A REEVALUTION OF TENNESSEE'S INVASIVE PLANT SPECIES USING SERNEC AND MAXIMUM ENTROPY SPECIES DISTRIBUTION MODELS

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A Thesis Submitted to the Faculty of The University of
Tennessee at Chattanooga in Partial
Fulfillment of the Requirements of the Degree
of Master of Science: Environmental Science

The University of Tennessee at Chattanooga
Chattanooga, Tennessee

December 2019

ABSTRACT

The detection and monitoring of invasive plant species present tremendous challenges to land managers. To reduce the economic and environmental costs associated with developing management plans for invasive plants, organizations such as the National Invasive Plant Council work to rank invasive plant species with regard to their invasiveness. Here, the Tennessee Invasive Plant Council's ranking system is evaluated by considering county documentation from four resources that are commonly used to understand species distribution, including SERNEC which has recently uploaded more than 800,000 herbarium specimen records. We use data from SERNEC and iNaturalist to model the current and potential distribution of 24 Tennessee Invasive Plant Council ranked species in Tennessee. In the end, a combination of these online sources as well as species distribution models are used to propose a layout for a new way of ranking invasive plant species in Tennessee.

ACKNOWLEDGMENTS

I am grateful for everyone who has helped and supported me through this process. First, I would like to thank my family and friends who have supported me. My mom, Beckie Alley, who has always encouraged and supported me throughout my life and my educational career. Thank you to the Shaw Lab, every one of you has been incredibly supportive and has motivated and inspired me to become a better scientist. A special thank you to Erica Rylander, Caleb Powell, and John Shelton who have been with me since the beginning of the program, your support and guidance have been invaluable.

I would like to thank Joey Shaw for his advice and guidance through this process. Thank you for your unwavering support, guidance, and for always challenging me accomplish more than I believe I am capable of. A special thank you to Nyssa Hunt for your GIS guidance, support, and snacks. Finally, thank you to my committee members, Dr. Matthew Heard, Dr. Azad Hossain, and Nyssa Hunt for your advice and input that made it possible to complete this project.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

AUC, Area Under the Curve

BONAP, Biota of North America Project

MaxEnt, Maximum Entropy

MTP, Minimum Training Presence

MSS, Maximum Sensitivity plus Specificity

TENN, University of Tennessee Herbarium

TN-IPC, Tennessee Invasive Plant Council

SERNEC, South East Regional Network of Expertise and Collections

SDM, species distribution model

USDA, United States Department of Agriculture

CHAPTER I

BACKGROUND

The growing human population followed by the rise in global trade, travel, and degradation of habitat have all contributed to the rapid increase of the establishment and spread of invasive plant species (Paini et al. 2016; Seebens et al. 2015; Turbelin et al. 2017). Invasions of exotic plant species impact native ecosystems by reducing biodiversity and altering ecosystem processes such as soil properties (Gibbons et al. 2017; Vilà et al. 2011). Controlling the spread of these species is necessary to maintain native diversity in natural areas, but management of invasive species is costly. Economic losses as a result of invasive species are estimated to cost the United States $120 billion annually (Pimentel, Zuniga, and Morrison 2005). Management plan development is critical to efficiently reduce the economic and environmental costs associated with invasive plant species (Papeş et al. 2011). An initial step in developing efficient management plans is to target species for research and legislation by creating a ranking system of species that identifies the most harmful invaders. Prioritization of species allows land managers, scientists, and legislators to direct funds toward those species that present the most harmful threat to the management area (Papeş et al. 2011). However, complexities are present due to species occupying varying ecologies and their establishment and spread are often governed by their differing ecologies; thus, there is a need for prioritization schemes to go beyond regional or even state-level ranks and consider these species in regard to the specific habitats they might be altering.

The flora of Tennessee includes 2,878 documented taxa; 493 of these species are non-native and naturalized in the state (Chester et al. 2014). Since Tennessee is longitudinally expansive, it contains 25 Level IV Ecoregions (EPA), each of which has many ecological associations. Additionally, Tennessee contains more than 535 rare vascular plant species (Crabtree 2016) whose populations could be vulnerable to the negative impacts of invasive species establishment. In addition to the conservation threats that these species pose to the state, the Tennessee Invasive Plant Council (TN-IPC) estimates that Tennessee taxpayers spend a minimum of $2.6 million annually in direct monetary costs to combat the spread of these species. With all of these ideas considered, it is essential to provide conservation workers with a more efficient way to identify the invasive species that pose the most significant threat to offset the potential costs associated with species management.

The Tennessee Invasive Plant Council is a non-profit organization that works to aid land managers in making decisions regarding non-native species by selecting and ranking species of concern in the state to monitor. In 2018, TN-IPC revised its ranking of invasive plant species to focus "on species most likely to significantly affect intact native plant communities or hinder their restoration." They did this by reducing their former ranking hierarchy of 145 species in four categories – Severe, Significant, Emerging, and Alert – into 64 species in only two categories: Established Threat and Emerging Threat. This committee ranked 40 species as Established Threats and 24 as Emerging Threats (TN-IPC). The complete list of species can be found here: http://www.tnipc.org/revised-list-of-invasive-plants/ (TN-IPC).

Designations of Established and Emerging threats were determined by a review committee of approximately 13 members who used data from the University of Tennessee Herbarium website, the USDA Plants Database, the Biota of North America Program (BONAP), the Southeastern Regional Network of Expertise and Collections (SERNEC) portal (SERNEC), and nearby Invasive/Exotic Pest Plant Councils to determine the current distributions of alien species across Tennessee as of November 2016. The plant species TN-IPC ranked as Established Threats are those the council perceive to be "archetypal invasive weeds known to every land manager" as well as having broad distributions throughout Tennessee. To be considered at this rank, a species must "have been reported from more than ten counties" and "cannot be eradicated on a landscape scale using methods currently available." This criterion is problematic because TN-IPC does not clarify what they consider "methods that are currently available," leaving those methods to interpretation. Emerging Threats are species that have "been previously reported from less than ten counties in Tennessee but are known to invade and disrupt natural plant communities in adjacent states." Unfortunately, these criteria do not consider the varied ecology of Tennessee. For example, a species that is known to occupy seven counties in one Level IV Ecoregion might be devastating to that ecoregion, but it would only be categorized as an Emerging Threat since it does not meet the criterion of being found in ten counties. As stated on their webpage, the reason for the revision from four categories with 145 species to two categories with 65 species was to provide land managers with the necessary information to aid in early detection and to educate citizens to minimize the use of invasive plant species in Tennessee (TN-IPC).

At the time the TN-IPC panel used county-level data to assign ranks in November 2016, the SERNEC: Key to the Cabinets specimen digitization effort in Tennessee (Shaw 2014: NSF: 1410069) to digitize all of Tennessee's herbarium specimens was barely underway, so very few herbarium specimens in Tennessee had data uploaded to the SERNEC portal. Thus, the council's understanding of species distributions included a limited number of vouchered herbarium specimens from SERNEC. It is also worth pointing out that nearly all of the data from USDA Plants and BONAP were mirrored from the UTK Herbarium website. Furthermore, the reliance on political boundaries, such as Tennessee, rather than ecological boundaries, like the Level IV Ecoregions, for species prioritization fails to provide the council with the understanding of ecology necessary to determine where the species will have the most impact on the state (Hulme 2003; Graham et al. 2004).

A December 2018 query of SERNEC data for all vouchered herbarium specimens of every non-native, naturalized plant species in Tennessee determined the total number of counties in which each of these species had been documented. This investigation revealed that 299 of the 493 non-native plant species in Tennessee were documented in over ten counties; thus, 299 non-native species met half the qualifications to be considered an Established Threat. Additionally, two species that TN-IPC considers to be an Established Threat were found in less than ten total Tennessee counties in the SERNEC database. Six species that were ranked as Emerging Threats were not documented by a single herbarium specimen collected in Tennessee.

Hulme (2003) argues that examining and evaluating distributions on a county by county basis across a state is misleading (although it may be all that can be done at the time). Coarse-resolution maps based on partial or incomplete data, such as those used by TN-IPC to rank species, overestimate species distribution, and neglect to accurately predict the spatial trends of a species. Alternatively, collection bias that tends to favor collecting specific taxa over others may result in gaps that underestimate the distribution of non-native plant species (Daru et al. 2018). For these reasons, utilizing county-level maps to describe invasive species distributions tends to be misleading when evaluating species prioritization (Hulme, 2003; Graham et al. 2004). Since the reliable spatial data necessary to understand species distributions are rarely available (Tulloch et al. 2016), species distribution models (SDMs) are recommended to create a detailed representation of invasive species distribution (Graham et al. 2004; Hulme 2003; Tulloch et al. 2016). Ideally, SDMs alone could be used to understand the distribution of invasive plant species, and ultimately lead to more reliable prioritization of these species. However, the development of SDMs is limited by the availability of occurrence data, and therefore are not always an option for understanding species distribution (Kadmon, Farber, and Danin 2003). Since the availability of occurrence data limits SDMs, it is still necessary in some cases to rely on county-level data for first impressions of threat potential.

The objectives of this study were to first consider the distribution of TN-IPC ranked species on a county level, then, when data were available develop SDMs for these species, and finally propose a new ranking system based on county level documentation and SDMs. Data from SERNEC and iNaturalist were used to model the potential distributions of 24 TN-IPC-ranked species in Tennessee. Unfortunately, there were not enough data available to model all of Tennessee's alien plant species. Therefore, county-level data were also gathered from four resources commonly used to understand species distributions: the Biota of North America Program (BONAP), the USDA Plants Database (USDA), University of Tennessee's Herbarium Database (TENN), and the Southeastern Regional Network of Expertise and Collections (SERNEC) to evaluate all 64 TN-IPC ranked species. However, since the time of TN-IPC's last analysis of these resources, more than 800,000 herbarium specimen records were added to the

SERNEC portal from Tennessee-based herbaria. Ultimately, the objective of this work was to take a holistic approach in using a combination of multiple online sources that provide county-level distribution data as well as SDMs to evaluate and improve our understanding of non-native, invasive species' distributions in Tennessee. The second chapter of this text chapter analyzes all herbarium specimens and county-level data in Tennessee both at the state and physiographic province level. The third chapter discusses the SDMs created for TN-IPC ranked invasive species. The final chapter summarizes data generated from this study and compares them to the current TN-IPC ranking system and proposes adjustments to the current ranking system.

CHAPTER II

ANALYSIS OF COUNTY-LEVEL DOCUMENTATION

Introduction

Many of the regional exotic pest plant councils (TN, SC, MS, AL, FL) have historically used county-level data as a greater or lesser part of their ranking criteria. Until the last few years, these coarse data were the best way to understand species distributions and, at a coarse level, their ecology. Using county-level data to understand broad distributions of species is a time-tested and effective method. When a species is reported in a county, that whole county is considered part of that species' distribution, regardless of the size of the population, where it was observed, or if it was found elsewhere in the county. For this reason, coarse county-level data may lead to an overestimation of species distribution (Hulme 2003). On the other hand, collection bias at this scale may underestimate the distribution of weedy or invasive species because workers are often biased against collecting them (Garcillán and Ezcurra 2011). Historically, herbarium specimens have mostly been used to build county-level distributions because they are verifiable and usually produced by people with extensive training.

Half of the criteria to be considered an Established Threat by the TN-IPC is the number of documented county occurrences in Tennessee. TN-IPC designates species as an Established Threat if they are found in over ten counties and as an Emerging Threat if they are found in less than ten counties (note that these criteria do not rank species known from exactly ten counties). For comparison to nearby states, one criterion (of six) for a species to be considered a Severe Threat by the South Carolina Exotic Plant Pest Council is to be documented in at least 13 counties. (Interestingly, South Carolina has 46 counties compared to Tennessee's 95, so a species would need to be noted from a significantly larger area within the state). County-level data can be used to determine the ecological boundaries of a species by evaluating the species' preference for each province based on the counties located inside the provinces. Invasive

Plant Councils in Alabama and Mississippi divide their respective states into regions or provinces and classify species as a Severe Threat if they occupy more than two provinces in Mississippi or three provinces in Alabama.

Regardless of the exact criteria, those states that use county-level distribution data in ranking non-native species gather information from data servers such as USDA Plants, BONAP, state atlases such as the UT Herbarium website in Tennessee (TENN), and SERNEC. Two of the four sources use only vouchered herbarium specimens to report county-level data; these are TENN and SERNEC. Workers at TENN currently only compile data from herbarium specimens in the University's collection; however, before the late 1990s, specimen data from the Austin Peay State University Herbarium (APSC) and the Vanderbilt University Herbarium (VDB-BRIT) were also included. SERNEC is an online herbarium data portal that compiles herbarium data from 233 herbaria in the Southeast. SERNEC was established in the early 2000s, but it was the 2014 Key to the Cabinets award (#1410069) that allowed workers to start generating specimen images and label data to be pushed to the portal. Within Tennessee, work started slowly, and the vast majority of Tennessee's herbarium data was not pushed to the SERNEC portal until late 2016 through early 2019. Data are still being uploaded daily, albeit at a much slower rate because the bulk of the initial work was in digitizing the backlogged specimens of the last ~200 years. BONAP and USDA Plants document county-level distribution from a variety of sources including state atlases and SERNEC as well as from published articles, natural heritage programs, and a variety of additional resources such as theses or personal communications. It is important to note that there is overlap between some of these sources.

Although county-level data can be misleading, it is often the most easily accessible and scientifically verifiable source of data; therefore it is widely used by councils to rank invasive species in their respective states. The Southeast Early Detection Network (SERNEC) has only recently grown large enough to begin supplanting other resources for data on non-native plant species.

Given the very recent and massive amount of newly accessible data from digitized herbarium collections in Tennessee, the focus of this chapter is to reassess county-level data from a variety of sources, and reevaluate TN-IPC's species rankings based on the criterion of greater or less than ten counties. The total number of documented county occurrences for each TN-IPC ranked species was determined from each source, along with the average number of counties documented across all sources (even though they are somewhat confounded by containing overlapping information). To understand species distribution using ecological boundaries, counties were assigned to physiographic provinces. The percentage county documentation within each province was also calculated.

Materials and Methods

Four commonly used web sources that report county-level distributions of plant species were reviewed to determine the total number of documented county occurrences for all TN-IPC ranked species. These were: The Biota of North America Program (BONAP), The USDA Plants Database (USDA), the Southeast Regional Network of Expertise and Collections (SERNEC), and The University of Tennessee's Online Herbarium (TENN).

For each TN-IPC-ranked species in Tennessee, the number of counties in which a particular species had been documented was averaged across the four sources of county-level distribution information. Additionally, for each species, the number of counties in each physiographic province was calculated using SERNEC data because it is the largest source of vouchered herbarium specimen data reviewed in this study. To delineate counties into physiographic provinces, a county was designated within a province if the county was found in 50% or more of the province. Typically, Tennessee is considered to have seven physiographic provinces (Chester et al. 2015); however, when assigning counties to each province, only one, Lake County, was considered part of the Mississippi Alluvial Plain. For simplicity, the Mississippi Alluvial Plain and Gulf Coastal Plain have been combined and are referred to as the Coastal/Mississippi Alluvial Plain. After combining those two provinces, the following six provinces were analyzed: Blue Ridge, Ridge and Valley, Cumberland Plateau, Interior Low Plateau, Nashville Basin, and Coastal/ Mississippi Alluvial Plain.

Results and Discussion

Each of the four sources surveyed by this study (BONAP, USDA, TENN, and SERNEC) varied greatly in regard to the number of counties an invasive plant species was reported (Table 2.1). There are 95 counties in Tennessee and the average number of counties in which all four sources documented the occurrence of an invasive species ranged from 0-67. Japanese honeysuckle (*Lonicera japonica*) was the only species to be reported in all 95 counties (BONAP, 2019). On average, across the four sources, Japanese honeysuckle was documented in the most counties (67). Interestingly, there is a wide range in the distributions of species considered by TN-IPC to be an Established Threat. Species in this category had distributions that ranged from seven counties to 67 counties. Likewise, species considered to be Emerging Threats ranged from 0-21 counties. In total, six species were documented in more than 50 counties, 12 species in 26-50 counties, 22 species in 10-25 counties, 14 species in one to nine counties, and ten species in less than one county. The following species were not reported in Tennessee by any of the reviewed data portals, but are on the current TN-IPC list: Russian knapweed (*Centaurea repens*), giant hogweed (*Heracleum mantegazzianum*), itchgrass (*Rottboellia cochinchinesis*), and giant salvinia (*Salvinia molesta*).

Four discrepancies between TN-IPCs ranking criteria and current available data were revealed. Two species did not meet the county-level documentation requirements to be considered an Established Threat. Common reed (*Phragmites australis*) was documented in less than ten counties by all sources and documented on average in only seven counties. Therefore, common reed is not reported in enough counties by any major source, including the up-to-date SERNEC portal, to currently be considered an Established Threat under TN-IPC's criteria. Water thyme (*Hydrilla verticillata*) also did not meet the qualifications to be considered an Established Threat, having been documented on average in only seven counties. The other two species, giant reed and sacred bamboo, exceed the requirements to be considered an Emerging Threat and have been reported in enough counties to be considered an Established Threat. Giant reed (*Arundo donax*), classified as an Emerging Threat, was found in more than ten counties by all sources, and on average was found in 21 counties; meeting half the qualifications to be considered an

Established Threat. Sacred bamboo (*Nandina domestica*), also classified as an Emerging Threat, was found in more than ten counties in all sources except for the USDA Plant Database, meaning it also meets the qualifications to be considered an Established Threat.

Of the 64 TN-IPC-ranked species reviewed, 29 were found in every physiographic province, nine species were documented in five provinces, four species were documented in four provinces, four species were documented in three provinces, seven species were documented in two provinces, and three species were documented in only one physiographic province (Table 2.2). Three species were documented in more than 50% of the counties in all provinces: Japanese honeysuckle (*Lonicera japonica*), mimosa (*Albizia julibrissin*), and Johnsongrass (*Sorghum halepense*). Species that stand out with such high levels of documentation in all physiographic provinces demonstrate the ability to establish populations across ecological boundaries and therefore are essential to prioritize statewide. However, many species are constrained by certain physiographic conditions to only a few provinces and would not be a concern to land managers in places where they cannot establish populations. For example, Japanese knotweed (*Fallopia japonica*) is known to occur in 100% of the counties in the Blue Ridge, while it is only known to occur in 24% of the counties of the Interior Low Plateau and 9% of the counties from the Coastal/ Mississippi Alluvial Plain. Wine raspberry (*Rubus phoenicolasius*) is known to occur in 50% of the counties in the Cumberland Plateau, yet is not known to occur in counties in the Nashville Basin or Coastal/Mississippi Alluvial Plain. Parrot feather watermilfoil (*Myriophyllum aquaticum*) is known to occur in 71% of counties in the Blue Ridge, 23% of counties in the Coastal/Mississippi Alluvial Plain, and only 11% of counties in the Nashville Basin.

Evaluating species distributions independently at the level of physiographic province revealed distinct distribution trends for several species. The following species had high percentages of county documentation in eastern provinces, but percentages began to decrease west of the Interior Low Plateau, and in some cases there was no documentation of these species past the Interior Low Plateau: Small carp grass (*Arthraxon hispidus*), purple loosestrife (*Lythrum salicaria*), Chinese silver grass (*Miscanthus sinensis*), wine raspberry (*Rubus phoenicolasius*), and Japanese meadowsweet (*Spiraea japonica*).

Chinese wisteria (*Wisteria sinensis*) was documented most frequently in Middle Tennessee provinces, particularly the Interior Low Plateau and the Nashville Basin. Common reed (*Phragmites australis*) was documented only in provinces in West and Middle Tennessee. Water chestnut (*Trapa natans*) and buckthorn (*Rhamnus cathartica*) were documented in only one county in western Tennessee (Table 2.2).

