Habitat Likelihood for Wavyleaf Basketgrass (*Oplismenus hirtellus* ssp. *undulatifolius*) in the Kanawha-New River Basin

By

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Submitted in fulfillment of the senior thesis requirements of the Department of Environmental Science and Sustainability at Allegheny College and approved by the senior thesis committee.

Christopher L. Shaffer	**Date**	**Dr. Jesse Swann-Quinn**	**Date**
5/4/21		5/4/21	

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-Jakob

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Title: Habitat Likelihood for Wavyleaf Basketgrass (*Oplismenus hirtellus* ssp. *undulatifolius*) in the Kanawha-New River Basin

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Abstract

Wavyleaf basketgrass (*Oplismenus hirtellus* ssp. *undulatifolius*) is an invasive grass that was unintentionally introduced to the Mid-Atlantic United States from Eurasia in 1996. The plant is able to thrive in suboptimal habitat and can spread quickly to new habitat via sticky seeds and epizoochory dispersal. Wavyleaf basketgrass has since decimated ecosystems across the east coast by forming dense mats that outcompete native shrubs and seedlings. Conservation organizations at multiple levels of governance are dedicated toward early detection and eradication of the grass as it spreads further from its original habitat. Mapping of current and predicted habitat is ongoing and serves as a critical tool in this effort. This study used GIS-based multi-attribute decision making and fuzzy logic to determine habitat likelihood for wavyleaf basketgrass in the Kanawha-New River basin of West Virginia, Virginia, and North Carolina. Results show that the region is moderately susceptible to the grass, but should be interpreted with caution as variables were adjusted to match findings of previous literature. Areas showing highest likelihood for wavyleaf basketgrass include the Charleston, WV Metropolitan Area; New River Gorge National Park, WV; and Elk Knob State Park, NC. These sites are suggested for immediate surveying of wavyleaf basketgrass with any necessary eradication measures taken. This study complements ongoing mapping efforts and provides insight into the likelihood of wavyleaf basketgrass invasion in a location where the grass is not yet found for land managers to become proactively educated and prepared.

INTRODUCTION

Invasive species

Invasive species are those that have traveled outside of their native range and proliferated and persisted in introduced habitat, often causing significant disruption (Mack et al., 2000). Alternatively called non-native, nonindigenous, alien, or exotic species (Davis & Thompson, 2000), invasive species were first mentioned in the writings of pioneering nineteenth century naturalists (Richardson & Pyšek, 2007). Initially seen as mere curiosities in biogeography, invasion biology became a devoted area of study in the mid-twentieth century (Richardson & Pyšek, 2007). The field has since blossomed into an area of concentration that comprises elements of geography, epidemiology, conservation biology, human history, and population ecology that sees well over a thousand scientific publications per year (Richardson & Pyšek, 2007; Davis, 2009).

Introduction of invasive species to novel habitat can be a natural or human process (Mack et al., 2000). Migration, for example, is one such natural phenomenon that drives invasive spread (Rafferty, 2019). Human introduction of invasives, whether intentional or unintentional, has drastically increased in the past centuries due to international trade and commerce (Mack et al., 2000; Williams, 1998). The growth of trade routes between previously disconnected countries and modernized transportation have greatly contributed to the heightened magnitude and frequency of invasions (Crowl et al., 2008). Reduced travel time due to modern transportation has also enabled invasives to proliferate, as more species are able to survive long distances (Williams, 1998). The shipping industry has been a leading contributor of invasive introduction, as invertebrates, fish, and plants are transported as fouling organisms on ship hulls or in ballast water (Brancato & MacLellan, 1999).

