements of *E. umbellate* and *M. vimineum* were added to autecological knowledge, and various other habitat traits concerning aspect and certain linear features (streams, roads, and trails) uncovered.

This study could have been improved in a number of ways, and future studies can benefit from these ideas. The inclusion of more environmental factors should be considered in any future studies of these species. Soil information could be very important and is readily available from the USGS in the form of SSURGO and STATSGO databases and shapefiles. Acquiring funding, trained volunteers to collect quadrat data, and an extended timeframe in which to complete the project could significantly increase the amount of valuable information which can be gathered for analysis. Also, as described in the case of rhododendron, the presence/absence of other species may be an important factor in determining likely habitat which should be taken into account. Finally, a method of representing in continuous, raster format those variables described in this study as discrete would allow their inclusion in the GIS analysis, and be of great help in producing a truly inclusive set of available habitat variables.

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