Table 2.1 TN-IPC Ranked Species County Documentation

Scientific Name	**Common Name**	**TN-IPC Category**	**USDA**	**BONAP**	**TENN**	**SERNEC**	**Average number of Counties**
Lonicera japonica	Japanese honeysuckle	Established	45	95	60	67	67
Lespedeza cuneata	Chinese bush-clover	Established	36	91	50	59	59
Microstegium vimineum	Japanese stilt grass	Established	36	94	45	53	57
Ligustrum sinense	Chinese privet	Established	25	93	43	58	55
Sorghum halepense	Johnson grass	Established	42	54	51	55	51
Lespedeza bicolor	two-color bush-clover	Established	27	88	39	46	50
Perilla frutescens	beefsteakplant	Established	42	49	49	56	49
Paulownia tomentosa	princess tree	Established	24	73	36	59	48
Ailanthus altissima	tree-of-heaven	Established	21	90	33	47	48
Albizia julibrissin	mimosa	Established	23	70	34	58	46

Rosa multiflora	multiflora rose	Established	27	51	42	54	44
Pueraria montana	kudzu	Established	28	70	33	31	41
Elaeagnus umbellata	autumn olive	Established	17	49	32	45	36
Vinca minor	lesser periwinkle	Established	24	32	28	51	34
Arthraxon hispidus	small carp grass	Established	28	35	30	28	30
Dioscorea polystachya	Chinese yam	Established	0	62	37	14	28
Alliaria petiolata	garlic mustard	Established	16	33	23	37	27
Lonicera maackii	amur honeysuckle	Established	14	32	26	37	27
Euonymus alatus	burning bush	Established	0	27	32	33	23
Centaurea stoebe	spotted knapweed	Established	17	32	31	11	23
Hedera helix	english ivy	Established	9	41	16	25	23
Arundo donax	giant reed	Emerging	20	23	22	19	21
Bromus inermis	smooth brome	Established	14	18	21	30	21
Pyrus calleryana	bradford pear	Established	15	22	14	31	21
Clematis terniflora	sweet autumn virgin's-bower	Established	15	19	21	20	19
Spiraea japonica	Japanese meadowsweet	Established	13	19	17	23	18
Myriophyllum spicatum	Eurasian water-milfoil	Established	14	19	18	19	18
Fallopia japonica	Japanese-knotweed	Established	14	25	0	27	17
Myriophyllum aquaticum	parrot feather watermilfoil	Established	15	24	22	5	17

Rubus phoenicolasius	wine raspberry	Established	12	17	18	19	17
Euonymus hederaceus	winter-creeper	Established	2	25	15	23	16
Miscanthus sinensis	Chinese silver grass	Established	0	23	19	23	16
Alternanthera philoxeroides	alligator-weed	Established	14	14	15	15	15
Nandina domestica	sacred bamboo	Emerging	0	26	10	22	15
Tussilago farfara	colt's-foot	Established	7	17	16	17	14
Celastrus orbiculatus	asian bittersweet	Established	10	16	14	16	14
Murdannia keisak	wart-removing-herb	Established	9	12	16	18	14
Wisteria floribunda	Japanese wisteria	Established	8	14	11	13	12
Wisteria sinensis	Chinese wisteria	Established	7	7	7	23	11
Lythrum salicaria	purple loosestrife	Established	8	14	10	10	11
Phyllostachys aurea	golden bamboo	Emerging	0	31	0	5	9
Buddleja davidii	common butterfly bush	Emerging	3	5	7	15	8
Phragmites australis	common reed	Established	7	7	7	9	8
Hydrilla verticillata	water thyme	Established	1	3	13	12	7
Humulus japonicus	Japanese hop	Emerging	4	4	5	9	6

Mahonia bealei	beale's barberry	Emerging	0	6	0	13	5
Melia azedarach	China-berry	Emerging	4	6	0	7	4
Tribulus terrestris	puncturevine	Emerging	3	3	4	5	4
Solanum viarum	tropical soda-apple	Emerging	0	14	0	0	4
Ampelopsis brevipedunculata	porcelainberry	Emerging	0	3	3	3	2
Firmiana simplex	Chinese parasol-tree	Emerging	0	3	0	5	2
Ranunculus ficaria	Eurasian-buttercup	Emerging	1	0	3	4	2
Lygodium japonicum	Japanese climbing fern	Emerging	0	1	1	2	1
Rhamnus cathartica	buckthorn	Emerging	0	0	1	3	1
Triadica sebifera	Chinese tallow	Emerging	0	1	0	2	1
Liriope spicata	creeping liriope	Emerging	0	0	0	2	1
Akebia quinata	five-leaf akebia	Emerging	0	0	0	1	0
Imperata cylindrica	cogon grass	Emerging	0	1	0	0	0
Persicaria perfoliata	Asiatic tearthumb	Emerging	0	1	0	0	0
Trapa natans	water chestnut	Emerging	0	0	0	1	0
Centaurea repens	rhaponticum repens	Emerging	0	0	0	0	0
Heracleum mantegazzianum	giant hogweed	Emerging	0	0	0	0	0

Rottboellia cochinchinensis	itchgrass	Emerging	0	0	0	0	0
Salvinia molesta	giant salvinia	Emerging	0	0	0	0	0

Table 2.2 Percentage of County Documentation by Province

Scientific Name	**Common Name**	**BR%**	**RV %**	**CP %**	**ILP %**	**NB %**	**CP/MS %**	**total number of provinces**
Ailanthus altissima	tree-of-heaven	57%	22%	58%	66%	89%	5%	6
Akebia quinata	five-leaf akebia	0%	6%	0%	0%	0%	0%	1
Albizia julibrissin	mimosa	71%	56%	58%	59%	89%	50%	6
Alliaria petiolata	garlic mustard	71%	33%	42%	41%	89%	5%	6
Alternanthera philoxeroides	alligator-weed	0%	22%	8%	21%	22%	9%	5
Ampelopsis brevipedunculata	porcelainberry	0%	6%	0%	3%	0%	0%	2
Arthraxon hispidus	small carp grass	71%	44%	42%	38%	22%	5%	6
Arundo donax	giant reed	29%	33%	17%	21%	22%	0%	5
Bromus inermis	smooth brome	57%	44%	42%	24%	67%	9%	6
Buddleja davidii	common butterfly bush	14%	39%	17%	10%	22%	5%	6
Celastrus orbiculatus	asian bittersweet	43%	22%	42%	14%	33%	5%	6
Centaurea repens	rhaponticum repens	0%	0%	0%	0%	0%	0%	0
Centaurea stoebe	spotted knapweed	14%	11%	0%	10%	0%	0%	3
Clematis terniflora	sweet autumn virgin's-bower	43%	28%	17%	21%	44%	5%	6
Dioscorea polystachya	Chinese yam	29%	22%	8%	14%	11%	5%	6

Elaeagnus umbellata	autumn olive	86%	28%	67%	52%	56%	18%	6
Euonymus alatus	burning bush	29%	50%	25%	34%	44%	9%	6
Euonymus hederaceus	winter-creeper	0%	28%	25%	31%	56%	0%	4
Fallopia japonica	Japanese-knotweed	100%	50%	42%	24%	44%	9%	6
Firmiana simplex	Chinese parasol-tree	0%	6%	0%	0%	11%	9%	3
Hedera helix	english ivy	57%	28%	25%	24%	44%	9%	6
Heracleum mantegazzianum	giant hogweed	0%	0%	0%	0%	0%	0%	0
Humulus japonicus	Japanese hop	0%	17%	0%	10%	11%	9%	4
Hydrilla verticillata	water thyme	14%	17%	8%	17%	0%	5%	5
Imperata cylindrica	cogon grass	0%	0%	0%	0%	0%	0%	0
Lespedeza bicolor	two-color bush-clover	86%	50%	75%	55%	44%	27%	6
Lespedeza cuneata	Chinese bush-clover	100%	44%	42%	72%	78%	32%	6
Ligustrum sinense	Chinese privet	86%	56%	67%	69%	67%	32%	6
Liriope spicata	creeping liriope	0%	6%	0%	0%	22%	5%	3
Lonicera japonica	japanese honeysuckle	86%	56%	83%	66%	67%	68%	6
Lonicera maackii	amur honeysuckle	43%	39%	25%	38%	89%	9%	6
Lygodium japonicum	Japanese climbing fern	0%	0%	0%	0%	11%	5%	2
Lythrum salicaria	purple loosestrife	14%	11%	17%	17%	0%	0%	4
Mahonia bealei	beale's barberry	29%	17%	17%	10%	22%	5%	6
Melia azedarach	China-berry	0%	11%	0%	0%	22%	14%	3
Microstegium vimineum	Japanese stilt grass	100%	67%	67%	66%	56%	32%	6
Miscanthus sinensis	Chinese silver grass	71%	61%	17%	17%	0%	5%	5
Murdannia keisak	wart-removing-herb	43%	39%	8%	21%	0%	5%	5
Myriophyllum aquaticum	parrot feather watermilfoil	71%	22%	50%	24%	11%	23%	6
Myriophyllum spicatum	Eurasian water-milfoil	43%	22%	8%	14%	0%	5%	5
Nandina domestica	sacred bamboo	29%	22%	50%	21%	56%	14%	6

Paulownia tomentosa	princess tree	57%	39%	67%	72%	78%	36%	6
Perilla frutescens	beefsteakplant	57%	44%	67%	62%	67%	41%	6
Persicaria perfoliata	Asiatic tearthumb	0%	0%	0%	0%	0%	0%	0
Phragmites australis	common reed	0%	0%	0%	14%	0%	9%	2
Phyllostachys aurea	golden bamboo	0%	11%	0%	10%	0%	0%	2
Pueraria montana	kudzu	43%	33%	8%	28%	33%	18%	6
Pyrus calleryana	bradford pear	14%	22%	17%	38%	67%	14%	6
Ranunculus ficaria	Eurasian-buttercup	0%	11%	8%	0%	0%	0%	2
Rhamnus cathartica	buckthorn	0%	0%	0%	0%	0%	5%	1
Rosa multiflora	multiflora rose	57%	39%	75%	52%	67%	41%	6
Rottboellia cochinchinensis	itchgrass	0%	0%	0%	0%	0%	0%	0
Rubus phoenicolasius	wine raspberry	43%	39%	50%	10%	0%	0%	4
Salvinia molesta	giant salvinia	0%	0%	0%	0%	0%	0%	0
Solanum viarum	tropical soda-apple	0%	0%	0%	0%	0%	0%	0
Sorghum halepense	Johnson grass	71%	72%	58%	62%	78%	45%	6
Spiraea japonica	japanese meadowsweet	57%	28%	58%	17%	22%	0%	5
Trapa natans	water chestnut	0%	0%	0%	0%	0%	5%	1
Triadica sebifera	Chinese tallow	0%	0%	0%	3%	0%	5%	2
Tribulus terrestris	puncturevine	0%	6%	0%	0%	0%	14%	2
Tussilago farfara	colt's-foot	43%	39%	17%	7%	11%	0%	5
Vinca minor	lesser periwinkle	71%	67%	50%	59%	56%	18%	6
Wisteria floribunda	Japanese wisteria	0%	11%	17%	14%	33%	9%	5
Wisteria sinensis	Chinese wisteria	14%	11%	33%	31%	44%	18%	6

Conclusions

Ideally, it would be possible to have robust data sets to use to evaluate all species distributions by developing Species Distribution Models (SDMs) for all of TN-IPC ranked species so that we could accurately predict habitats in need of conservation efforts; however, the data to accomplish this task were not available for all TN-IPC-ranked species. Incidentally, the SEEDN web portal through EDDMapS (EDDMapS) has become a massive data aggregator for numerous sources, including some of those used to provide data to this investigation. However, data are also gathered by other means such as volunteer observations and forest surveys. In the near future, this resource may provide more georeferenced data to SDMs than could be obtained in this study.

Invasive Plant Councils in the Southeast have used county-level data in a variety of ways to evaluate the invasiveness of non-native plant species. Like TN-IPC, the South Carolina Exotic Plant Pest Council (SC-EPPC) uses the number of documented county occurrences as a criterion to be considered a Severe Threat. Along with meeting five other criteria to be considered a Severe Threat by the SC-EPPC, a species must be documented in at least 13 counties in South Carolina. Notably, South Carolina is smaller in comparison to Tennessee and only contains 46 counties, while Tennessee contains 95. Therefore, to be considered a Severe Threat to the SC-EEP, a species must meet six different criteria and be found in almost 30% of the counties in South Carolina. In comparison, to be considered an Established Threat in Tennessee, a species must only be documented in approximately 10% of the state and meet a vague management requirement. This criterion does not effectively identify species that are most invasive because a majority of non-native plant species are documented in more than ten counties, as shown by this study that reports 39 of the 64 species from more than ten counties in the state.

Both the Alabama and Mississippi Invasive Plant Councils have begun to look at invasive species in a similar way to this study by dividing their counties into provinces. If a species in Alabama or Mississippi is documented in three or two provinces respectively within the state, it is considered a Severe Threat. This method allows councils to prioritize threats that can inhabit a variety of ecological boundaries and are therefore threats to most of the state. What this system does not accomplish is prioritizing species that may not threaten the whole state but do threaten individual provinces. This study shows that species documentation varies across physiographic provinces. For instance, small carp grass is documented in more than 40% of the Blue Ridge, Ridge and Valley, and Cumberland Plateau; however, beyond these provinces, its documentation decreases, and small carp grass is only documented in one county in the Coastal/Mississippi Alluvial Plain. Given its low documentation in western provinces, land managers in these areas should not prioritize the management of small carp grass, but this species should be prioritized in the east. Chapter IV outlines a ranking system that combines SDMs and county-level data to produce a new way of ranking species in the state.

CHAPTER III

SPECIES DISTRIBUTION MODELING

Introduction

Species distribution models (SDMs) are a correlative statistical technique used to predict the distribution of a species across a geographic space by associating the presence or absence of a species with environmental data (Elith et al. 2011). Experts have repeatedly recommended using SDMs to make conservation decisions because they are inexpensive and have strong predictive power and accuracy (Guisan et al. 2013; Phillips et al. 2006; Tulloch et al. 2016), and recent advancements in museum-based informatics have resulted in the increased availability of natural history collections data through online portals. Specifically, the Southeast Regional Network of Expertise and Collections (SERNEC) has added about 4.5 million herbarium specimen records to online data portals since 2014. In addition to natural history data, citizen science platforms such as iNaturalist (Crall et al. 2015) contribute reliable presence data to SDMs and have been shown to improve the accuracy specifically of invasive species SDMs (Crall et al. 2015). For instance, a case study in Portugal found that the inclusion of citizen science data significantly increased the predicted spatial distribution of Acacia trees (Plant Family: Fabaceae) (César de Sá et al. 2019). The increased availability of presence data has enhanced the field of SDMs (Ponder et al. 2001) and allowed for their use to become more available for land management and conservation (Guisan et al. 2013; Wang et al. 2015; Williams et al. 2008).

SDMs have long been used in ecology and have recently become more common in invasion ecology to understand and predict distribution patterns of invasive species (Thapa et al. 2018; Wang et al. 2017; Wasowicz and Przedpelska-wasowicz 2013). For instance, predictive modeling is frequently used to investigate invasive species' response to climate change (Shrestha et al. 2018; Thapa et al. 2018; Wasowicz and Przedpelska-wasowicz 2013) and has been used to explore the temporal and spatial dynamics of past invasion (Briscoe et al. 2019). The use of invasive species SDMs has been applied more directly to conservation and management efforts in a variety of ways; however, there is still a strong demand for SDMs that are more applicable to land management and conservation (Tulloch et al. 2016). Zhong et al. (2018) used SDMs to identify protected areas worldwide that are vulnerable to the invasion of ten aggressive species of trees. Other studies have used SDMs to prioritize areas within protected land that are most at risk for invasion to appropriately allocate funding to areas that need it most (Brummer et al. 2013; Lookingbill et al. 2014).

Interestingly, Lookingbill et al. (2014) incorporated SDMs into prioritizing sites within the national park landscapes of the Mid-Atlantic Untied States to predict the areas most vulnerable to reinvasion of tree-of-heaven (*Ailanthus altissima*, Plant Family: Sapindaceae). While many papers have addressed and given suggestions for land managers (Brummer et al. 2013; Lookingbill et al. 2014; Wan et al. 2018), a majority of models published do not provide conservation recommendations (Guisan et al. 2013; Tulloch et al. 2016). Long et al. (2017) addressed this issue by applying a previously published distribution model to prioritize the management of common reed (*Phragmites australis*, Plant Family: Poaceae) in the Great Salt Lake wetlands (Long et al. 2017). However, more effort is needed to incorporate SDMs more effectively in conservation work (Guisan et al. 2013).

While frequently used to prioritize areas most vulnerable to invasion, SDMs have been used less frequently to prioritize and rank species (Berthon et al. 2018; Chai et al. 2016). In one example, Chai et al. (2016) used the total area of suitable habitat in combination with a traditional risk assessment to rank species for management in preparation for climate change (Chai et al. 2016). Instead of prioritizing invasive species, Berthon et al. (2018) used SDMs to rank species that are at risk of being infected by myrtle rust (*Austropuccinia psidii*, Fungi Family: Sphaerophragmiaceae).

National policy and legislation that address mitigating the harmful effects of invasive species are beginning to incorporate SDMs into their decision-making process. SDMs have become key components for selecting species of national or local significance for legislation that restrict their movement in and out of several countries. Pheloung et al. (1999) recommend that pre-border risk assessments of potential threats utilize SDMs to aid in decisions about allowing the import of new plant species (Soberon et al. 2001). The United States Plant Protection Act uses SDMs as a tool to determine if species are eligible to be considered a Noxious Weed, and therefore prohibits or limits the species' entry into and transportation within the United States before the species is established (Title 7 U.S.C sections 7701 *et. Seq.*). Mexico used SDMs to model the potential impacts of cactus moth (*Cactoblastis cactorum*, Insect Family: Pyralidae) on *Opuntia* spp. (Plant Family: Cactaceae) to facilitate land management planning and mitigation of future impacts (Guisan et al. 2013).

While SDMs are valuable tools in evaluating invasive species for legislation and land management, in most cases they have not been utilized for these purposes (Tulloch et al. 2016). The underutilization of SDMs may be a result of limitations associated with developing models. Of particular concern to this study, these limitations include the availability of occurrence data (Kadmon et al. 2003). While data availability continues to increase (Newbold 2010), collection bias that favors specific taxa over others results in weedy, "less interesting" taxa, like non-native species, having low numbers of occurrence data. Additionally, the modeling of species distribution is limited by the availability of expertise. Complex species distribution modeling requires a knowledge of the selected algorithm to select appropriate parameters, variables, and thresholds to develop accurate models (Magarey et al. 2018).

The Tennessee Invasive Plant Council (TN-IPC) is a non-profit organization that works to prioritize species in the state by evaluating the status of invasive plant species in Tennessee by selecting and ranking species of concern to monitor. However, this organization has not begun to use SDMs to rank species and instead relies on county-level data to determine the distribution of invasive threats in Tennessee. TN-IPC considers species an Established Threat if they "have been reported from more than ten counties" and "cannot be eradicated on a landscape scale using methods currently available." Species are considered an Emerging Threat if they have "been previously reported from less than ten counties in Tennessee but are known to invade and disrupt natural plant communities in adjacent states." The incorporation of data generated from SDMs into ranking systems such as TN-IPC's will increase our understanding of species distributions in the state and allow for more informed rankings of invasive plant species.

Despite the advantages of using SDMs for invasive species management, selecting a suitable modeling algorithm when using presence-only data for invasive species is challenging (Elith et al. 2006). Presence only data are easy to obtain; however, few modeling algorithms can accurately predict the distribution of species without absence data. Maximum Entropy (MaxEnt) is a machine learning algorithm applied to create SDMs using presence-only data (Phillips et al. 2006). This algorithm is commonly chosen to model distributions of invasive species and has proven to have consistently high accuracy when modeling for invasive plant species distribution in comparison to other frequently chosen modeling algorithms (Magarey et al. 2018). In addition to producing models validated through statistical analysis, field validation of MaxEnt was proven to be highly accurate in predicting the range of the invasive plant species cheatgrass (*Bromus tectorum*, Plant Family: Poaceae) (West et al. 2016).

As of summer 2019, workers in Tennessee have come close to digitizing all of the nearly 900,000 herbarium specimens housed in Tennessee's 12 herbarium collections (with ~750,000 from North America and about 500,000 from Tennessee). This study incorporates newly generated digitized herbarium data into SDMs to better understand current distributions of non-native species in the state. Comparisons were made between the amount of potentially suitable habitat in Tennessee and TN-IPC's current ranking system. The goal of this work is to provide data that workers, including those at TN-IPC, might use to better understand invasive species distributions in Tennessee.

Materials and Methods

Data Acquisition and Processing

Occurrence data to develop SDMs were acquired from two sources: iNaturalist and SERNEC. Data from the citizen science platform iNaturalist were only incorporated if they were considered Research Grade, a status that is reached only "when more than 2/3 of identifiers agree on a taxon." Since iNaturalist data contain GPS coordinates, no further action was necessary to prepare these data for modeling; however, most data from herbarium specimens have not been georeferenced, which required multiple platforms and steps to generate GPS coordinates from label information. Data from the Early Detection and Distribution Mapping System (EDDMapS) were not incorporated into models, but these occurrence points are used to evaluate the predictive ability of SDMs. This site combines data from other databases and organizations as well as from volunteer observations. Large portions of these data were unverified volunteer coordinates or coordinates with large uncertainty radiuses. Time constraints prevented these data from being incorporated; however, these coordinates are used to verify species distributions in Tennessee.

SERNEC data are initially uploaded as incomplete data and only contain “skeletal fields” for each specimen; specifically, the herbarium acronym, species name, county, and state in which the specimen was collected. Since this information does not contain GPS coordinates or locality strings, specimen data derived from SERNEC are not immediately useful for modeling. For this reason, 2,420 specimen images were uploaded to Notes from Nature (NFN), a citizen science platform that gives people from around the world the opportunity to contribute to making natural history collections more available to researchers (Notes from Nature 2019). To our knowledge, this platform has not been used to gather locality strings for developing SDMs; however, it has been used to update transcriptions of endangered species for large datasets (Belitz et al. 2018; Will, Madan, and Hsu 2017). NFN accomplishes its goal of making data more available by creating expeditions where citizen scientists are asked to interpret data from specimen images. The data collected in this case were the locality string or GPS data when present, the collector, the date, and the habitat. The data were then keystroked into a database. Two NFN expeditions were created to gather textual locality strings for all SERNEC specimens of invasive species in Tennessee that were listed by TN-IPC.