Successful invasive species typically have characteristic traits that enable them to outcompete native species. These general characteristics include high rates of reproduction, broad native range, phenotypic plasticity, high tolerance to a variety of conditions, broad diets, commensalism with humans, high body mass, etc. (Kolar & Lodge, 2001; Williams, 1998). These traits vary based on taxonomy; for example, successful invasive weeds are adaptable, able to grow in a variety of conditions, produce many seeds, reproduce vegetatively, and grow quickly (Baker, 1965). Multiple hypotheses have been put forth in an attempt to explain how invasive species become established in novel habitat. The empty niche hypothesis suggests that alien species utilize resources that are unused by locals (Elton, 1958; Hierro et al., 2005). Another hypothesis explains that rapid genetic changes enable invasives to be successful in new habitats (Brommer et al., 2005; Hierro et al., 2005). Others suggest that species-poor communities

are more prone to invasion or that invasives utilize biochemical weapons, such as the phytotoxin catechin, against native species (Bais et al., 2003; Elton, 1958; Hierro et al., 2005).

Invasives pose severe ecological threats to their introduced habitat. Nearly half of worldwide vertebrate extinctions have been caused by invasives (Williams, 1998). Behind human population growth, invasives are the second leading cause of extinction and endangerment in the U.S. (Crowl et al., 2008). Besides outright extinction, invasives lower the abundance of native species, change ecosystem structure and function, and rearrange trophic relations (Williams, 1998). In addition to the significant ecological implications posed to introduced habitat, invasives create severe economic burdens as well (Crowl et al., 2008). In the U.S., invasive species are estimated to cause $120 billion in environmental damages per year; invasive plants alone cause roughly $35 billion (Pimentel et al., 2005). Societal costs are likely much higher, as data on damages and control costs is lacking (Jardine & Sanchirico, 2018). One study found that the cost of removing invasive cordgrass (*Spartina*) in the San Francisco Bay Area was roughly $300 per acre (Jardine & Sanchirico, 2018).

Invasive grasses in particular have caused widespread global damage. Japanese stiltgrass was first introduced to Tennessee in 1919 and has since spread across the eastern half of the country (Adams & Engelhardt, 2009; Barden, 1987; Brewer, 2011; EDDMapS, 2020). Land managers are concerned about the potential long-term biodiversity consequences caused by the grass (Adams & Engelhardt, 2009). Other notable invasive grasses include jaragua (*Hypparhenia rufa*) and molasses grass (*Melinis minutiflora*) in South America, which have displaced native pasture grasses (D'Antonio & Vitousek, 1992), and Columbian bluestem (*Schizachyrium condensatum*) in Hawaii, which increases fire risk due to its high and continuous production of biomass (D'Antonio et al., 1998).

Wavyleaf Basketgrass

The rapid spread of the invasive species wavyleaf basketgrass (*Oplismenus hirtellus* ssp. *undulatifolius*) in the Mid-Atlantic U.S. has been highly concerning for the scientific community (Westbrooks & Imlay, 2009). The origin of the species is unclear, but it was likely unintentionally transported from Eurasia as a contaminant of hanging baskets (Westbrooks & Imlay, 2009). Wavyleaf basketgrass, or WLBG, was first discovered in 1996 in Howard County, Maryland and has since spread to Virginia, West Virginia, and Pennsylvania (EDDMapS, 2020; Westbrooks & Imlay, 2009). As of 2021, there are 877 confirmed sightings of WLBG across thousands of acres in these four states (Bell, 2014; EDDMapS, 2020). WLBG is currently present in 14 counties in Virginia, 15 in Maryland, 1 in

Pennsylvania, 1 in West Virginia, and in the District of Columbia (EDDMapS, 2021). For context, only 7 Virginia counties had WLBG in 2013 (Beauchamp et al., 2013).

WLBG has been labeled a high-risk invasive species by the U.S. Department of Agriculture (USDA) Animal and Plant Health Inspection Service (DCR, 2019). Once established, the grass forms dense mats that inhibit the growth of native shrubs and tree seedlings (DCR, 2019; USDA, 2012). Although a weak competitor, WLBG is able to thrive in suboptimal habitats (Kepner & Beauchamp, 2020). The species can survive at a range of soil pH levels and prefers shade (Moore, 2011). This enables WLBG to possibly occupy the empty niches that define the East coast, such as post-agricultural land or forested areas heavily browsed by deer (Moore, 2011). WLBG may also use a "sit and wait" strategy of distribution in which seeds survive in species-rich conditions and then proliferate once a disturbance wipes out native populations (Kepner & Beauchamp, 2020).