Of the 2,420 specimens that were transcribed in the NFN expeditions, approximately 72 contained GPS coordinates. The remaining 2,348 specimen locality strings were transferred to a collaborative georeference data management portal called GEOLocate (Rios and Bart 2010), which is a web application designed to translate textual locality from natural history collections to GPS coordinates.

The algorithm used by GEOLocate parses out geographic identifiers in the locality string (such as road names and compass directions) to determine GPS coordinates. Once the algorithm has selected the potential location of a specimen, the user can visualize and correct the calculated coordinates and determine polygonal error descriptions. A GEOLocate web-based collaborative project was created, which is a type of project that provides a mechanism where users can form communities to collaborate and georeference data for large projects such as aggregating documentation of endangered species (Belitz et al. 2018) and extracting coordinates from specimens to develop SDMs (Hutter et al. 2016; Lee et al. 2012). After duplicates and specimens lacking locality strings were removed, 2,154 specimens were uploaded to a GEOLocate collaborative project. A collaboration and classroom activity was created with J. Shaw's biogeography class of ~45 students to help georeference 1,357 of the 2,154 specimens to complete this project. Once the expedition was completed, the data were georeferenced by creating a collaborative project to review and correct 422 specimens that had been skipped or contained an uncertainty radius higher than 5,000 meters. During the final cleaning, any specimens that contained an inadequate amount of locality information to obtain accurate GPS coordinates were removed. The final, clean data set consisted of 1,754 georeferenced specimens.

Species Selection

A recent study (van Proosdij et al. 2016), found that prevalent species require between 20 and 45 data points to create accurate MaxEnt models. For this reason, species from TN-IPC's list with less than 20 data points were not modeled. After cleaning the SERNEC data and combining the iNaturalist occurrence points, 24 non-native species from TN-IPC's list met this criterion. The final dataset contained 24 to 150 data points per species. The species that were modeled along with the number of occurrence points used are shown in Table 3.1.

Table 3.1 Number of Occurrence and Time Since Introduction for All Species That Were Selected for Distribution Modeling

Species	Family	Common Name	Number of Occurrence Points	Time Since Introduction (Years)
Ailanthus altissima	Simaroubaceae	tree-of-heaven	98	179
Albizia julibrissin	Fabaceae	mimosa	106	212
Alliaria petiolata	Brassicaceae	garlic mustard	107	151
Arthraxon hispidus	Poaceae	small carp grass	24	~70
Celastrus orbiculatus	Celastraceae	Asian bittersweet	27	159
Clematis terniflora	Ranunculaceae	sweet autumn virgin's-bower	28	145
Elaeagnus umbellata	Elaeagnaceae	autumn olive	49	189
Euonymus alatus	Celastraceae	burning bush	37	159
Euonymus fortunei	Celastraceae	winter-creeper	51	112
Hedera helix	Araliaceae	English ivy	67	292
Hydrilla verticillata	Hydrocharitaceae	hydrilla	26	68
Lespedeza cuneata	Fabaceae	Chinese bush-clover	103	150
Ligustrum sinense	Oleaceae	Chinese privet	147	167
Lonicera japonica	Caprifoliaceae	Japanese honeysuckle	150	113
Lonicera maackii	Caprifoliaceae	amur honeysuckle	100	~200
Mahonia bealei	Berberidaceae	beale's barberry	63	~150
Nandina domestica	Berberidaceae	sacred bamboo	65	215

Pueraria montana	Fabaceae	kudzu	45	103
Pyrus calleryana	Rosaceae	bradford pear	49	133
Rosa multiflora	Rosaceae	rambler rose	116	133
Saxifraga tridactylites	Saxifragaceae	nailwort	40	7
Sorghum halepense	Poaceae	Johnson grass	105	179
Spiraea japonica	Rosaceae	Japanese meadowsweet	33	149
Vinca minor	Apocynaceae	lesser periwinkle	80	~300

Environmental Variables

A combination of climate, soil, land cover, and topographical variables was used to model species distribution. If variables negatively affected the evaluation area under the curve (AUC) or had a percent contribution above 50%, they were removed to avoid skewing the distribution towards only one variable. Climate data were comprised of 19 bioclimatic variables from Worldclim version 2.0. Because of the similarity of climate variables, a correlation analysis was run using ENMtools, and correlated climate variables with a Pearson's correlation value above 0.75 were removed (Warren et al. 2019). The following climate variables were used to process all 24 SDMs: Bio1(annual mean temperature), Bio5(max temperature of the warmest month), Bio7(temperature annual range), Bio8(mean temperature of the driest quarter), Bio12 (annual precipitation), Bio15(precipitation seasonality), and Bio18(precipitation of the warmest quarter) (Fick and Hijmans, 2017). Land cover data for 2006, 2011, and 2016 were gathered from the National Land Cover Database (Homer, Fry, and Barnes 2012). Gap analysis program (GAP), elevation, and slope data were obtained from USGS (USGS 2011) and Gridded Soil Survey Geographic (gSSURGO) data were obtained from USDA (Soil Survey Staff 2016). Finally, given the relationship between human disturbance and the spread of invasive plant species, the human footprint variable was incorporated. The human footprint is an index of the human impact on the landscape; the higher the number, the more impacted the area is by human interaction (Venter et al. 2016). This variable has been shown to contribute to the accuracy of invasive plant SDMs (Beans et al. 2012). Finally, all variables were modified to be the same extent, the state of Tennessee, and rendered to a resolution of 30m.

Model Algorithm and Settings Selection

Maximum Entropy (version 3.4.1) (MaxEnt), a machine learning algorithm designed by Phillips et al. (2006), was used to predict habitat suitability for each study species in Tennessee. MaxEnt discerns patterns in presence data given variables or constraints and selects the most probable distribution based on maximum entropy (Phillips et al. 2006). This algorithm is an appropriate choice for this study because it predicts habitat suitability based on presence-only data (Elith et al. 2011) and has proven to have the best predictive power when working with small sample sizes (Wisz et al. 2008). Additionally, MaxEnt has consistently outcompeted similar modeling algorithms (e.g. GARP, BIOCLIM, GLM, DOMAIN, ect). For instance, Elith et al. found that out of 16 different algorithms, MaxEnt was one of the most well-performing methods for predicting distributions using presence-only data (Elith et al. 2006). Along with MaxEnt, GARP and BIOCLIM are two well established modeling methods for presence-only data; however MaxEnt has been shown to outperform these algorithms (Ray et al. 2018; Tarkesh and Jetschke 2012). GARP has been criticized for overprediction of a species distribution in comparison to MaxEnt (Ray, Behera, and Jacob 2018), and MaxEnt generates higher AUCs than both GARP and BIOCLIM (Ray et al. 2018; Tarkesh and Jetschke 2012). Finally, MaxEnt modeling is well researched (Merow, et al. 2013) and has proven successful in producing accurate models that predict invasive species distribution (Hanan-A. et al. 2016; Li et al. 2014; West et al. 2016).

A set of guidelines derived from Phillips & Dudík (2008) and Young et al. (2011) were used to ensure proper selection of settings for MaxEnt. Models were developed using 15 replicates and 5,000 iterations to allow each model to have adequate time for convergence. The number of background points was set to 10,000 (Young et al. 2011). The MaxEnt output was set to “logistic” for an easier and more accurate interpretation of results (Phillips and Dudık 2008), and features were set to default and automatically selected by the algorithm based on the number of occurrence points (Phillips and Dudık 2008).

Since MaxEnt models are prone to overfitting (Phillips and Dudık 2008), the process of tuning changes model settings to achieve an optimal level of model complexity (Radosavljevic and Anderson 2014). MaxEnt models were tuned to ensure optimal model complexity by adjusting the regularization multiplier - a setting that applies a penalty in the form of a β regularization parameter specific to each class to reduce model complexity (Phillips et al. 2006). The regularization multiplier was increased if the difference between the training and testing AUC exceeded 0.05 until the smallest difference between AUC scores was achieved while maintaining maximal or near-maximal values for the testing AUC (Springer et al. 2015).

Model Evaluation and Analysis

To evaluate model performance, the replicated run type was set to cross-validation, and distribution data were divided into training and testing data. Each replicate was run using a different set of randomly chosen presences to train and test the model. Models were evaluated using the area under the curve (AUC) and receiver operating characteristic (ROC) (Manel et al. 2001). An AUC value of 0.5 or below implies that the predictive accuracy of the model is no better than random. Values above 0.7, 0.8, and 0.9 represent good, very good, and excellent, respectively (Manel et al. 2001; Swets and Swets 2016).

Despite the advantages of SDMs, there are uncertainties associated with modeling invasive plant species distribution because modeling invasive species violates the core concepts of predictive modeling. For example, if invasive species are not established in their non-native habitat, they violate the core assumption of SDMs by not being at equilibrium in their environment (Gallien et al. 2012). Therefore, SDMs that use presence points from the non-native distribution of species may not model the full potential distribution and therefore may underestimate the range of invasive species in their non-native range (Václavík and Meentemeyer 2012). However, Václavík and Meentemeyer propose that the more established a species is, the less likely the model would be to underestimate the distribution (2012). All species modeled here were introduced on average 160 years ago (Table 3.1). Therefore, this study hopes to avoid any issues associated with species being at non-equilibrium. The exception being *Saxifraga tridactylites*, which has only recently been documented in the United States (Marttalla 2011; Alley et al. in press) and is currently spreading rapidly throughout Tennessee, Alabama, and Mississippi. *S. tridactylites* is expected to potentially have a broader distribution throughout the state than predicted by the SDM.

To better understand and analyze species distributions in Tennessee, the models were converted from continuous data into a binary model using the maximum sum of sensitivity and specificity (MSS) and the minimum training presence threshold (MTP), and the 10 percentile training presence (10 PTP) (Liu et al. 2013). The selection of thresholds in MaxEnt is disputed, and different thresholds provide researchers with important information. For example, it may be most important to include all areas of suitable habitat for widely distributed species by using low thresholds (Liu et al. 2013), or it may be important to prioritize sites for management using a high threshold (Escalante et al. 2013). In an effort to present binary data in the most usable format, this study uses three thresholds to create a range of suitable habitat for each species. Sensitivity is the probability that the model correctly predicts the presence of the species, and specificity is the probability that an absence is correctly predicted. The MSS threshold reduces the risk of selecting unsuitable sites for species (Pearce and Ferrier 2000). Since the MSS threshold is conservative in its selection of suitable habitat, this number was used to delineate highly suitable habitat for each species within the state. The 10 PTP considers the probability at which 10% of the training presence records are omitted, particularly outliers (Escalante et al. 2013). Studies have shown this predicts a middle range of suitable habitat for species, and for this reason it will be used to delineate median suitable habitat for species (Escalante et al. 2013). In contrast, the MTP uses the suitability associated with the least suitable training presence record to set the threshold (Norris 2014). Since the MTP threshold includes all habitat that was predicted suitable by MaxEnt, this threshold was used to determine the total area of suitable habitat within Tennessee. Finally, the same calculations were determined for the aquatic species water thyme (*Hydrilla verticillata*); however, to avoid an underestimation of percent coverage, only water bodies in Tennessee were considered when calculating percentages.

Using the MTP threshold, the total amount of suitable habitat predicted in protected lands was calculated to gain a better understanding of the impact each species could have on sensitive natural areas. Data on protected areas were obtained from the Protected Areas Database (PADS version 2.0) (USGS, 2018). Additionally, using the MTP and MSS, the percentage of total suitable habitat within each physiographic region was determined (physiographic provinces shown in Figure 3.1). All maps were created using ESRI ArcPro version 2.3.2.

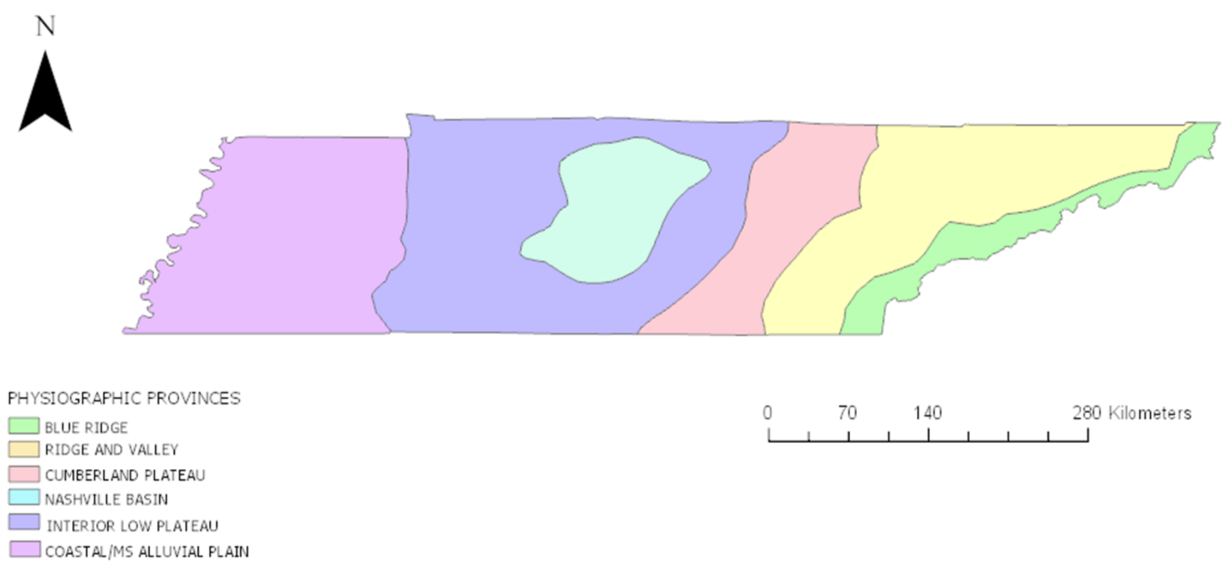

Figure 3.1 The Physiographic Province Divisions Used in this Study

Results and Discussion

The predictive power of models was on average 0.841 and ranged from 0.707 to 0.912. All AUCs are shown in Table 3.2. Statewide, all species were evaluated based on percentages of highly suitable habitat and total suitable habitat. First, percentages of highly suitable habitat for each species were delineated using the maximum sensitivity and specificity (MSS) threshold, a high threshold that is designed to select only habitat that is considered most suitable. On average, highly suitable habitat for species was predicted to cover 15% of Tennessee and ranged from 2% (Beale's barberry) to 45% (water thyme). The percentage of highly suitable habitat predicted in protected lands on average covered 18% and ranged from 2% (Beale's barberry) to 46% (autumn olive). Percentages of suitable habitat were calculated using the 10 PTP threshold to determine a median level of suitable habitat. On average, 31% of Tennessee was predicted to have median suitable habitat. When evaluated, statewide percentages for median suitable habitat ranged from 12% (sacred bamboo) to 60% (water thyme) (Table 3.4). Additionally, percentages for total suitable habitat for each species were delineated using the minimum training presence (MTP) threshold, a low threshold designed to include all suitable habitat predicted for a species. On average, total suitable habitat for a species was predicted to cover 77% of Tennessee. Prediction of total suitable habitat ranged from 36.94% (sweet virgin's bower) to 99% (kudzu). The percentage of total suitable habitat predicted in protected lands on average covered 80% of these areas. Coverage of total suitable habitat in protected lands ranged from 27% (sweet autumn virgin's bower) to 100% (kudzu) (Table 3.6).

The percentage of total suitable habitat was calculated for each species in six Tennessee physiographic provinces. The two provinces with the largest average of predicted suitable habitat were the Cumberland Plateau (83%) and the Nashville Basin (86%). The province with the lowest percentage of average predicted suitable habitat was the Coastal/Mississippi Alluvial Plain (62%). The percentage of predicted habitat in each province for all species modeled is found in Table 3.2.

Six species were predicted to have a majority of suitable habitat in eastern Tennessee, with suitable habitat decreasing dramatically in western portions of the state. These species include small carp grass (Figure 3.2), Asian bittersweet (Figure 3.2), garlic mustard (Figure 3.2), autumn olive (Figure 3.3), Japanese meadowsweet (Figure 3.5), and lesser periwinkle (Figure 3.5). Visual inspection of the models reveals that 21 of the 24 SDMs predicted highly suitable habitat focused in mostly populated areas of the state: Knoxville, Chattanooga, Nashville, and Memphis. In contrast, three species (small carp grass (Figure 3.2), autumn olive (Figure 3.3), and Japanese meadowsweet (Figure 3.4)) were not predicted to have suitable habitat focused in large cities, and these distributions appear to follow the shape of physiographic provinces. Each species is discussed in more detail below.

SDMs provide valuable contributions to our understanding of species distribution; however, they can be negatively influenced by collection bias — a result of nonrandom sampling. Geographic collection bias occurs when specimens are collected more frequently in one place than another. This bias favors collections made in more locations, like roadsides or trails, and favors areas where more universities and herbaria are located (Daru et al. 2018). Geographic collection bias is observed in Tennessee because specimens tend to be collected more frequently in the middle and eastern regions since these areas contain more universities and herbariums. Geographic collection bias may explain the reason that, on average, MaxEnt predicted a lower percentage of suitable habitat in the Coastal/Mississippi Alluvial Plain.

Evaluating models using thresholds to create binary distributions is the simplest way to interrupt the results of SDMs. The threshold selection should consider the importance of omission and inclusion of suitable habitat for the study. For example, studies prioritizing work with rare species should consider using high thresholds such as the MSS threshold that limit the distribution only to areas that are most likely to contain populations (Escalante et al. 2013). However, when studying a species that can exploit large areas of suitable habitat, researchers recommend using low threshold values (Norris 2014). For this reason, species distributions are evaluated using the MTP threshold; however, this threshold does overestimate species distribution, and this should be considered when evaluating models using this threshold (Escalante et al. 2013). To address this issue, the distribution of each species was also evaluated using the MSS threshold (Table 3.2) to determine only areas of highly suitable habitat and the 10 PTP threshold to determine the percentage of suitable habitat that lies between these two extremes (Table 3.3).

Table 3.2 Statewide Results and AUCs of Species Distribution Models

Species	**Common Name**	**AUC**	**Percentage of Highly Suitable Habitat in TN (MSS)**	**Percentage of Median Habitat in TN (10 PTP)**	**Percentage of Total Suitable Habitat in TN (MTP)**
Ailanthus altissima	tree-of-heaven	0.849	9%	32%	72%
Albizia julibrissin	mimosa	0.890	9%	26%	93%
Alliaria petiolata	garlic mustard	0.866	16%	29%	70%
Arthraxon hispidus	small carp grass	0.718	7%	54%	77%
Celastrus orbiculatus	Asian bittersweet	0.838	12%	20%	64%
Clematis terniflora	sweet autumn virgin's-bower	0.816	10%	14%	37%
Elaeagnus umbellata	autumn olive	0.707	26%	32%	62%
Euonymus alatus	burning bush	0.823	12%	32%	63%
Euonymus fortunei	winter-creeper	0.902	3%	16%	92%
Hedera helix	English ivy	0.900	14%	29%	90%
Hydrilla verticillata	hydrilla	0.912	45%	60%	96%
Lespedeza cuneata	Chinese bush-clover	0.783	12%	43%	90%
Ligustrum sinense	Chinese privet	0.830	14%	38%	80%
Lonicera japonica	Japanese honeysuckle	0.819	19%	37%	83%
Lonicera maackii	amur honeysuckle	0.876	16%	17%	70%
Mahonia bealei	Beale's barberry	0.901	2%	19%	82%
Nandina domestica	sacred bamboo	0.904	5%	12%	86%
Pueraria montana	kudzu	0.809	16%	33%	99%
Pyrus calleryana	Bradford pear	0.886	7%	24%	92%
Rosa multiflora	multiflora rose	0.758	17%	52%	89%
Saxifraga tridactylites	nailwort	0.877	4%	31%	59%
Sorghum halepense	Johnson grass	0.795	23%	35%	78%
Spiraea japonica	Japanese meadowsweet	0.854	16%	28%	53%
Vinca minor	lesser periwinkle	0.830	22%	32%	65%

Table 3.3 Results of Species Distribution Models by Province Using the MSS Threshold to Delineate Highly Suitable Habitat for Each Species

Species	Common Name	BR	RV	CP	ILP	NB	CP/MS
Ailanthus altissima	tree-of-heaven	4%	6%	8%	7%	12%	16%
Albizia julibrissin	mimosa	4%	9%	4%	6%	33%	7%
Alliaria petiolata	garlic mustard	34%	22%	17%	14%	34%	4%
Arthraxon hispidus	small carp grass	29%	9%	18%	4%	3%	1%
Celastrus orbiculatus	Asian bittersweet	34%	27%	17%	5%	8%	3%
Clematis terniflora	sweet autumn virgin's-bower	3%	23%	6%	8%	26%	3%
Elaeagnus umbellata	autumn olive	57%	45%	68%	12%	17%	2%
Euonymus alatus	burning bush	5%	18%	10%	11%	18%	10%
Euonymus hederaceus	winter-creeper	1%	5%	1%	2%	5%	6%
Hedera helix	English ivy	10%	13%	8%	6%	6%	7%
Hydrilla verticillata	water thyme	48%	52%	82%	74%	81%	37%
Lespedeza cuneata	Chinese bush-clover	25%	16%	17%	9%	20%	4%
Ligustrum sinense	Chinese privet	10%	22%	8%	10%	23%	12%
Lonicera japonica	Japanese honeysuckle	16%	25%	18%	14%	44%	14%
Lonicera maackii	amur honeysuckle	29%	20%	6%	14%	29%	13%
Mahonia bealei	Beale's barberry	1%	4%	3%	1%	2%	3%
Nandina domestica	sacred bamboo	1%	9%	2%	1%	6%	8%
Pueraria montana	kudzu	43%	22%	24%	9%	14%	9%
Pyrus calleryana	bradford pear	5%	15%	6%	4%	15%	3%
Rosa multiflora	multiflora rose	19%	32%	25%	9%	19%	8%
Saxifraga tridactylites	nailwort	3%	5%	4%	3%	7%	3%
Sorghum halepense	Johnson grass	32%	34%	25%	17%	42%	13%
Spiraea japonica	Japanese meadowsweet	50%	15%	70%	4%	4%	0%
Vinca minor	lesser periwinkle	64%	38%	42%	12%	20%	2%

Table 3.4 Results of Species Distribution Models by Province Using the 10 PTP Threshold to Delineate Total Suitable Habitat for Each Species

Species	Common Name	BR	RV	CP	ILP	NB	CP/MS
Ailanthus altissima	tree-of-heaven	23%	16%	30%	30%	42%	46%
Albizia julibrissin	mimosa	6%	22%	17%	23%	71%	27%
Alliaria petiolata	garlic mustard	50%	36%	30%	27%	56%	12%

Arthraxon hispidus	small carp grass	87%	67%	92%	57%	52%	13%
Celastrus orbiculatus	Asian bittersweet	49%	37%	41%	10%	11%	5%
Clematis terniflora	sweet autumn virgin's-bower	5%	30%	8%	10%	38%	4%
Elaeagnus umbellata	autumn olive	70%	54%	76%	17%	24%	3%
Euonymus alatus	burning bush	7%	25%	16%	24%	25%	21%
Euonymus fortunei	winter-creeper	10%	27%	7%	10%	15%	24%
Hedera helix	English ivy	35%	29%	38%	24%	25%	28%
Hydrilla verticillata	Water thyme	48%	56%	85%	84%	90%	42%
Lespedeza cuneata	Chinese bush-clover	65%	44%	68%	38%	68%	21%
Ligustrum sinense	Chinese privet	41%	50%	30%	33%	56%	34%
Lonicera japonica	Japanese honeysuckle	36%	42%	42%	30%	67%	27%
Lonicera maackii	amur honeysuckle	36%	27%	12%	22%	39%	18%
Mahonia bealei	Beale's barberry	21%	22%	33%	17%	13%	13%
Nandina domestica	sacred bamboo	9%	20%	7%	5%	14%	19%
Pueraria montana	kudzu	75%	41%	51%	20%	25%	25%
Pyrus calleryana	Bradford pear	22%	47%	28%	16%	41%	10%
Rosa multiflora	multiflora rose	64%	68%	73%	48%	50%	31%
Saxifraga tridactylites	nailwort	24%	30%	36%	24%	37%	38%
Sorghum halpense	Johnson grass	40%	46%	43%	26%	59%	22%
Spiraea japonica	Japanese meadowsweet	77%	34%	87%	14%	16%	0%
Vinca minor	lesser periwinkle	79%	51%	64%	19%	30%	25%

Table 3.5 Results of Species Distribution Models by Province Using the MTP Threshold to Delineate Total Suitable Habitat for Each Species

Species	**Common Name**	**BR**	**RV**	**CP**	**ILP**	**NB**	**CP/MS**
Ailanthus altissima	tree-of-heaven	68%	43%	71%	73%	95%	85%
Albizia julibrissin	mimosa	66%	91%	94%	93%	100%	97%
Alliaria petiolata	garlic mustard	85%	79%	71%	77%	97%	38%
Arthraxon hispidus	small carp grass	98%	89%	99%	85%	80%	41%
Celastrus orbiculatus	Asian bittersweet	97%	87%	95%	54%	56%	35%
Clematis terniflora	sweet autumn virgin's-bower	12%	57%	21%	43%	75%	14%
Elaeagnus umbellata	autumn olive	98%	88%	96%	52%	72%	23%
Euonymus alatus	burning bush	34%	64%	58%	71%	65%	62%
Euonymus hederaceus	winter-creeper	90%	91%	94%	91%	85%	98%
Hedera helix	English ivy	85%	90%	98%	89%	86%	91%
Hydrilla verticillata	Water thyme	79%	89%	96%	100%	100%	100%

Lespedeza cuneata	Chinese bush-clover	88%	78%	95%	81%	93%	55%
Ligustrum sinense	Chinese privet	85%	87%	81%	84%	94%	68%
Lonicera japonica	Japanese honeysuckle	80%	84%	95%	68%	98%	70%
Lonicera maackii	amur honeysuckle	74%	77%	75%	78%	94%	53%
Mahonia bealei	Beale's barberry	75%	85%	94%	83%	82%	81%
Nandina domestica	sacred bamboo	77%	86%	92%	98%	84%	89%
Pueraria montana	kudzu	100%	99%	100%	87%	98%	98%
Pyrus calleryana	Bradford pear	95%	99%	95%	91%	97%	89%
Rosa multiflora	multiflora rose	95%	98%	99%	59%	95%	72%
Saxifraga tridactylites	nailwort	32%	39%	59%	75%	68%	78%
Sorghum halepense	Johnson grass	69%	83%	90%	42%	95%	66%
Spiraea japonica	Japanese meadowsweet	97%	79%	97%	59%	59%	12%
Vinca minor	lesser periwinkle	97%	82%	94%	62%	66%	36%

Table 3.6 Percentage of Suitable Habitat in Protected Lands Using the MSS and MTP Thresholds

Species	**Common Name**	**Percentage of Highly Suitable Habitat in Protected Land (MSS)**	**Percentage of Total Suitable Habitat in Protected Land (MTP)**
Ailanthus altissima	tree-of-heaven	5%	78%
Albizia julibrissin	mimosa	7%	83%
Alliaria petiolata	garlic mustard	26%	79%
Arthraxon hispidus	small carp grass	17%	82%
Celastrus orbiculatus	Asian bittersweet	21%	80%
Clematis terniflora	sweet autumn virgin's-bower	9%	27%
Elaeagnus umbellata	autumn olive	46%	83%
Euonymus alatus	burning bush	7%	52%
Euonymus fortunei	winter-creeper	2%	95%
Hedera helix	English ivy	10%	90%
Hydrilla verticillata	hydrilla	36%	95%
Lespedeza cuneata	Chinese bush-clover	24%	87%
Ligustrum sinense	Chinese privet	14%	84%
Lonicera japonica	Japanese honeysuckle	21%	86%
Lonicera maackii	amur honeysuckle	21%	76%
Mahonia bealei	Beale's barberry	2%	81%
Nandina domestica	sacred bamboo	4%	86%
Pueraria montana	kudzu	29%	100%
Pyrus calleryana	Bradford pear	4%	96%

Rosa multiflora	multiflora rose	21%	94%
Saxifraga tridactylites	nailwort	2%	48%
Sorghum halepense	Johnson grass	31%	78%
Spiraea japonica	Japanese meadowsweet	41%	77%
Vinca minor	lesser periwinkle	44%	86%

Tree-of-heaven (*Ailanthus altissima*)

Using three thresholds that determined highly suitable habitat, median suitable habitat, and total suitable habitat, the SDM predicted the following range of statewide suitable habitat for tree of heaven: 9% highly suitable (Table 3.3), 32% median suitable habitat (Table 3.4), and 72% total suitable habitat (Table 3.5), hereafter written as (9%)–32–(72%) suitable habitat (AUC 0.849). The continuous map of predicted distribution of this species is shown in Figure 3.2. When it comes to protected land, 5% of all protected land contains highly suitable habitat for this species, and 78% of protected land contains suitable habitat. The SDM predicted suitable habitat for this species in all six provinces. The following are the ranges of suitable habitat found in each province: Blue Ridge (4%)–23–(68%), Ridge and Valley (6%)–16–(43%), Cumberland Plateau (8%)–30–(71%), Interior Low Plateau (7%)–30–(73%), Nashville Basin (12%)–42–(95%), and the Coastal/Mississippi Alluvial Plain (16%)–46–(85%).

Tree-of-heaven is considered an Established Threat by the TN-IPC. This ranking is supported by data generated from the SDM that predicted a large range of suitable habitat statewide ((9%)–32–(72%)). In contrast to most species modeled in this study, tree-of-heaven is predicted to have highly suitable habitat across the state, but predominantly in western and middle Tennessee. Additionally, the SDM predicts that disturbed areas, such as large cities and habitats along major interstates, are most suitable for tree-of-heaven. This distribution is consistent with studies that have shown that this weedy tree is a pioneer of disturbed sites, especially cities (Marvier et al2004). The prediction of suitable habitat is also consistent with occurrence points documented by EDDMapS which show a majority of occurrence points documented in and around cities (EDDMapS 2019). Natural areas such as Reelfoot Lake State Natural

Area & Wildlife Management Area and the Land Between the Lakes National Recreation Area are also highly suitable areas for this species.

Mimosa (Albizia *julibrissin*)

The SDM predicted the following range of statewide habitat (9%)–26–(93%) (AUC 0.889). The continuous map of predicted distribution of this species is shown in Figure 3.2. When it comes to protected lands, 7% of protected lands contain highly suitable habitat, and 83% of protected lands contain suitable habitat. The SDM predicted suitable habitat for this species in all six provinces. The following are the ranges of suitable habitat found in each province: Blue Ridge (4%)–6–(66%), Ridge and Valley (9%)–22–(91%), Cumberland Plateau (4%)–17–(94%), Interior Low Plateau (6%)–23–(93%), Nashville Basin (33%)–71–(100%), Coastal/Mississippi Alluvial Plain (7%)–27–(97%).

Mimosa is considered an Established Threat by TN-IPC. Given that this species was predicted to have more than 20% median suitable habitat and more than 50% total suitable in all provinces this ranking appears justified. A majority of highly suitable habitats are centered around large cities, a finding supported by literature that documents mimosa as a species that frequently invades disturbed habitat (Weber 2003). Mimosa is predicted to have less suitable habitat available in the Blue Ridge physiographic province, perhaps because mimosa does not tolerate the higher elevations in this region (Weber 2003). The predication of widespread suitable habitat, focused in areas of disturbance, like large cities, is confirmed by EDDMapS (EDDMapS 2019). Additionally, EDDMapS confirms the absence of mimosa in higher elevation areas in the Blue Ridge (EDDMapS 2019).

Garlic mustard (*Alliaria petiolata*)

The SDM predicted the following range of statewide habitat (16%)–29–(70%) (AUC 0.866). The continuous map of predicted distribution of this species is shown in Figure 3.2. When it comes to protected lands, 26% of protected land in Tennessee contains highly suitable habitat, and 79% of protected lands contain suitable habitat for garlic mustard. The SDM predicted suitable habitat for this species in all six provinces. The following are the ranges of suitable habitat found in each province: Blue Ridge (34%)–50–(85%), Ridge and Valley (22%)–36–(79%), Cumberland Plateau (17%)–30–(71%), Interior Low Plateau (14%)–27–(77%), Nashville Basin (34%)–56–(97%), Coastal/Mississippi Alluvial Plain (4%)–12–(38%).

Garlic mustard is considered an Established Threat by TN-IPC. The high percentage of suitable habitat for garlic mustard predicted by the SDM confirms this ranking. The SDM predicts the most suitable habitat for garlic mustard is located in middle and eastern Tennessee, a prediction that is confirmed by occurrence points on EDDMapS (EDDMapS 2019). In comparison to other species modeled in this study, garlic mustard has suitable habitat in a large amount of protected land, including the Great Smoky Mountains National Park and the Cherokee National Forest.

Small carp grass (*Arthraxon hispidus*)

The SDM predicted the following range of statewide habitat (7%)–54–(77%) (0.718 AUC). The continuous map of predicted distribution of this species is shown in Figure 3.2. When it comes to protected land, 17% of Tennessee's protected lands contain highly suitable habitat, and 82% of protected lands contain suitable habitat. The SDM predicted suitable habitat for this species in all six provinces. The following are the ranges of suitable habitat found in each province: Blue Ridge (29%)–87–(98%), Ridge and Valley (9%)–67–(89%), Cumberland Plateau (18%)–92–(99%), Interior Low Plateau (4%)–57–(85%), Nashville Basin (3%)–52–(80%), Coastal/Mississippi Alluvial Plain (1%)–13–(41%).

TN-IPC considers small carp grass an Established Threat. Over 50% of Tennessee is predicted to contain median suitable habitat for small carp grass, supporting this ranking; however, a majority of highly suitable habitat is found in eastern Tennessee, and more attention to the spread of this species should be given to this region of the state. The predicted distribution of small carp grass is larger than known county-level distributions (SERNEC 2018) and larger than distribution reported by EDDMapS (outside of the Arnold Airforce Base, EDDMapS only documents 6 occurrences of this species) (EDDMapS 2019). Aside from taxonomic collection bias that tends to favor certain taxonomic groups over others (Daru et al. 2018b), this discrepancy may be a result of the inability to model for important drivers of distribution such as dispersal (Pulliam 2000). Small carp grass is reliant on moving water for seed dispersal (Anderson et al. 2015), a variable that was not possible to account for when building the SDM. Therefore, the SDM may be locating sites of suitable habitat that small carp grass is incapable of reaching because the conditions are not appropriate for seed dispersal to that area. While small carp grass cannot spread naturally to certain areas, other means of dispersal such as increased outdoor recreation contribute to the dispersal of invasive plants, and therefore it is still important to locate areas that could be vulnerable to the invasion of this species (Anderson et al. 2015).

Asian bittersweet (*Celastrus orbiculatus*)

The SDM predicted the following range of statewide habitat (12%)–20%–(64%) (AUC 0.838). The continuous map of predicted distribution of this species is shown in Figure 3.2. When it comes to protected land, 21% of protected land is highly suitable habitat, and 80% of protected land contains suitable habitat. The SDM predicted suitable habitat for this species in all six provinces. The following are the ranges of suitable habitat found in each province: Blue Ridge (34%)–49–(97%), Ridge and Valley (27%)–37–(87%), Cumberland Plateau (17%)–41–(95%), Interior Low Plateau (5%)–10–(54%), Nashville Basin (8%)–11–(56%), Coastal/Mississippi Alluvial Plain (3%)–5–(35%).

TN-IPC considers Asian bittersweet an Established Threat. This rank is justified, considering that more than 50% of the state is predicted to contain total suitable habitat and that highly suitable habitat is frequently predicted in protected land. However, special attention should be given to this species in eastern and middle regions of the state. A noticeable trend in predicted suitable habitat for Asian bittersweet is the decrease in suitable habitat predicted in western provinces. The SDM predicted that over 30% of habitat in the Blue Ridge, Ridge and Valley, and Cumberland Plateau provinces contain median suitable habitat for Asian bittersweet. However, SDMs predict that only 10% of the habitat in the Interior Low Plateau and 11% of habitat in the Nashville Basin provinces contain median suitable habitat. This trend is also seen in occurrence points on EDDMapS which show a majority of documented occurrences in eastern provinces (EDDMapS 2019). Additionally, the SDM predicts highly suitable habitat for Asian bittersweet in large urban areas, an observation made by another modeling study that investigated the distribution of Asian bittersweet in Indiana (Pande 2005). Visual inspection of the data show that protected areas with highly suitable habitat for Asian bittersweet are primarily located in the east and include the Big South Fork National River and Recreation Area, the Cove Creek Wildlife Management Area, and the Dale Hollow Recreation Area.

Sweet autumn virgin's-bower (*Clematis terniflora*)

The SDM predicted the following range of statewide habitat: (10%)–14–(37%) (AUC 0.8161). The continuous map of predicted distribution of this species is shown in Figure 3.2. When it comes to protected land, 9.13% of protected land is highly suitable habitat for sweet autumn virgin's-bower and 27% of protected land contains suitable habitat. The SDM predicted suitable habitat for this species in all six provinces. The following are the ranges of suitable habitat found in each province: Blue Ridge (3%)–5–(12%), Ridge and Valley (23%)–30–(57%), Cumberland Plateau (6%)–8–(21%), Interior Low Plateau (8%)–10–(43%), Nashville Basin (26%)–38–(75%), Coastal/Mississippi Alluvial Plain (3%)–4–(14%).

While TN-IPC currently ranks sweet autumn virgin's-bower as an Established Threat, the total suitable habitat predicted by the SDM suggests that this ranking exaggerates the threat this species presents to the state. The SDM also predicts that a majority of highly suitable habitat is found in the middle and eastern regions of the state. More specifically, the SDM predicts highly suitable habitat appearing most frequently in the Ridge and Valley and Interior Low Plateau provinces. J. Percy Priest Recreation Area and Dale Hollow Recreation Area appear to contain the largest percentage of highly suitable habitat of all the protected areas in the state. In comparison to other species modeled in this study, sweet autumn virgin's bower has considerably lower levels of predicted total suitable habitat throughout the state (only 37% total in comparison to an average of 81%). Analysis of predicted habitat in physiographic provinces shows that this species may only be a moderate concern to the eastern and middle regions of the state and a lower concern to the western region.

Only 4 occurrences of sweet autumn virgins bower were reported by EDDMapS. All occurrences were found in the Blue Ridge and the Ridge and Valley. This distribution is like the suitable habitat predicted by the SDM; however, the SDM also predicted highly suitable habitat in the Nashville Basin and Interior Low Plateau (EDDMapS 2019). The discrepancy between EDDMapS and the SDM may be a result of under collection, or sweet autumn virgins bower has not spread to establish populations in these areas.

Autumn olive (*Elaeagnus umbellata*)

The SDM predicted the following range of statewide habitat: (26%)–32–(62%) (AUC 0.707). The continuous map of predicted distribution of this species is shown in Figure 3.3. Of all species analyzed, autumn olive had the highest percentage of highly suitable habitat found in protected lands with 46% of all habitat being highly suitable for this species. The SDM predicted that 83% of protected lands contained suitable habitat for autumn olive. The SDM predicted suitable habitat for this species in all six provinces. The following are the ranges of suitable habitat found in each province: Blue Ridge (57%)–70–(98%), Ridge and Valley (45%)–54–(88%), Cumberland Plateau (68%)–76–(96%), Interior Low Plateau (12%)–17–(52%), Nashville Basin (17%)–24–(75%), Coastal/Mississippi Alluvial Plain (2%)–3–(23%).

TN-IPC ranks autumn olive as an Established Threat. Since the SDM predicts that more than 50% of the state and a majority of eastern protected lands are suitable habitat for autumn olive, this ranking is justified. The SDM predicts highly suitable habitat in the eastern region of the state, with moderately suitable habitat appearing in the middle and western regions of the state. The distribution of autumn olive does not appear to center around large cities. Instead, highly suitable habitat for autumn olive tends to follow the Cumberland Plateau, Ridge and Valley, and Blue Ridge provinces. The prediction of suitable habitat for autumn olive focused mostly in eastern provinces is confirmed by EDDMapS which show a majority of occurrence points in the east (EDDMapS 2019). Out of all species modeled, autumn olive was found to have the highest percentage of suitable habitat in protected lands, a finding consistent with literature that documents autumn olive frequently escaping cultivation or ruderal habitat to occupy more natural areas (Nestleroad et al. 1987). Protected lands that contain highly suitable habitat for autumn olive include the Great Smoky Mountains National Park, the Cherokee National Forest, and the Big South Fork National River and Recreation Area.

Burning bush (*Euonymus alatus*)

The SDM predicted the following range of statewide habitat: (12%)–32–(63%) (AUC 0.823). The continuous map of predicted distribution of this species is shown in Figure 3.3. When it comes to protected land, 7% was predicted to contain highly suitable habitat, and 52% of protected land was predicted to contain suitable habitat. The SDM predicted suitable habitat for this species in all six provinces. The following are the ranges of suitable habitat found in each province: Blue Ridge (5%)–7–(34%), Ridge and Valley (18%)–25–(64%), Cumberland Plateau (10%)–16–(58%), Interior Low Plateau (11%)–24–(71%), Nashville Basin (18%)–25–(65%), Coastal/Mississippi Alluvial Plain (10%)–21–(62%).

Burning bush is considered an Established Threat by TN-IPC. Given the high levels of total and median suitable habitat distributed across the state, the designation of Established Threat for burning bush is justified by the SDM. The SDM predicts that suitable habitat for burning bush is focused in highly urbanized areas throughout the whole state; however, burning bush does not appear to have highly suitable habitat outside areas of high disturbance. The prediction of suitable habitat is confirmed by EDDMapS which documents a majority of occurrence points for burning bush in large cities, and few to no points outside these areas. However, EDDMapS does report more occurrences in eastern provinces than western provinces, which is not consistent with the predictions made by the SDM (EDDMapS 2019). This may be a result of collection bias which tends to favor areas certain areas for collecting over others (Garcillán and Ezcurra 2011). The western part of Tennessee may be suitable for burning bush, there may not have been collections made yet in these areas.

Winter-creeper (*Euonymus fortunei*)

The SDM predicted the following range of statewide habitat: (3%)–16–(92%) (AUC 0.902). The continuous map of predicted distribution of this species is shown in Figure 3.3. When it comes to protected land, 2% of protected land contains highly suitable habitat, and 95% of protected land is suitable habitat. The SDM predicted suitable habitat for this species in all six provinces. The following are the ranges of suitable habitat found in each province: Blue Ridge (1%)–10–(90%), Ridge and Valley (5%)–27–(91%), Cumberland Low Plateau (1%)–7–(94%), Interior Low Plateau (2%)–10–(91%), Nashville Basin (5%)–15–(85%), Coastal/Mississippi Alluvial Plain (6%)–24–(98%).

Winter-creeper is currently considered an Established Threat by TN-IPC. This ranking is justified because it is predicted to have total suitable habitat in more than 50% of all provinces in Tennessee. EDDMapS, like the model presented in this study, shows most occurrences of winter creeper are documented in areas of disturbance (EDDMapS 2019). County-level data for winter-creeper report a more conserved distribution in the state (SERNEC 2018). One reason for the difference between county-level data and the SDM predictions could be that winter-creeper has not expanded to occupy all areas of suitable habitat in the state. Even though winter-creeper may not have established populations in these areas, it is still essential to monitor these lands because winter-creeper disperses seeds via birds and mammals, which allows it to disperse easily from an original population (Schwegman 1996).

English ivy (*Hedera helix*)

The SDM predicted the following range of statewide habitat: (14%)–29–(90%) (AUC 0.899). The continuous map of predicted distribution of this species is shown in Figure 3.3. When it comes to protected lands, 10% of protected lands contain highly suitable habitat, and 90% of protected lands contain suitable habitat. The SDM predicted suitable habitat for this species in all six provinces. The following are the ranges of suitable habitat found in each province: Blue Ridge (10%)–35–(85%), Ridge and Valley (13%)–29–(90%), Cumberland Plateau (8%)–38–(98%), Interior Low Plateau (6%)–25–(86%), Nashville Basin (6%)–25–(65%), Coastal/Mississippi Alluvial Plain (6%)–28–(91%).

English ivy is considered an Established Threat by TN-IPC. This ranking is justified considering that almost 30% of each province in the state contains median suitable habitat for this species. Highly suitable habitat for English ivy is predicted to occur primarily in large urban areas of the state, a distribution that is similar to occurrence points documented by EDDMapS (EDDMapS 2019). English ivy is one of the few species modeled that has the highest percentage of predicted habitat in the Coastal/Mississippi Alluvial Plain. However, suitable habitat for English ivy is found frequently across the state; almost 85% of each province in Tennessee was predicted to contain total suitable habitat for English ivy and almost 30% of each province was predicted to contain median suitable habitat. Upon visual inspection of the SDM, protected areas with highly suitable habitat include the Land Between the Lakes National Recreation Area and the Cherokee National Forest.

Water thyme (*Hydrilla verticillata*)

The SDM predicted the following range of statewide habitat: (45%)–60–(96%) (AUC 0.912). The continuous map of predicted distribution of this species is shown in Figure 3.3. When it comes to protected land, 36% of protected land contains highly suitable habitat, and 95% of protected land contains suitable habitat for water thyme. The SDM predicted suitable habitat for this species in all six provinces. The following are the ranges of suitable habitat found in each province: Blue Ridge (48%)–48–(79%), Ridge and Valley (52%)–56–(96%), Cumberland Plateau (82%)–85–(96%), Interior Low Plateau (74%)–84–(100%), Nashville Basin (81%)–90–(100%), Coastal/Mississippi Alluvial Plain (37%)–42–(100%).

Water thyme is considered an Established Threat by the TN-IPC, a threat that is warranted considering the SDM predicted a large amount of state's water bodies are suitable habitat ((45%)–60–(96)). Water thyme was predicted to have the highest percentage of highly suitable habitat. In comparison to EDDMapS distribution, the SDM predicts larger amounts of suitable habitat for water thyme than reported by EDDMapS. It could be that these areas have not been collected, or that water thyme has not yet managed to establish populations in areas predicted to be suitable (EDDMapS 2019). Despite lower levels of documented occurrences from EDDMapS, the aggressive invasive tendencies of water thyme are well known, and therefore if given the opportunity it is likely that this species could spread to inhabit a majority of Tennessee's water bodies (Gu 2006).

Chinese bush-clover (*Lespedeza cuneata*)

The SDM predicted the following range of statewide habitat: (12%)–43–(90%) (AUC 0.912). (AUC 0.783). The continuous map of predicted distribution of this species is shown in Figure 3.3. When it comes to protected land, 24% of protected land contains highly suitable habitat, and 87% of protected land contains suitable habitat. The SDM predicted suitable habitat for this species in all six provinces. The following are the ranges of suitable habitat found in each province: Blue Ridge (25%)–65–(88%), Ridge and Valley (16%)–44–(78%), Cumberland Plateau (17%)–68–(95%), Interior Low Plateau (9%)–38–(81%), Nashville Basin (20%)–68–(93%), Coastal/Mississippi Alluvial Plain (4%)–21–(55%).

Chinese bush clover is considered an Established Threat by the TN-IPC, a ranking backed by the large percentage of suitable habitat predicted by the SDM across Tennessee (12%)–43–(90%). The SDM predicts highly suitable habitat primarily in the eastern and middle regions of the state, particularly in the Blue Ridge, Ridge and Valley, and Interior Plateau provinces. Chinese bush-clover is predicted to have total suitable habitat in more than 50% of each province, the prediction of widespread distribution is not surprising given Chinese bush clovers' tolerance of a variety of habitats and its ability to invade a variety of ecosystems from forests to prairies (Allred et al. 2010). This prediction is confirmed by EDDMapS, which reports occurrences of this species statewide (EDDMapS 2019). After visual inspection, the protected areas containing highly suitable habitat for this species includes the Big South Fork National River and Recreation Area, the Great Smoky Mountains National Park, and the Cherokee National Forest.

Chinese privet (*Ligustrum sinense*)

The SDM predicted the following range of statewide habitat: (14%)–38–(90%) (AUC 0.831). The continuous map of predicted distribution of this species is shown in Figure 3.4. When it comes to protected lands, 14% of protected lands have highly suitable habitat, and 84% of protected lands contain suitable habitat for Chinese privet. The SDM predicted suitable habitat for this species in all six provinces. The following are the ranges of suitable habitat found in each province: Blue Ridge (10%)–41–(85%), Ridge and Valley (22%)–50–(87%), Cumberland Plateau (8%)–30–(81%), Interior Low Plateau (10%)–33–(84%), Nashville Basin (23%)–56–(94%), Coastal/Mississippi Alluvial Plain (12%)–34–(68%).

Chinese privet is considered an Established Threat by TN-IPC. The SDM confirms this ranking because it predicted that 30% or more of each province contains median suitable habitat for this species. Highly suitable habitat for Chinese privet is predicted in and around cities. Occurrence points from EDDMapS confirm both widespread distribution across the state and the highly suitable habitat focused around cities (EDDMapS). This is an unsurprising result considering the well-known threat this species poses to Southeastern habitats (Hart and Holmes 2013).

Japanese honeysuckle (*Lonicera japonica*)

The SDM predicted the following range of statewide habitat: (19%)–37–(83%) (AUC 0.819). The continuous map of predicted distribution of this species is shown in Figure 3.4. When it comes to protected land, 21% of protected lands have highly suitable habitat, and 86% of protected lands contain suitable habitat for Japanese honeysuckle. The SDM predicted suitable habitat for this species in all six provinces. The following are the ranges of suitable habitat found in each province: Blue Ridge (16%)–36–(80%), Ridge and Valley (25%)–42–(84%), Cumberland Plateau (18%)–42–(95%), Interior Low Plateau (14%)–30–(68%), Nashville Basin (44%)–67–(98%), Coastal/Mississippi Alluvial Plain (14%)–27–(70%).

Japanese honeysuckle is considered an Established Threat by TN-IPC, and this ranking is confirmed by the SDM that predicts almost 30% or more of each province contains suitable habitat for this species. Japanese honeysuckle tolerates a variety of habitats from closed-canopy forest to disturbed roadsides (Lemke et al. 2011); therefore, a range of high percentages of predicted habitat for this species is not unusual. The prediction of suitable habitat made here by the SDM is similar to the occurrence points documented by EDDMapS. Both sources show a widespread distribution of Japanese honeysuckle across the state (EDDMapS 2019).

Amur honeysuckle (*Lonicera maackii*)

The SDM predicted the following range of statewide habitat: (16%)–17–(70%). (AUC 0.876). The continuous map of predicted distribution of this species is shown in Figure 3.4. When it comes to protected land, 20% of protected lands have highly suitable habitat, and 76% of protected lands contain suitable habitat for amur honeysuckle. The SDM predicted suitable habitat for this species in all six provinces. The following are the ranges of suitable habitat found in each province: Blue Ridge (29%)–36–(74%), Ridge and Valley (20%)–27–(77%), Cumberland Plateau (6%)–12–(75%), Interior Low Plateau (14%)–22–(78%), Nashville Basin (29%)–39–(94%), Coastal/Mississippi Alluvial Plain (13%)–18–(53%).

Amur honeysuckle is considered an Established Threat by TN-IPC. Highly suitable habitat for amur honeysuckle is found across all provinces and is seen mostly in northern parts of Tennessee, the Blue Ridge, and the Nashville Basin. In comparison to documented occurrences by EDDMapS the SDM shows highly suitable habitat in and around cities; however, the SDM predicts more suitable habitat for amur honeysuckle in natural areas than EDDMapS occurrences currently report (EDDMapS 2019).

Beale's barberry (*Mahonia bealei*)

The SDM predicted the following range of statewide habitat: (2%)–19–(82%) (AUC 0.901). The continuous map of predicted distribution of this species is shown in Figure 3.4. When it comes to protected land, 2% of protected land contains highly suitable habitat, and 81% of protected land contains suitable habitat for Beale's barberry. The SDM predicted suitable habitat for this species in all six provinces. The following are the ranges of suitable habitat found in each province: Blue Ridge (1%)–21–(75%), Ridge and Valley (4%)–22–(85%), Cumberland Plateau (3%)–33–(94%), Interior Low Plateau (1%)–17–(83%), Nashville Basin (2%)–13–(82%), Coastal/Mississippi Alluvial Plain (3%)–13–(81%).

Beale's barberry is considered an Emerging Threat by TN-IPC. Given the large percentage of predicted suitable habitat in the state, Beale's barberry does not justify the rank of Emerging Threat. Instead, this species should be considered a more significant threat to Tennessee. The occurrence data documented by EDDMapS is similar to the predicted suitable habitat generated by the SDM. Most occurrences from EDDMapS and predicted suitable habitat are found in eastern provinces. However, the SDM does predict suitable habitat in some areas in the western region of Tennessee where no occurrence points are documented by EDDMapS (EDDMapS 2019). There may be no documented occurrences because collections have not been made or because Beale's barberry has not yet spread to occupy these areas or because collections of this species have not been made in these areas. Studies have found that this species shows aggressive invasive tendencies in wooded and open areas, therefore areas in both eastern and western provinces should consider the threats of Beale's barberry (Allen et al. 2006). Therefore, it is essential to understand the full extent of this species' potential distribution to prevent the spread of Beale's barberry to suitable unoccupied habitat.

Sacred bamboo (*Nandina domestica*)

The SDM predicted the following range of statewide habitat: (5%)–12–(86%) (AUC of 0.901). The continuous map of predicted distribution of this species is shown in Figure 3.4. When it comes to protected land, 4% of protected land contains highly suitable habitat, and 85.54% of protected land contains suitable habitat. The SDM predicted suitable habitat for this species in all six provinces. The following are the ranges of suitable habitat found in each province: Blue Ridge (1%)–9–(77%), Ridge and

Valley (9%)–20–(86%), Cumberland Plateau (2%)–7–(92%), Interior Low Plateau (1%)–5–(98%), Nashville Basin (6%)–14–(84%), Coastal/Mississippi Alluvial Plain (8%)–19–(89%).

Sacred bamboo is considered an Emerging Threat by TN-IPC. However, it has demonstrated a threat to the state that is beyond the classification of Emerging Threat. An Emerging Threat is considered a species documented in ten counties or less in the state, yet the SDM predicts more than 10% of the state contains median and total percentages of suitable habitat. Perhaps the discrepancy between the SDM data shown here and TN-IPC's ranking system is attributed to a geographic collection bias that tends to favor collecting specific taxa over others (Daru et al. 2018). This collection bias may have resulted in the under-collection of sacred bamboo and thus an underestimation of the threat it presents to the state. Noticeably, sacred bamboo's distribution seems to be focused in middle and eastern Tennessee. SDMs show highly suitable habitat surrounding large urban areas and in the Ridge and Valley and Nashville Basin provinces. EDDMapS contains less than 20 occurrence points for sacred bamaboo; however, it can confirm that this species prefers areas of disturbance (EDDMapS 2019).

Kudzu (*Pueraria montana*)

The SDM predicted the following range of statewide habitat: (16%)–33–(99%) (AUC 0.809). The continuous map of predicted distribution of this species is shown in Figure 3.4. When it comes to protected lands, 29% of protected land is highly suitable habitat, and 99.84% of protected land contains suitable habitat for kudzu. The following are the ranges of suitable habitat found in each province: Blue Ridge (43%)–75–(100%), Ridge and Valley (22%)–41–(99%), Cumberland Plateau (24%)–51–(100%), Interior Low Plateau (9%)–20–(87%), Nashville Basin (14%)–25–(98%), Coastal/Mississippi (9%)–25–(98%).

Kudzu is considered an Established Threat by TN-IPC. This ranking is verified because the SDM predicted that large amounts of the state contain suitable habitat for kudzu. The SDM predicts an almost even distribution of Kudzu across Tennessee, although more suitable habitat was predicted in the eastern and middle regions than the western regions. Kudzu was predicted to have the highest percentage of total suitable habitat in the state and protected lands in the state. This statistic is an overestimation of the habitat that kudzu can occupy for two significant reasons. First, in comparison to its native habitat, kudzu rarely seeds in the United States (Tsugawa 1986); instead, it more frequently propagates vegetatively (Everest et al. 1999). Since kudzu relies so heavily on propagation, its invasions are generally localized, and it may not be able to reach suitable habitat by relying on this method of propagation. Kudzu is predicted to have an unusually high percentage of suitable habitat statewide. In cases where the algorithm has selected a large percentage of total suitable habitat, the highly suitable habitat for a species is also evaluated. The largest percentage of highly suitable habitat for kudzu was predicted in the Blue Ridge (43%), Cumberland Plateau (24%), and Ridge and Valley (22%) provinces (Table 2.3). Less than 20% of the remaining provinces had highly suitable habitat for kudzu. Documented occurrence points from EDDMapS show a statewide distribution of kudzu ; however, a majority of documented occurrences are reported in the east (similar to the predictions made by the SDM) (EDDMapS 2019). Given kudzu's localized invasion, provinces in the east with already established populations are most at risk.

Bradford pear (*Pyrus calleryana*)

The SDM predicted the following range of statewide habitat: (7%)–24–(92%) (AUC 0.886). The continuous map of predicted distribution of this species is shown in Figure 3.5. When it comes to protected land, 4% of protected land contains highly suitable habitat for Bradford pear, and 96% of protected land contains suitable habitat. The SDM predicted suitable habitat for this species in all six provinces. The following are the ranges of suitable habitat found in each province: Blue Ridge (5%)–22–(95%), Ridge and Valley (15%)–47–(99%), Cumberland Plateau (6%)–28–(95%), Interior Low Plateau (4%)–16–(91%), Nashville Basin (15%)–41–(97%), Coastal/Mississippi Alluvial Plain (3%)–10–(89%).

Bradford pear is considered an Established Threat by TN-IPC, a warranted threat considering the high percentage of total and median potential suitable habitat. The SDM predicts a majority of suitable habitat for Bradford pear in the eastern and middle portions of the state. Much of the highly suitable habitat lies within the Ridge and Valley province and along roads and urban areas. EDDMapS does document Bradford pear in these areas; however, occurrence points from EDDMapS do not show Bradford pear favoring any provinces (EDDMapS 2019).

Multiflora rose (*Rosa multiflora*)

The SDM predicted the following range of statewide habitat: (17%)–52–(89%) (AUC 0.758). The continuous map of predicted distribution of this species is shown in Figure 3.5. When it comes to protected lands, 21% of protected land has highly suitable habitat, and 94% of protected land contains suitable habitat for rambler rose. The SDM predicted suitable habitat for this species in all six provinces. The following are the ranges of suitable habitat found in each province: Blue Ridge (19%)–64–(95%), Ridge and Valley (32%)–68–(98%), Cumberland Plateau (25%)–73–(99%), Interior Low Plateau (9%)–48–(59%), Nashville Basin (19%)–50–(95%), Coastal/Mississippi Alluvial Plain (8%)–31–(72%).

Multiflora rose is considered an Established Threat by TN-IPC. This ranking is confirmed by the SDM created for multiflora rose that predicted more than 40% of every province except the Coastal/Mississippi Alluvial Plain are predicted to contain median suitable habitat for multiflora rose. A widespread distribution that does not appear to favor one province over another is similar to the documented occurrences available on EDDMapS (EDDMapS,2019). Upon visual inspection, much of the protected land in the northern portions of Tennessee contains highly suitable habitat for multiflora rose. These lands include the Big South Fork National River and Recreation Area and the Land Between the Lakes National Recreation Area.

Nailwort (*Saxifraga tridactylites*)

The SDM predicted the following range of statewide habitat: (4%)–31–(59%) (AUC 0.877). The continuous map of predicted distribution of this species is shown in Figure 3.5. When it comes to protected lands, 2% of protected lands contain suitable habitat and 48% of protected lands contain suitable habitat for nailwort. The SDM predicted suitable habitat for this species in all six provinces. The following are the ranges of suitable habitat found in each province: Blue Ridge (3%)–24–(32%), Ridge and Valley (5%)–30–(39%), Cumberland Plateau (4%)–36–(59%), Interior Low Plateau (3%)–24–(75%), Nashville Basin (7%)–37–(68%), Coastal/Mississippi Alluvial Plain (3%)–38–(78%).

Nailwort is not ranked by TN-IPC. This species was recently introduced to the southeastern United States (Alley et al. in press) and has not yet established a full distribution in Tennessee. Documentation of this species in Tennessee is limited to one study (Alley et al. in press). Without established populations, SDMs may underestimate species distribution (Gallien et al. 2012). A high percentage of suitable habitat predicted in the Coastal/Mississippi Alluvial Plain is unusual given nailwort's affinity for limestone habitat. Currently the occurrence points for nailwort are located along roadside habitats; therefore, it is likely the algorithm selected places of disturbance and roadsides as suitable habitat. However, despite having the highest percentage of total suitable habitat in the Coastal/Mississippi Alluvial Plain, highly suitable habitat for nailwort is observed in the Nashville Basin (7%) and the Ridge and Valley (5%) provinces.

Johnsongrass (*Sorghum halepense*)

The SDM predicted the following range of statewide suitable habitat: (23%)–35–(78%) (AUC 0.795). The continuous map of predicted distribution of this species is shown in Figure 3.5. When it comes to protected lands, 31% of protected land contains highly suitable habitat, and 78% of protected land contains suitable habitat for Johnsongrass. The SDM predicted suitable habitat for this species in all six provinces. The following are the ranges of suitable habitat found in each province: Blue Ridge (32%)–40–(69%), Ridge and Valley (34%)–46–(83%), Cumberland Plateau (25%)–43–(90%), Interior Low Plateau (17%)–26–(42%), Nashville Basin (42%)–59–(95%), Coastal/Mississippi Alluvial Plain (13%)–22–(66%).

Johnsongrass is considered an Established Threat by TN-IPC. This ranking is justified considering the large amounts of suitable habitat for Johnsongrass is predicted across Tennessee. Highly suitable habitat is predicted primarily in the middle and southeastern parts of the state. The SDM predicted that at least 50% of every province contained total suitable habitat for this species and at least

20% of each province contains median suitable habitat. The predictions of suitable habitat made here by the SDM is similar to the distribution reported by EDDMapS. However, the SDM predicts more suitable habitat in areas outside of cities than occurrence data from EDDMapS currently reports (EDDMapS 2019). Upon visual inspection of the model, the Great Smoky Mountains National Park and the Land Between the Lakes National Recreation Area contain highly suitable habitat for this species.

Japanese meadowsweet (*Spiraea japonica*)

The SDM predicted the following range of statewide suitable habitat: (16%)–28–(53%) (AUC 0.854). The continuous map of predicted distribution of this species is shown in Figure 3.5. When it comes to protected lands, 41% is highly suitable habitat and 77% contain suitable habitat for Japanese meadowsweet. The SDM predicted suitable habitat for this species in all six provinces. The following are the ranges of suitable habitat found in each province: Blue Ridge (50%)–77–(97%), Ridge and Valley (15%)–34–(79%), Cumberland Plateau (70%)–87–(97%), Interior Low Plateau (4%)–14–(59%), Nashville Basin (4%)–16–(59%), Coastal/Mississippi Alluvial Plain (0%)–0–(12%).

The SDM verifies the TN-IPC classification of Japanese meadowsweet as an Established Threat to Tennessee, since the SDMS predicted that more than 50% of Tennessee contains suitable habitat for this species. Japanese meadowsweet appears to favor conditions in eastern provinces of the state. According to predictions made by the SDM, the following eastern provinces contain 50% or more total suitable habitat and more than 30% median suitable habitat: Blue Ridge, Ridge and Valley, and the Cumberland Plateau. The percentage of suitable habitat reported by both sources decreases in the Interior Low Plateau and Nashville Basin provinces. The SDM predicted that only 12% of this Coastal/Mississippi Alluvial Plain contains suitable habitat for Japanese meadowsweet. The predictions of suitable habitat made here by the SDM is similar to the distribution reported by EDDMapS. Like the SDM, which predicts decreasing percentages of suitable habitat in western and middle provinces, EDDMapS does not report any occurrences of Japanese meadowsweet further west than Nashville, Tennessee (EDDMapS 2019). It may not threaten the entirety of the state; however, this species is predicted to have highly suitable habitat in almost 50% of eastern provinces, and this threat to natural areas deserves the classification of Established Threat.

Lesser periwinkle (*Vinca minor*)

The SDM predicted the following range of statewide suitable habitat: (22%)–32–(65%) (AUC 0.8304). The continuous map of predicted distribution of this species is shown in Figure 3.5. When it comes to protected lands, 44% of protected land contains highly suitable habitat and 86% of protected land contains suitable habitat for lesser periwinkle. The SDM predicted suitable habitat for this species in all six provinces. The following are the ranges of suitable habitat found in each province: Blue Ridge (64%)–79–(97%), Ridge and Valley (38%)–51–(82%), Cumberland Plateau (42%)–64–(94%), Interior Low Plateau (12%)–19–(62%), Nashville Basin (20%)–30–(66%), Coastal/Mississippi Alluvial Plain (2%)–25–(36%).

TN-IPC considers lesser periwinkle an Established Threat. This ranking is justified given lesser periwinkle's predicted ability to inhabit protected areas as well as a large amount of suitable habitat predicted throughout the state. Lesser periwinkle's distribution is predicted to be equally prevalent in all provinces except for the Coastal/Mississippi Alluvial Plain, where the SDM predicted that only 36% of the province contained total suitable habitat. In eastern and middle Tennessee, lesser periwinkle's distribution is predicted to be focused in cities and roadsides in Nashville, Chattanooga, and Knoxville; this trend in periwinkle inhabiting mostly disturbed areas has been previously observed (Hyatt 2017). The predictions of suitable habitat made here by the SDM is similar to the distribution of occurrence points reported by EDDMapS. Most occurrence points are documented in the eastern and middle region of the state (EDDMapS 2019). Additionally, occurrence points are documented in the west; however, only in more disturbed areas of western Tennessee. Finally, of the species modeled, lesser periwinkle was predicted to have the second highest percentage of highly suitable habitat predicted in protected lands.

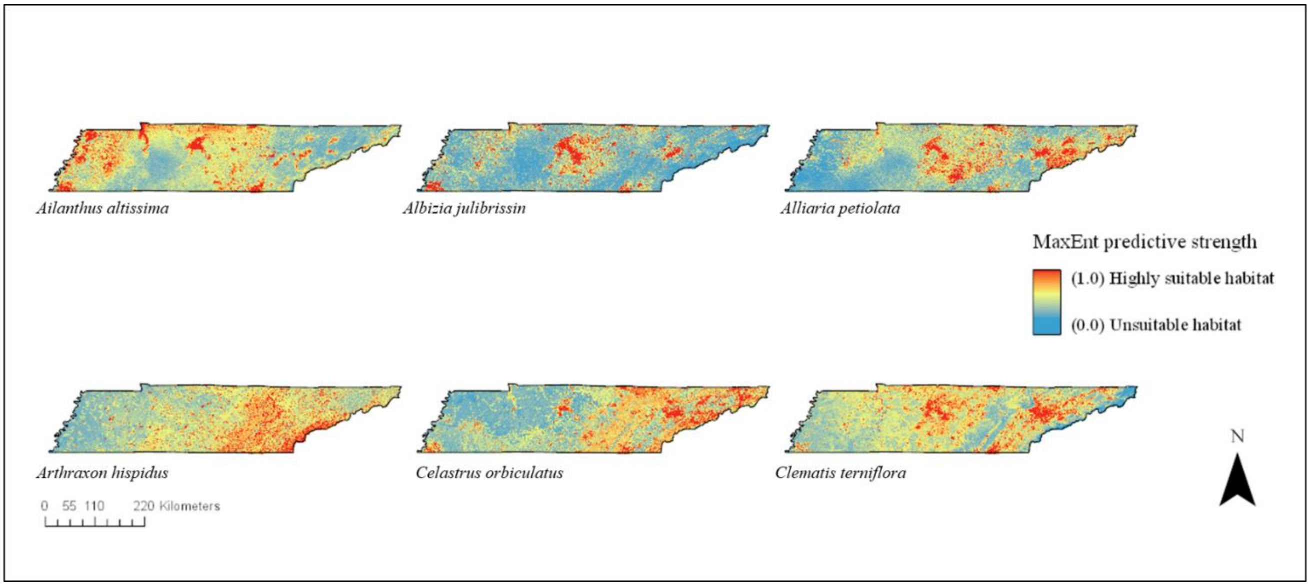

Figure 3.2 MaxEnt Predicted Distributions, *Ailanthus altissima* to *Clematis terniflora*. This figure shows the continuous distribution predicted by MaxEnt for each species. MaxEnt ranks habitat suitability on a scale of 0 – 1.0. Areas in red are predicted to have the highest probability of suitable habitat and areas in blue have the lowest predicted probabilities of suitable habitat.

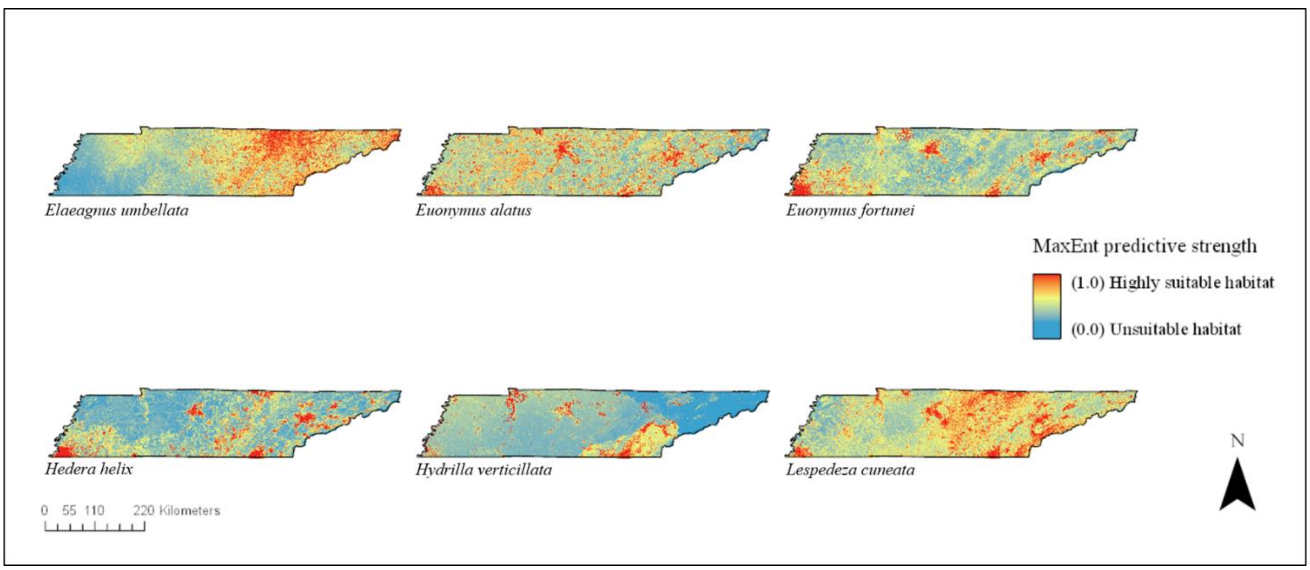

Figure 3.3 MaxEnt Predicted Distributions, *Elaeagnus umbellate* to *Lespedeza cuneata*. This figure shows the continuous distribution predicted by MaxEnt for each species. MaxEnt ranks habitat suitability on a scale of 0 – 1.0. Areas in red are predicted to have the highest probability of suitable habitat and areas in blue have the lowest predicted probabilities of suitable habitat.

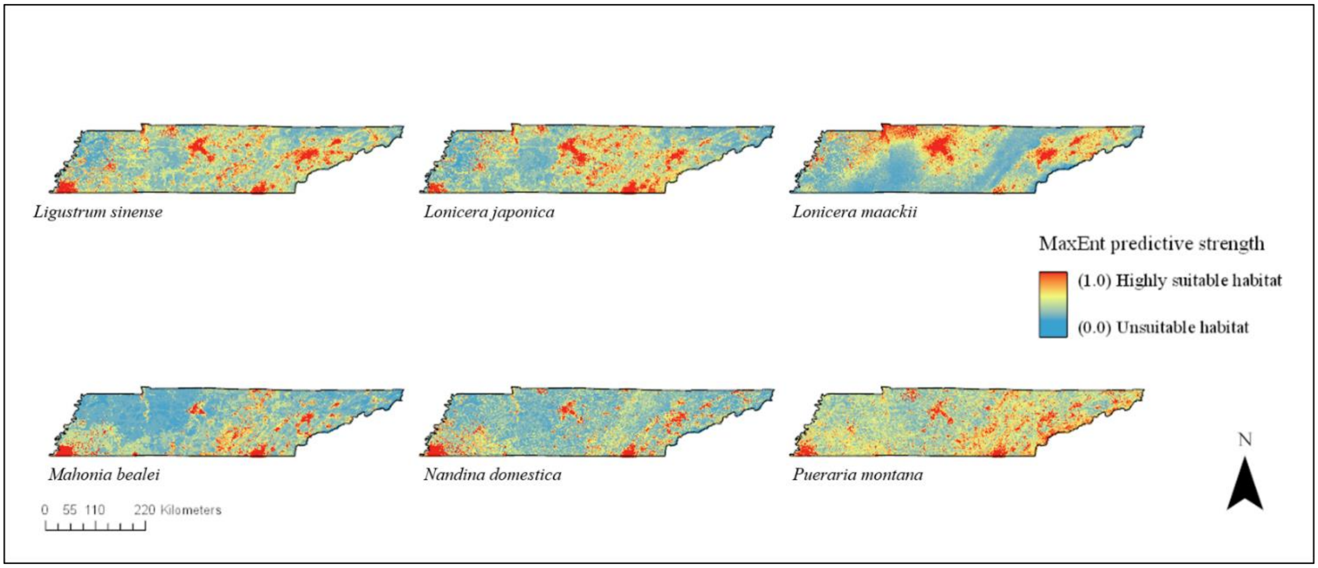

Figure 3.4 MaxEnt Predicted Distributions, *Ligustrum sinense* to *Pueraria montana*. This figure shows the continuous distribution predicted by MaxEnt for each species. MaxEnt ranks habitat suitability on a scale of 0 – 1.0. Areas in red are predicted to have the highest probability of suitable habitat and areas in blue have the lowest predicted probabilities of suitable habitat.

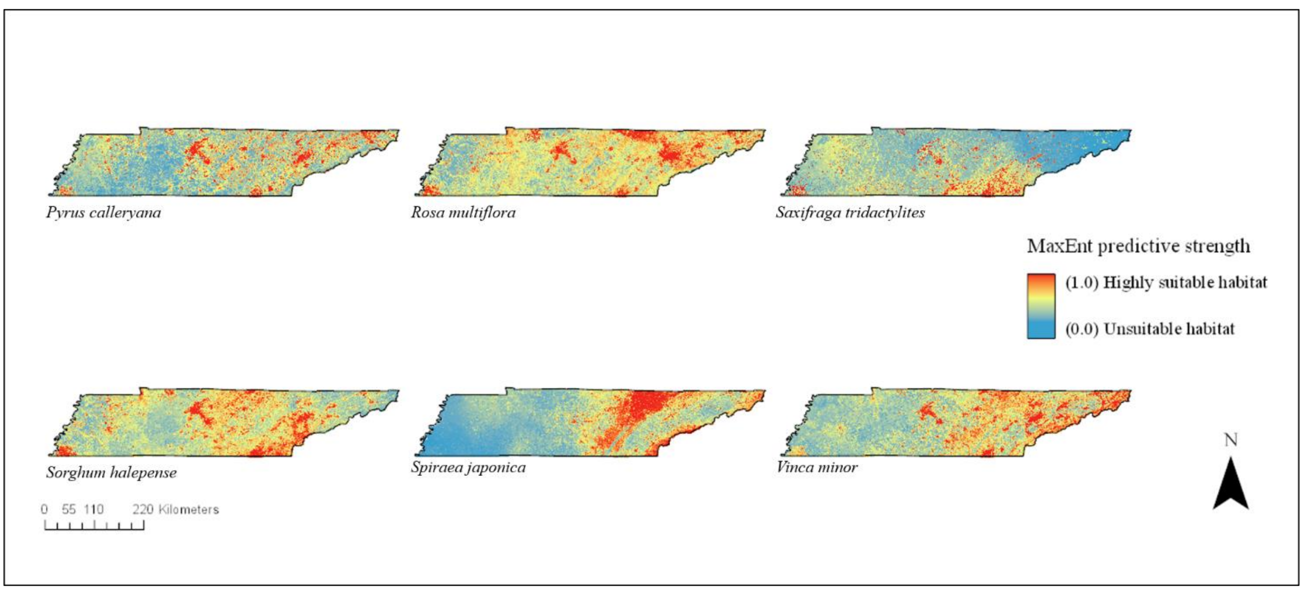

Figure 3.5 MaxEnt Predicted Distributions *Pyrus calleryana* to *Vinca minor*. This figure shows the continuous distribution predicted by MaxEnt for each species. MaxEnt ranks habitat suitability on a scale of 0 – 1.0. Areas in red are predicted to have the highest probability of suitable habitat and areas in blue have the lowest predicted probabilities of suitable habitat.

Conclusions

Our continued reliance on county level data means there are still considerable gaps in our understanding of invasive species distributions (Hulme 2003). SDMs help to fill these gaps by validating already known habitat preferences for invasive species such as areas of high disturbance (Marvier et al, 2004), revealing patterns of invasion, and prioritizing areas for management (Franklin 2013). Here, SDMs were used to improve our understanding of invasive plant species distributions in Tennessee to ultimately present a new idea for ranking these species. While it is not possible to precisely compare the SDMs developed in this study to the county-level ranking system used by TN-IPC, a majority of species categorized by TN-IPC (21 of 24) are predicted to be widely distributed, and therefore the TN-IPC ranks appear to be justified. However, three species that were modeled did not agree with TN-IPC's ranking designation.

Two species considered by TN-IPC to be Emerging Threats, the lowest threat level category, were found to have high percentages of suitable habitat in the state, potentially underestimating the threat they present to Tennessee. Additionally, sweet autumn virgin's bower is considered an Established Threat to Tennessee; however, the SDM predicted relatively low percentages of suitable habitat for this species in the state, and therefore this ranking seems to overestimate the threat sweet autumn virgin's bower presents to the state. Of the 24 species modeled, 22 were considered and verified to be Established Threats by TN-IPC, and all SDMs modeled for these species predicted high percentages of suitable habitat across the state, confirming the high-level ranking. This large consensus is most likely a result of prevalent species being collected more frequently, and therefore more data points were available to create SDMs for these species. Of the species modeled in this study, only sweet autumn virgin's bower and sacred bamboo were not considered to meet the criterion of TN-IPC's rank designation of Emerging Threat. The SDM predicted that 85.88% of Tennessee was suitable habitat for sacred bamboo, and therefore it is most likely naturalized in considerably more than ten counties (or at least has the suitable habitat available to spread to these areas), especially since it is likely planted as an ornamental in all of Tennessee's counties. Additionally, only 36.94% of Tennessee is predicted to have suitable habitat for sweet autumn virgin's bower. It is uncertain if this area spans ten counties; regardless, this low amount of suitable habitat does not warrant the highest threat level classification in the state. Although sweet autumn virgin's bower is not as strong of a threat compared to other ranked species, it is still an aggressive invasive that deserves to be categorized, though perhaps not at the highest threat level. An increase in the number of categories in TN-IPC's ranking system would allow such species to still be considered threats without this misleading classification of highest priority.

Additionally, several species such as autumn olive, lesser periwinkle, and Japanese meadowsweet have suitable habitat primarily in eastern physiographic provinces of the state. All three of these species were predicted to have highly suitable habitat in almost 50% of protected lands and were predicted to have suitable habitat covering more than 50% of the state. However, the majority of this suitable habitat (and highly suitable habitat) is located in the eastern and middle regions of Tennessee. Since these species are predicted to rarely occupy habitat in the western region of the state, they might not warrant the same high-level ranking in this portion of the state.

In conclusion, the development of SDMs has shown that TN-IPC's ranking system is justified for the very prevalent threats modeled here. However, it reveals that this system of prioritizing species might be flawed for two primary reasons, the first being that TN-IPC ranks threats based on political boundaries rather than by ecological boundaries. A better way of determining a threat to the state may be to look at the percentage of suitable habitat located within a physiographic province (or as East, Middle, and West Tennessee), so managers in these areas are able to prioritize the species that pose the greatest threat to areas they are trying to manage. The second issue is that TN-IPC's use of only two categories likely overestimates or underestimates the threat a species poses to the state. For example, sweet autumn virgin's bower is a threat to East and Middle Tennessee; however, since only 36% of Tennessee contains suitable habitat for this species, categorizing it in the highest threat category seems misleading. The creation of multiple categories would allow for species like sweet autumn virgin's bower to be considered a threat to the state without overestimating the danger it poses by placing it in an equal category with species that pose significantly higher threats. The issues presented here are addressed more fully in Chapter IV, where a new ranking system for Tennessee invasive plant species is proposed.

CHAPTER IV

PROPOSED RANKING SYSTEM

Introduction

Categorizing and ranking invasive species is difficult work that, to do effectively, requires a lot of data. Even in the absence of data, time-tested methods, like expert opinion or the averaged opinion of several experts on a committee or board, may suffice until data are available. Ultimately, species need to be classified, or ranked, as a means of grouping information regarding the ecological threat of these species. Philosophically, TN-IPCs ranks span the entire state of Tennessee, which is ecologically broad given the latitudinal span from the Blue Ridge Mountains to the Mississippi River. TN-IPC places species in two categories, based on two criteria: whether the species "can be eradicated using available management methods" and the number of documented county occurrences. There are no clear, written criteria about threats on different ecological systems, and instead, the threat level is a statewide determination. Its limited criteria, simplified categories, and choice to evaluate species statewide tend to inflate or underestimate threats that these species pose. This chapter addresses these issues and lays out an argument and potential model for moving the current ranking system toward one that better addresses the data available and more clearly ranks the threat each species poses to Tennessee's diverse ecology.

During November of 2016, TN-IPC compiled data for the current ranking system. A list of the sources they used in this most recent revision is found at this link: http://tnipc.org/wp-content/uploads/2017/08/TN-IPC-2017-List-Revision-Sources.pdf. No sources were provided for information relating to the criterion that describes the use of available management methods. The management of invasive species involves dealing with high levels of uncertainty when planning for expenses and deciding on strategies. The estimation of the costs associated with invasion impacts or mitigation is challenging because of complex invasion dynamics and economic processes (Epanchin-Niell

2017). Invasive species that have visible effects on the economy are studied more frequently and quantified more efficiently; however, it is difficult to calculate the cost of a species that affects biodiversity and ecological processes due to the difficulty of assigning a monetary value to these benefits (Holmes et al. 2014). Estimating the costs of invasive species management is made more complicated because decisions about species management often involve considering how much to control or what level of management to implement. Managers must also evaluate the cost-effectiveness of control options and consider if eradication of a species is possible (Epanchin-Niell 2017). Given the uncertainty associated with the management of invasive species, using this as a criterion to rank species is not appropriate, and even misleading in some circumstances because of the complexity in assigning value to management strategies and biodiversity benefits. Last, given funding issues and the lack of broad public interest in devoting tax dollars to this issue, there is not likely ever to be any statewide management of a single species and the same species might need to be managed in different ways in different ecological systems or depending on whether it is around sensitive species; thus, this criterion seems unwieldy.

Regarding the criterion that addresses distribution at the county level, TN-IPC has not described which source or combination of sources was used to determine the total number of counties each species was reported within the state. As shown in Chapter II, these sources may vary widely in the numbers of counties reported for each species and this study. Chapters II revealed that several species did not meet this ranking criterion from any single source, either because more county data were likely generated since the ranks were assigned, which leaves species at a lower threat level than their county distribution suggests (e.g., sacred bamboo (*Nandina domestica*, Chapter III) or the TN-IPPC committee ranked species that were not yet known to occur in the requisite numbers of counties (e.g., common reed (*Phragmites australis*) Chapter III).

Since Tennessee has 95 counties, the criterion of greater or fewer than ten counties may be misleading because it can exaggerate the threat that some species pose to the state. For example, a species that has only been documented in 10 counties or about 10% of the counties in the state, would be assigned the same ranking as an invasive species that is distributed in 65-95 counties throughout Tennessee. For example, on average Japanese honeysuckle (*Lonicera japonica*) is documented in 66 counties across all of Tennessee, while Chinese silver grass (*Miscanthus sinensis*) was documented on average in 16 counties and these are mostly in East Tennessee; however, both species are at the equal rank of Established Threat, which gives the impression they are equal. The designation of Chinese silver grass as an Established Threat, despite the low documentation of known occurrences, inflates the status of this species and indicates that it warrants the same allocation of resources and attention as Japanese honeysuckle. Furthermore, most non-native plant species in Tennessee are found in 10 or more counties. Our sweep of SERNEC data revealed that 299 of 473 non-native plant species in Tennessee are found in more than ten counties, meaning that these species already meet half of TN-IPC's requirements to be considered and Established Threat in the state. There are only nine states that have a higher number of counties than Tennessee, making the ~10% threshold seemingly low and leaving a wide range of invasiveness unreported within the highest rank. A ranking criterion that requires a species to be documented in such a low number of counties across a state is not a defining characteristic of invasiveness for a species and does not allow for an accurate representation of the threat they present to the state.

A reason species such as Japanese honeysuckle and Chinese silver grass have been forced into the same category is the reduction in the number of categories from four to two. Before the 2016 reduction in categories, species that had not been reported in the state, but still required attention, were placed in a separate 'Alert' category. The Alert category established the importance of maintaining awareness for these species without implying a current impact on the state. A reduction in the number of categories forced species that have not been documented in Tennessee, such as giant hogweed (*Heracleum mantegazzianum*), to be ranked in the same category as species like golden bamboo (*Phyllostachys aurea*) which has been documented in an average of 9 counties. Although giant hogweed could pose a threat to Tennessee, it has not been documented in the state and does not currently warrant the same rank as a species that has established populations within the state.

Currently, there are eight Invasive Plant Councils in the United States that provide information on their ranking system, and seven of these councils' place species into four categories. Most of the invasive plant councils reviewed follow a similar system to the original TN-IPC ranking system. In these systems, the four categories into which species are ranked include Severe, Significant, Emerging, and Alert. This method of ranking lessens the chance of species like Japanese honeysuckle and Chinese silver grass being placed in the same category. Additionally, the inclusion of an Alert category allows for species like giant hogweed to be recognized without being perceived as currently having an impact on the state.

It is also essential to address that using political boundaries does not inform users with an understanding of which species threaten our natural areas, or different ecological systems from the high elevations of the Southern Appalachian Mountains to the bottomlands of the Mississippi River floodplains. Since species exist within their ecological tolerances, it is essential to consider these when prioritizing species for management. Tennessee crosses seven physiographic provinces, and species composition and diversity change dramatically across them. Since physiographic conditions influence the floristic composition, a species that may present a significant threat to provinces in the east may not threaten provinces in the west. For example, Japanese meadowsweet (*Spiraea japonica*) is documented in over 50% of the counties in the Blue Ridge and Cumberland Plateau provinces; however, documentation of this species beyond the Cumberland Plateau decreases substantially, and it has not been reported in counties within the Coastal/Mississippi Alluvial Plain. This distribution has also been confirmed by species distribution modeling (Chapter III). Therefore, considering Japanese meadowsweet at the same rank across the entire state is misleading. This example demonstrates how consideration of a species' ecology, at least at the coarse level of physiographic provinces, is also essential to understanding the threat a species poses, rather than the use of political boundaries.

Incorporating physiographic provinces into ranking systems is an approach used by several invasive plant councils. For example, the Mississippi Exotic Pest Plant Council and Alabama Invasive Plant Council require a species to occur in three or more physiographic provinces before it can be ranked into the most severe category for each system, Category 1. This way of ranking species has the advantage of highlighting significant, broad threats to the state; for example, in Tennessee Japanese honeysuckle would fit into this category because it is documented in 66 counties and at least 50% of the counties in every province (distribution confirmed by SDM, Chapter III). Still, this approach cannot highlight species that can cause significant damage to particular habitats found in individual physiographic provinces. For example, obligate wetland species such as common reed (*Phragmaites australis*) are detrimental to wetland spaces; however, habitats that meet the needs of this species are uncommon in Tennessee. Common reed has only been documented in the Interior Low Plateau and Coastal/Mississippi Alluvial Plain. A system that considers the entire area of the state, rather than one that takes ecology into account, would not consider this species a high threat; however, the threat it poses to wetland habitat in these provinces is essential for managers in these areas to consider. North Carolina Invasive Plant Council considers provinces and regions in the formulation of ranks. Instead of ranking species statewide, North Carolina workers have created a species list for each major region in the state to highlight regional threats. This approach begins to focus less on political boundaries and more on habitats that would influence the invasion of a species. An approach that ranks species within physiographic provinces of Tennessee would provide land managers with a better understanding of which species are the most significant threat within the area they might be trying to manage.

It is evident that the current ranking system for non-native species in Tennessee is oversimplified. This study represents a large aggregation of information on Tennessee's invasive species. More data and future work are needed to effectively model potential distributions of all of Tennessee's non-native species. The field of SDMs is relatively new, and advancements in this science along with increased availability of locality data will make it possible to increase our understanding of species distribution and ultimately create more informed ranking systems for invasive plant species. As a thought exercise, below is a potential ranking system for non-native plant species in Tennessee that includes Species Distribution Models and consideration of physiography.

Materials and Methods

As a thought exercise to include Species Distribution Models within a new potential ranking system for non-native plant species in Tennessee, the total percentage of county documentation in combination with the total percentage of predicted total suitable habitat within each province were combined to inform a revised three-rank system for Tennessee: Severe, Moderate, or Low. (These categories could also be Severe, Significant, and Emerging, to align with categories of other states and return to the Tennessee system before the current two-rank system.) The ten percentile training presence threshold (10 PTP) was used to delineate suitable habitat for species in this system. This threshold considers the probability at which 10% of the training presence records are omitted, particularly outliers (Escalante et al. 2013). Studies have shown this predicts a middle range of suitable habitat for species, and for this reason it will be used to delineate median suitable habitat for species (Escalante et al. 2013).

Below is a thought exercise that ranks species according to the percentage of documented county occurrences within a province, plus, if available, the percentage of total suitable habitat predicted by the SDM in that province. To be considered a Severe Threat to the province, a species must be documented in 50% or more of the counties or have a predicted distribution of total suitable habitat that is greater than 50% of the province. A Moderate Threat is a species documented in 20-49% of the counties within a province or predicted to have suitable habitat in 20-49% of the province. Finally, a Low Threat is a species that is found in less than 20% of the counties in that province or was predicted to potentially occupy less than 20% of the province. If no occurrence of a species was documented in a province, which, for the purpose of generating SDMs would also imply no suitable habitat was predicted in that province, it is not considered a threat to that area. Species such as these would be placed on a Watch List (or Alert) category. A summary of these categories is in Table 4.1.

Table 4.1 Criteria for the Proposed Ranking System

Threat Level	Description
Severe	• An invasive species that is documented in 50% or more in the physiographic province or • An invasive species that is predicted to have suitable habitat in 50% or more in the physiographic province
Moderate (or Significant)	• An invasive species that is documented in 20-49% of the physiographic province or • An invasive species that is predicted to have suitable habitat in 20% - 49% in the physiographic province
Low (or Emerging)	• A species that is present in the physiographic province but has been reported in less than 20% of the counties in that province or • An invasive species that is predicted to have suitable habitat in 20% or less in the physiographic province
Watch List (or Alert)	• A species that has been documented in 2 counties or less or is on a ranked list in surrounding states.

Results and Discussion

Outlined below is a potential model for ranking invasive plant species in Tennessee. First, the species designated as watchlist species are discussed, followed by a breakdown of the ranking system by physiographic province.

Watchlist Species

Watchlist species are any species that have been reported in zero-two counties in Tennessee and exhibit invasive tendencies in surrounding states. These species are outlined in Table 4.2, and below these species are reviewed.

Currently, 14 species listed by TN-IPC are found on average in less than two counties. Four threats listed by the TN-IPC were not documented in Tennessee by any of the sources reviewed in Chapter II. These species include Russian knapweed (*Centaurea repens*), giant hogweed (*Heracleum mantegazzianum*), itchgrass (*Rottboellia cochinchinensis*), giant salvania (*Salvinia molesta*). A sweep of SERNEC data did not return any specimens of these species in Tennessee. A review of BONAP, USDA, and SERNEC show that these species are occasionally present in the eight surrounding states. Table 4.2 summarizes the documented presence of each species in the surrounding eight states by BONAP, USDA, and SERNEC.

Table 4.2 Average Number of Documented Counties for Watchlist Species

Watchlist Species	**Common name**	**Average Number of Documneted Counties**
Akebia quinata	five-leaf akebia	0.25
Centaurea repens	Russian knapweed	0
Firmiana simplex	Chinese parasol-tree	2
Heracleum mantegazzianum	giant hogweed	0
Imperata cylindrica	cogon grass	0.25
Liriope spicata	creeping liriope	0.25
Lygodium japonicum	Japanese climbing fern	1
Persicaria perfoliata	Asiatic tearthumb	0.25
Ranunculus ficaria	Eurasian-buttercup	2
Rhamnus cathartica	buckthorn	1
Rottboellia cochinchinensis	itchgrass	0
Salvinia molesta	giant salvinia	0
Trapa natans	water chestnut	0
Triadica sebifera	Chinese tallow	0.75

Giant salvinia was on average documented in the most surrounding states, being found in six out of the eight surrounding states, followed by itchgrass, which was on average found in five surrounding states (Table 4.4). Giant hogweed and Russian knapweed were both on average found in only one surrounding state. All reviewed sources reported giant hogweed only in North Carolina, and Russian knapweed was reported in Kentucky, Arkansas, Missouri, and Georgia (Table 4.3).

Table 4.3 Surrounding States with Documented Occurrences of Watchlist species not yet documented in Tennessee

BONAP										
Species	**Common Name**	**NC**	**VA**	**KY**	**GA**	**AL**	**AR**	**MO**	**MS**	**Total**
Salvinia molesta	giant salvinia	Y	Y	N	Y	Y	Y	Y	Y	7
Rottboellia cochinchinensis	itchgrass	Y	N	N	Y	N	Y	N	y	4
Heracleum mantegazzianum	giant hogweed	Y	N	N	N	N	N	N	N	1
Centaurea repens	rhaponticum repens	N	N	N	N	N	N	N	N	0
USDA										
Species	**Common Name**	**NC**	**VA**	**KY**	**GA**	**AL**	**AR**	**MO**	**MS**	**Total**
Salvinia molesta	giant salvinia	Y	Y	N	Y	Y	N	N	Y	5
Rottboellia cochinchinensis	itchgrass	Y	N	N	Y	Y	Y	Y	Y	6
Heracleum mantegazzianum	giant hogweed	Y	N	N	N	N	N	N	N	1
Centaurea repens	Russian knapweed	N	N	Y	N	N	Y	Y	N	3

SERNEC										
Species	**Common Name**	**NC**	**VA**	**KY**	**GA**	**AL**	**AR**	**MO**	**MS**	**Total**
Salvinia molesta	giant salvinia	Y	Y	N	Y	Y	Y	Y	Y	7
Rottboellia cochinchinensis	itchgrass	Y	Y	N	Y	Y	Y	Y	Y	7
Heracleum mantegazzianum	giant hogweed	Y	N	N	N	N	N	N	N	1
Centaurea repens	Russian knapweed	N	N	N	Y	N	N	Y	N	2

Table 4.4 Average Number of Documented Occurrences of Watchlist Species in Surrounding States

Species	Common Name	Average number of surrounding states
Salvinia molesta	giant salvinia	6
Rottboellia cochinchinensis	itchgrass	5
Heracleum mantegazzianum	giant hogweed	1
Centaurea repens	rhaponticum repens	1

Species Ranked Within Physiographic Provinces

Blue Ridge Province

There are 42 species that are considered a threat to the Blue Ridge province. The Blue Ridge contains the largest number of Severe Threats of all provinces (23). Japanese-knotweed (*Fallopia* *japonica*), Japanese stilt grass (*Microstegium vimineum*), and Chinese bush-clover (*Lespedeza cuneata*) were all reported in 100% of Blue Ridge counties. Small carp grass (*Arthraxon* hispidus) was predicted to have the highest percentage of suitable habitat in the Blue Ridge (87%), followed by lesser periwinkle (*Vinca minor*) (71%) and Japanese meadowsweet (*Spiraea japonica*) (77%). Table 4.5 presents a list of all species and their corresponding rank for the Blue Ridge Province, cells highlighted in red are Severe Threats (present in >50% of counties or >50% of the province predicted to contain suitable habitat), cells in green are Moderate Threats (present in 20-40% of counties or 20-40% of the province predicted to contain suitable habitat), and cells in yellow are Low Threats (present in < 20% of counties or <20% of the province predicted to contain suitable habitat). Aquatic species names are shown in purple text and wetland species names in orange text.

Table 4.5 Ranking of Invasive Plant Species in the Blue Ridge Province

Blue Ridge				
Species	**Common Name**	**TN-IPC Ranking**	**Percentage of Counties**	**SDM Percent Total Suitable Habitat**
Lespedeza cuneata	Chinese bush-clover	*Established*	100	65
Fallopia japonica	Japanese-knotweed	*Established*	100	
Microstegium vimineum	Japanese stilt grass	*Established*	100	
Lonicera japonica	Japanese honeysuckle	*Established*	86	36
Ligustrum sinense	Chinese privet	*Established*	86	41
Elaeagnus umbellata	autumn olive	*Established*	86	70
Lespedeza bicolor	two-color bush-clover	*Established*	86	
Albizia julibrissin	mimosa	Established	71	6
Sorghum halepense	Johnson grass	*Established*	71	40
Alliaria petiolata	garlic mustard	Established	71	50
Vinca minor	lesser periwinkle	*Established*	71	79
Arthraxon hispidus	small carp grass	Established	71	87
Miscanthus sinensis	Chinese silver grass	*Established*	71	
Myriophyllum aquaticum	parrot feather watermilfoil	***Established***	71	

Ailanthus altissima	tree-of-heaven	Established	57	23
Hedera helix	English ivy	*Established*	57	35
Rosa multiflora	Multiflora rose	*Established*	57	64
Spiraea japonica	Japanese meadowsweet	*Established*	57	77
Bromus inermis	smooth brome	*Established*	57	
Paulownia tomentosa	princess tree	*Established*	57	
Hydrilla verticillata	water thyme	*Established*	14	48
Perilla frutescens	beefsteakplant	*Established*	57	
Pueraria montana	kudzu	*Established*	43	75
Saxifraga tridactylites	nailwort	*NA*	57	24
Lonicera maackii	amur honeysuckle	*Established*	43	36
Clematis terniflora	sweet autumn virgin's-bower	*Established*	43	5
Celastrus orbiculatus	Asian bittersweet	*Established*	43	49
Murdannia keisak	Wart removing herb	***Established***	43	
Myriophyllum spicatum	Eurasian water-milfoil	***Established***	43	
Rubus phoenicolasius	colt's-foot	*Established*	43	
Tussilago farfara	Colt's foot	*Established*	43	
Euonymus alatus	Burning bush	*Established*	29	7
Nandina domestica	sacred bamboo	*Emerging*	29	9
Mahonia bealei	beale's barberry	*Emerging*	29	21
Arundo donax	Giant reed	*Emerging*	29	
Dioscorea polystachya	Chinese yam	*Established*	29	
Hydrilla verticillata	water thyme	*Established*	14	48
Pyrus calleryana	Bradford pear	*Established*	14	22
Buddleja davidii	common butterfly bush	*Emerging*	14	
Centaurea stoebe	spotted knapweed	*Emerging*	14	
Lythrum salicaria	purple loosestrife	***Emerging***	14	
Wisteria sinensis	Chinese wisteria	*Established*	14	
Euonymus hederaceus	winter-creeper	*Established*	0	10

Ridge and Valley Province

There are 49 species that are considered a threat to the Ridge and Valley. This province has 13 Severe Threats. Multiflora rose (*Rosa multiflora*) was predicted to have the largest amount of suitable habitat in this province (68%) followed by small carp grass (*Arthraxon hispidus*) (67%) , and water thyme

(*Hydrilla verticillate*) (56%). Four watchlist species, creeping liriope (*Liriope spicata*), Eurasian-buttercup (*Ranunculus ficaria*), five-leaf akebia (*Akebia quinata*), Chinese parsol-tree (*Firmiana simplex*) have been reported in the Ridge and Valley. Table 4.6 presents a list of all species and their corresponding rank for the Ridge and Valley Province; Cells highlighted in red are Severe Threats (present in >50% of counties or >50% of the province predicted to contain suitable habitat), cells in green are Moderate Threats (present in 20-40% of counties or 20-40% of the province predicted to contain suitable habitat), and cells in yellow are Low Threats (present in < 20% of counties or <20% of the province predicted to contain suitable habitat). Aquatic species names are shown in purple text and wetland species names in orange text.

Table 4.6 Ranking of Invasive Plant Species in the Ridge and Valley Province

Ridge and Valley				
Species	**Common Name**	**TN-IPC Ranking**	**Percentage of Counties**	**Percentage Total Suitable Habitat**
Sorghum halepense	*Johnson grass*	*Established*	72	46
Vinca minor	*lesser periwinkle*	*Established*	67	51
Microstegium vimineum	*Japanese stilt grass*	*Established*	67	
Miscanthus sinensis	*Chinese silver grass*	*Established*	61	
Ligustrum sinense	*Chinese privet*	*Established*	56	50
Lonicera japonica	*Japanese honeysuckle*	*Established*	56	42
Albizia julibrissin	*mimosa*	*Established*	56	22
Euonymus alatus	*burning bush*	*Established*	50	25
Fallopia japonica	*Japanese-knotweed*	*Established*	50	
Lespedeza bicolor	*two-color bush-clover*	*Established*	50	
Arthraxon hispidus	*small carp grass*	*Established*	44	67
Hydrilla verticillata	***water thyme***	***Established***	**17**	**56**
Elaeagnus umbellata	*autumn olive*	*Established*	28	54
Rosa multiflora	*multiflora rose*	*Established*	39	68
Lonicera maackii	*amur honeysuckle*	*Established*	39	27
Lespedeza cuneata	*Chinese bush-clover*	*Established*	44	44

Perilla frutescens	*beefsteakplant*	*Established*	44	
Buddleja davidii	*common butterfly bush*	*Emerging*	39	
Murdannia keisak	***wart-removing-herb***	***Established***	39	
Paulownia tomentosa	*princess tree*	*Established*	39	
Rubus phoenicolasius	*wine raspberry*	*Established*	39	
Tussilago farfara	*colt's-foot*	*Established*	39	
Pueraria montana	*kudzu*	*Established*	33	41
Alliaria petiolata	*garlic mustard*	*Established*	33	36
Arundo donax	*giant reed*	*Emerging*	33	
Spiraea japonica	*Japanese meadowsweet*	*Established*	28	34
Clematis terniflora	*sweet autumn virgin's-bower*	*Established*	28	30
Saxifraga tridactylites	*nailwort*	*NA*	28	30
Hedera helix	*English ivy*	*Established*	28	29
Euonymus hederaceus	*winter-creeper*	*Established*	28	27
Pyrus calleryana	*bradford pear*	*Established*	22	47
Celastrus orbiculatus	*Asian bittersweet*	*Established*	22	37
Nandina domestica	*sacred bamboo*	*Emerging*	22	20
Ailanthus altissima	*tree-of-heaven*	*Established*	22	16
Alternanthera philoxeroides	***alligator-weed***	***Established***	22	
Dioscorea polystachya	*Chinese yam*	*Established*	22	
Myriophyllum aquaticum	***parrot feather watermilfoil***	***Established***	22	
Myriophyllum spicatum	***Eurasian water-milfoil***	***Established***	22	
Mahonia bealei	*beale's barberry*	*Emerging*	17	22
Humulus japonicus	*Japanese hop*	*Emerging*	17	
Centaurea stoebe	*spotted knapweed*	*Emerging*	11	
Lythrum salicaria	*purple loosestrife*	*Emerging*	11	
Melia azedarach	*China-berry*	*Emerging*	11	
Phyllostachys aurea	*golden bamboo*	*Emerging*	11	
Wisteria floribunda	*Japanese wisteria*	*Established*	11	
Wisteria sinensis	*Chinese wisteria*	*Established*	11	
Ampelopsis brevipedunculata	*porcelainberry*	*Emerging*	6	
Tribulus terrestris	*puncturevine*	*Emerging*	6	

Cumberland Plateau Province

There are 43 species that are considered threats to the Cumberland Plateau. This province has 19 Severe Threats. Small carp grass was predicted to have the highest percent of suitable habitat in this province (92%) followed by Japanese meadowsweet (*Spiraea japonica*) and water thyme (*Hydrilla verticillata*). Watchlist species, Eurasian-buttercup (*Ranunculus ficaria*) is found in one county in the Cumberland Plateau. Table 4.7 presents a list of all species and their corresponding rank for the Cumberland Plateau Province. Cells highlighted in red are Severe Threats (present in >50% of counties or >50% of the province predicted to contain suitable habitat), cells in green are Moderate Threats (present in 20-40% of counties or 20-40% of the province predicted to contain suitable habitat), and cells in yellow are Low Threats (present in < 20% of counties or <20% of the province predicted to contain suitable habitat). Aquatic species names are shown in purple text and wetland species names in orange text.

Table 4.7 Ranking of Invasive Plant Species in the Cumberland Plateau Province

Cumberland Plateau				
Species	**Common Name**	**TN-IPC Ranking**	**Percentage of Counties**	**SDM Percentage Total Suitable Habitat**
Lonicera japonica	*Japanese honeysuckle*	*Established*	83	42
Rosa multiflora	*multiflora rose*	*Established*	75	73
Lespedeza bicolor	*two-color bush-clover*	*Established*	75	
Elaeagnus umbellata	*autumn olive*	*Established*	67	76
Ligustrum sinense	*Chinese privet*	*Established*	67	30
Microstegium vimineum	*Japanese stilt grass*	*Established*	67	
Paulownia tomentosa	*princess tree*	*Established*	67	
Perilla frutescens	*beefsteakplant*	*Established*	67	
Spiraea japonica	*Japanese meadowsweet*	*Established*	58	87
Sorghum halepense	*Johnson grass*	*Established*	58	43
Ailanthus altissima	*tree-of-heaven*	*Established*	58	30
Albizia julibrissin	*mimosa*	*Established*	58	17

Vinca minor	*lesser periwinkle*	*Established*	50	64
Nandina domestica	*sacred bamboo*	*Emerging*	50	7
Myriophyllum aquaticum	***parrot feather watermilfoil***	*Established*	50	
Rubus phoenicolasius	*wine raspberry*	*Emerging*	50	
Arthraxon hispidus	*small carp grass*	*Established*	42	92
Hydrilla verticillata	***water thyme***	*Established*	8	85
Pueraria montana	*kudzu*	*Established*	8	51
Lespedeza cuneata	*Chinese bush-clover*	*Established*	42	68
Celastrus orbiculatus	*Asian bittersweet*	*Established*	42	41
Alliaria petiolata	*garlic mustard*	*Established*	42	30
Bromus inermis	*smooth brome*	*Established*	42	
Fallopia japonica	*Japanese-knotweed*	*Established*	42	
Wisteria sinensis	*Chinese wisteria*	*Established*	33	
Hedera helix	*English ivy*	*Established*	25	38
Saxifraga tridactylites	*nailwort*	*NA*	25	36
Euonymus alatus	*burning bush*	*Established*	25	16
Lonicera maackii	*amur honeysuckle*	*Established*	25	12
Euonymus hederaceus	*winter-creeper*	*Established*	25	7
Mahonia bealei	*beale's barberry*	*Emerging*	17	33
Pyrus calleryana	*bradford pear*	*Established*	17	28
Clematis terniflora	*sweet autumn virgin's-bower*	*Established*	17	8
Arundo donax	*giant reed*	*Emerging*	17	
Buddleja davidii	*common butterfly bush*	*Emerging*	17	
Lythrum salicaria	*purple loosestrife*	*Emerging*	17	
Miscanthus sinensis	*Chinese silver grass*	*Established*	17	
Tussilago farfara	*colt's-foot*	*Established*	17	
Wisteria floribunda	*Japanese wisteria*	*Established*	17	
Alternanthera philoxeroides	***alligator-weed***	***Established***	8	
Dioscorea polystachya	*Chinese yam*	*Established*	8	
Murdannia keisak	***wart-removing-herb***	*Established*	8	
Myriophyllum spicatum	*Eurasian water-milfoil*	*Established*	8	

Interior Low Plateau Province

There are 48 species that are considered threats to the Interior Low Plateau province. This province has 14 species considered Severe Threats. Water thyme was predicted highest amount of suitable habitat in this province (84%) followed by small carp grass (*Arthraxon hispidus*) and multiflora rose (*Rosa multiflora*). One suggested watchlist species, Chinese tallow tree (*Triadica sebifera*) was documented in the Interior Low Plateau. Table 4.8 presents a list of all species and their corresponding rank for the Interior Low Plateau Province; cells highlighted in red are Severe Threats (present in >50% of counties or >50% of the province predicted to contain suitable habitat), cells in green are Moderate Threats (present in 20-40% of counties or 20-40% of the province predicted to contain suitable habitat), and cells in yellow are Low Threats (present in < 20% of counties or <20% of the province predicted to contain suitable habitat). Aquatic species names are shown in purple text and wetland species names in orange text.

Table 4.8 Ranking of Invasive Plant Species in the Interior Low Plateau Province

Interior Low Plateau				
Species	**Common Name**	**TN-IPC Ranking**	**Percentage of Counties**	**SDM Percentage Total Suitable Habitat**
Lonicera japonica	*Japanese honeysuckle*	*Established*	83	30
Rosa multiflora	*multiflora rose*	*Established*	75	48
Paulownia tomentosa	*princess tree*	*Established*	72	
Ligustrum sinense	*Chinese privet*	*Established*	67	33
Elaeagnus umbellata	*autumn olive*	*Established*	67	17
Microstegium vimineum	*Japanese stilt grass*	*Established*	66	
Perilla frutescens	*beefsteakplant*	*Established*	62	
Ailanthus altissima	*tree-of-heaven*	*Established*	58	30
Sorghum halepense	*Johnson grass*	*Established*	58	26
Albizia julibrissin	*mimosa*	*Established*	58	23
Spiraea japonica	*japanese meadowsweet*	*Established*	58	14

Lespedeza bicolor	*two-color bush-clover*	*Established*	55	
Vinca minor	*lesser periwinkle*	*Established*	50	19
Hydrilla verticillata	***water thyme***	*Established*	**8**	**84**
Nandina domestica	*sacred bamboo*	*Emerging*	50	5
Arthraxon hispidus	*small carp grass*	*Established*	42	57
Lespedeza cuneata	*Chinese bush-clover*	*Established*	42	38
Alliaria petiolata	*garlic mustard*	*Established*	42	27
Celastrus orbiculatus	*asian bittersweet*	*Established*	42	10
Wisteria sinensis	*Chinese wisteria*	*Established*	31	
Hedera helix	*English ivy*	*Established*	25	24
Euonymus alatus	*burning bush*	*Established*	25	24
Saxifraga tridactylites	*nailwort*	*NA*	25	24
Lonicera maackii	*amur honeysuckle*	*Established*	25	22
Euonymus hederaceus	*winter-creeper*	*Established*	25	10
Bromus inermis	*smooth brome*	*Established*	24	
Fallopia japonica	*Japanese-knotweed*	*Established*	24	
Myriophyllum aquaticum	***parrot feather watermilfoil***	*Established*	**24**	
Alternanthera philoxeroides	***alligator-weed***	***Established***	**21**	
Arundo donax	*giant reed*	*Emerging*	21	
Murdannia keisak	***wart-removing-herb***	*Established*	**21**	
Pueraria montana	*kudzu*	*Established*	8	20
Lythrum salicaria	*purple loosestrife*	*Emerging*	17	
Miscanthus sinensis	*Chinese silver grass*	*Established*	17	
Mahonia bealei	*beale's barberry*	*Emerging*	17	17
Pyrus calleryana	*bradford pear*	*Established*	17	16
Clematis terniflora	*sweet autumn virgin's-bower*	*Established*	17	10
Dioscorea polystachya	*Chinese yam*	*Established*	14	
Myriophyllum spicatum	***Eurasian water-milfoil***	*Established*	**14**	
Phragmites australis	***common reed***	*Established*	**14**	
Wisteria floribunda	*Japanese wisteria*	*Established*	14	
Buddleja davidii	*common butterfly bush*	*Emerging*	10	
Centaurea stoebe	*spotted knapweed*	*Established*	10	
Humulus japonicus	*Japanese hop*	*Emerging*	10	
Phyllostachys aurea	*golden bamboo*	*Emerging*	10	
Rubus phoenicolasius	*wine raspberry*	*Emerging*	10	
Tussilago farfara	*colt's-foot*	*Established*	7	
Ampelopsis brevipedunculata	*porcelainberry*	*Emerging*	3	

Nashville Basin Province

There are 46 species that are considered threats to the Nashville Basin province. This province has 19 species that are considered Severe Threats. Water thyme was predicted to have the highest percentage of suitable habitat in this province (90%), followed by mimosa (71%), and Chinese bush-clover (68%). In addition to having the largest percentage of predicted suitable habitat in this province, water thyme was also documented in 100% of the counties. Three watchlist species, creeping liriope (*Liriope spicata)*, Chinese parasol-tree (*Firmiana simplex*), and Japanese climbing fern (*Lygodium japonicaum*) were documented in the Nashville Basin. Table 4.9 presents a list of all species and their corresponding rank for the Nashville Basin Province; cells highlighted in red are Severe Threats (present in >50% of counties or >50% of the province predicted to contain suitable habitat), cells in green are Moderate Threats (present in 20-40% of counties or 20-40% of the province predicted to contain suitable habitat), and cells in yellow are Low Threats (present in < 20% of counties or <20% of the province predicted to contain suitable habitat). Aquatic species names are shown in purple text and wetland species names in orange text.

Table 4.9 Ranking of Invasive Plant Species in the Nashville Basin Province

Nashville Basin				
Species	**Common Name**	**TN-IPC Ranking**	**Percentage of Counties**	**SDM Percentage of Total Suitable Habitat**
Hydrilla verticillata	***water thyme***	*Established*	**100**	**90**
Albizia julibrissin	*mimosa*	*Established*	89	71
Alliaria petiolata	*garlic mustard*	*Established*	89	56
Ailanthus altissima	*tree-of-heaven*	*Established*	89	42
Lonicera maackii	*amur honeysuckle*	*Established*	89	39
Lespedeza cuneata	*Chinese bush-clover*	*Established*	78	68
Sorghum halepense	*Johnson grass*	*Established*	78	59

Paulownia tomentosa	*Princess tree*	*Established*	78	
Lonicera japonica	*Japanese honeysuckle*	*Established*	67	67
Ligustrum sinense	*Chinese privet*	*Established*	67	56
Rosa multiflora	*multiflora rose*	*Established*	67	50
Pyrus calleryana	*bradford pear*	*Established*	67	41
Bromus inermis	*smooth brome*	*Established*	67	
Perilla frutescens	*beefsteakplant*	*Established*	67	
Vinca minor	*lesser periwinkle*	*Established*	56	30
Elaeagnus umbellata	*autumn olive*	*Established*	56	24
Euonymus hederaceus	*winter-creeper*	*Established*	56	15
Nandina domestica	*sacred bamboo*	*Emerging*	56	14
Microstegium vimineum	*Japanese stilt grass*	*Established*	56	
Arthraxon hispidus	*small carp grass*	*Established*	22	52
Clematis terniflora	*sweet autumn's virgin bower*	*Established*	44	38
Hedera helix	*English ivy*	*Established*	44	25
Euonymus alatus	*burning bush*	*Established*	44	24
Fallopia japonica	*Japanese-knotweed*	*Established*	44	
Lespedeza bicolor	*two-color bush-clover*	*Established*	44	
Clematis terniflora	*sweet autumn's virgin bower*	*Established*	44	38
Hedera helix	*English ivy*	*Established*	44	25
Wisteria sinensis	*Chinese wisteria*	*Established*	44	
Saxifraga tridactylites	*nailwort*	*NA*	33	37
Puearia montana	*kudzu*	*Established*	33	25
Celastrus orbiculatus	*Asian bittersweet*	*Established*	33	11
Wisteria floribunda	*Japanese wisteria*	*Established*	33	
Spiraea japonica	*Japanese meadowsweet*	*Established*	22	16
Mahonia bealei	*beale's barberry*	*Emerging*	22	13
Alternanthera philoxeroides	*alligaotr-weed*	*Established*	22	
Arundo donax	*giant reed*	*Emerging*	22	
Buddleja davidii	*common butterfly bush*	*Emerging*	22	
Melia azedarach	*China-berry*	*Emerging*	22	
Dioscorea polystachya	*Chinese yam*	*Established*	11	
Humulus japonicus	*Japanese hop*	*Emerging*	11	
Myriophyllum aquaticum	***parrot feather watermilfoil***	*Established*	**11**	
Tussilago farfara	*colt's-foot*	*Established*	11	

Coastal/Mississippi Alluvial Plain Province

There are 40 threats that are considered threats to the Coastal/Mississippi Alluvial Plain province. This province contains the lowest number of Severe Threats (4). This could be a result of collection bias that tends to favor certain locations over others (Garcillán and Ezcurra 2011). Tree-of-heaven was predicted to have the largest percentage of suitable habitat in the province (46%) followed by nailwort (*Saxifraga tridactylites*) and multiflora rose (*Rosa multiflora*). Five watchlist species, Chinese parasol-tree (*Firmiana simplex*), creeping liriope (*Liriope spicata*), Japanese climbing fern (*Lygodium japonicum*), water chestnut (*Trapa natans*), and Chinese tallow (*Triadica sebifera*) were documented in the Nashville Basin. Table 4.10 presents a list of all species and their corresponding rank for the Blue Ridge Province; Cells highlighted in red are Severe Threats (present in >50% of counties or >50% of the province predicted to contain suitable habitat), cells in green are Moderate Threats (present in 20-40% of counties or 20-40% of the province predicted to contain suitable habitat), and cells in yellow are Low Threats (present in < 20% of counties or <20% of the province predicted to contain suitable habitat). Aquatic species names are shown in purple text and wetland species names in orange text.

Table 4.10 Ranking of Invasive Plant Species in the Coastal/Mississippi Alluvial Plain Province

Coastal/Mississippi Alluvial Plain				
Species	**Common Name**	**TN-IPC Ranking**	**Percentage of Counties**	**Percentage Suitable Habitat**
Lonicera japonica	*Japanese honeysuckle*	*Established*	67	27
Sorghum halepense	*Johnson grass*	*Established*	52	22
Albizia julibrissin	*mimosa*	*Established*	50	27
Rosa multiflora	*multiflora rose*	*Established*	48	31
Perilla frutescens	*beefsteakplant*	*Established*	48	
Paulownia tomentosa	*princess tree*	*Established*	36	
Lespedeza cuneata	*Chinese bush-clover*	*Established*	32	21
Microstegium vimineum	*Japanese stilt grass*	*Established*	32	
Lespedeza bicolor	*two-color bush-clover*	*Established*	27	

Ligustrum sinense	*Chinese privet*	*Established*	24	34
Vinca minor	*lesser periwinkle*	*Established*	24	25
Myriophyllum aquaticum	***parrot feahter watermilfoil***	***Established***	**23**	
Pueraria montana	*kudzu*	*Established*	18	25
Elaeagnus umbellata	*autumn olive*	*Established*	18	3
Nandina domestica	*sacred bamboo*	*Emerging*	14	19
Pyrus calleryana	*bradford pear*	*Established*	14	10
Saxifraga tridactylites	*nailwort*	*NA*	0	38
Euonymus hederaceus	*winter-creeper*	*Established*	0	24
Hedera helix	*English ivy*	*Established*	9	28
Euonymus alatus	*burning bush*	*Established*	9	21
Ailanthus altissima	*tree-of-heaven*	*Established*	5	46
Hydrilla verticillata	***water thyme***	***Established***	**5**	**28**
Mahonia bealei	*beale's barberry*	*Emerging*	5	13
Arthraxon hispidus	*small carp grass*	*Established*	5	13
Alliaria petiolata	*garlic mustard*	*Established*	5	12
Celastrus orbiculatus	*asian bittersweet*	*Established*	5	5
Lonicera maackii	*amur honeysuckle*	*Established*	9	18
Melia azedarach	*China-berry*	*Emerging*	14	
Alternanthera philoxeroides	***alligator-weed***	***Established***	**9**	
Bromus inermis	*smooth brome*	*Established*	9	
Fallopia japonica	*Japanese-knotweed*	*Established*	9	
Humulus japonicus	*Japanese hop*	*Emerging*	9	
Phragmites australis	***common reed***	***Established***	**9**	
Wisteria floribunda	*Japanese wisteria*	*Established*	9	
Clematis terniflora	*sweet autumn's virgin bower*	*Established*	5	4
Buddleja davidii	*common butterfly bush*	*Emerging*	5	
Dioscorea polystachya	*Chinese yam*	*Established*	5	
Miscanthus sinensis	*Chinese silver grass*	*Emerging*	5	
Murdannia keisak	***wart-removing-herb***	***Emerging***	**5**	
Myriophyllum spicatum	***Eurasian water-milfoil***	***Established***	**5**	
Rhamnus cathartica	*buckthorn*	*Established*	5	

Conclusions

The increasing availability of observational data and analytical tools has made studies like this possible. Even at coarse, county-level resolutions, access to large amounts of vouchered natural history data increase our understanding and knowledge of species distribution. Additionally, an increase in computational programs and modeling algorithms provide researchers the opportunity to fill the gaps left by county-level data and increase our understanding of species distributions. This study is the first in Tennessee to take advantage of these technological advancements and compile county-level data along with SDMs to create a more informed ranking system for invasive plant species in Tennessee. Three significant issues with TN-IPC's ranking system are addressed in this proposed system: the low number of categories, the low threshold separating species of different threats, and ranking species based only on political boundaries.

One major issue in TN-IPC's ranking system is the low number of categories which forces species like Chinese silver grass and Japanese honeysuckle to be considered the same level of threat to Tennessee. A system like the one outlined here addresses this issue by increasing the number of ranking categories from two to four. Instead of Chinese silver grass and Japanese honeysuckle being forced into the same Category, the new system considers Japanese honeysuckle a Severe Threat to all six provinces, and it considers Chinese silver grass a Low Threat to the Cumberland Plateau, Interior Low Plateau, and Coastal/Mississippi Alluvial Plain and a Severe Threat to the Blue Ridge and Ridge and Valley.

The second major issue with TN-IPC's ranking system that was addressed by this study was the reliance on political boundaries rather than evaluating species using ecological boundaries that determine species distributions. Therefore, species that may be prevalent in one part of the state may not have the ability to thrive in other areas of the state. For example, Japanese meadowsweet is predicted and documented in only eastern provinces of the state; therefore land managers in the west do not have to consider this species a threat to the area they are trying to manage. The ranking system outlined here address this issue by ranking species within each province. For instance, instead of being considered a statewide threat, this ranking system considers Japanese meadowsweet a Severe Threat to all provinces except for the Coastal/Mississippi Alluvial Plain where it is considered a Low Threat by both SDM data and county-level data. This proposed system allows land managers in the Coastal/Mississippi Alluvial Plain to allocate time and attention to higher-level threats to their province.

Several species considered Emerging Threats by TN-IPC are reevaluated in this proposed ranking system. Giant reed (*Arundo donax*) was previously considered an Emerging Threat by TN-IPC. County-level data reported this species in over ten counties, therefore it surpasses the requirements for this rank, and its threat to the state is underestimated. The proposed system considers giant reed a Moderate Threat to the Blue Ridge, Cumberland Plateau, Interior Low Plateau, and Nashville Basin. Additionally, sacred bamboo and Beale's barberry are considered Emerging Threats by the TN-IPC. In contrast, the proposed ranking system considers sacred bamboo a Severe Threat to the Nashville Basin, Interior Low Plateau, and Cumberland Plateau and considers Beale’s barbaerry a Moderate Threat to the Blue Ridge, Cumberland Plateau, and Nashville Basin.

The thought experiment presented brings to light inconsistencies when relying on only two categories and political boundaries to rank invasive plant species. When considering the threat a species can present to the state, it is more efficient to consider species within their ecological boundaries rather than their statewide distributions. Additionally, a two-category ranking system tends to overestimate or underestimate the threats a species can present to the area. Although more work is necessary to incorporate data from new sources (EDDMapS) and to model additional species, this study suggests a new way of prioritizing invasive plant species in Tennessee so future conservation workers can continue to improve management methods in the state.

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VITA

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