The grass is notable for its sticky seeds that aid it in rapid epizoochory seed dispersal. The seeds adhere to clothing, skin, hair, or fur, enabling it to spread to other habitats via human and non-human vectors (Beauchamp et al., 2013). Other characteristics aiding WLBG in its rapid proliferation are self-reproduction and a short generation time (USDA, 2012).

WLBG has deep green rippled leaves that are 0.5 inches wide and 1.5-4 inches long (Swearingen et al., 2014). Short hairs are present along the leaf stem and sheath, and flowers with sticky awns alternate along the plant stalk and bloom in late September to October (Swearingen et al., 2014). WLBG has relatives that are native to the southeastern U.S. (*Oplismenus hirtellus* ssp. *fasciculatus* and *Oplismenus hirtellus* ssp. *setarius*), but neither are found in the Mid-Atlantic (Swearingen et al., 2014). Deer-tongue panicgrass (*Dichanthelium clandestinum*), a species native to the eastern U.S., and small carpetgrass (*Arthraxon hispidus*), an invasive species found in the eastern U.S., look similar to WLBG but lack wavy ripples on their leaves and grow in upright clumps (Imlay & Kyde, 2017; Swearingen et al., 2014). The tendency of WLBG to lay flat on the ground helps to distinguish it from these other similar species (Gundlach & Robinson, 2009).



Figure 1: Left: Japanese stiltgrass, center: wavyleaf basketgrass, right: small carpetgrass. From Imlay & Kyde (2017).

Current preventative efforts are underway but limited. Leading the charge is the Wavyleaf Basketgrass Task Force, a multi-level governmental group composed of the Maryland Department of Natural Resources, Anacostia Watershed Society, National Park Service, USDA, U.S. Geological Survey, and other environmental agencies. WLBG is most often removed by the task force and others through hand-pulling or herbicides (DCR, 2019; Swearingen et al., 2014; USDA, 2012). Clethodim, marketed as Envoy, is a grass-selective herbicide that is most effective when applied early in the season before bloom ("Global Invasive Species Database Species profile: Oplismenus undulatifolius", 2015). Glyphosate (Roundup) has been used later in the growing season for areas fully infested with WLBG ("Global Invasive Species Database Species profile: Oplismenus undulatifolius", 2015; USDA, 2012). Herbicide application excessively late in the growing season is not advised, as WLBG seeds could be easily spread by the personnel working on site (MIPFG, 2019). Two herbicide treatments during the same growing season are recommended and several years of control are required to fully eliminate the seed bank (DCR, 2019). Biocontrol options are not effective for WLBG, as low herbivory rates demonstrate that efforts to apply insects to manage populations fail (Heiselmeyer et al., 2019).

Mapping of both current WLBG populations and potential future habitat is ongoing and serves as a critical tool for removal efforts ("Global Invasive Species Database Species profile: Oplismenus undulatifolius", 2015). Suitability maps for the species exist and have contributed to the growing knowledge of WLBG habitat potential. The USDA (2012) has predicted that roughly 30% of the U.S. is habitable for WLBG, but only considered plant hardiness zones, precipitation levels, and climate types in the analysis. Moore (2011) provided a robust analysis of WLBG suitability in a portion of the Chesapeake

Bay watershed (Maryland, Delaware, north-central Virginia, and eastern West Virginia) and found highest likelihood in central Virginia and Maryland. WLBG has spread well beyond its original habitat in the Baltimore-Washington D.C. area, so examining an area outside of its introduced region will best guide future removal efforts (EDDMapS, 2020). Bowen & Stevens (2020) examined WLBG habitat likelihood using ecological niche modeling at a landscape scale (Shenandoah National Park, VA) and a regional scale (Mid-Atlantic states); the southern portions of West Virginia and Virginia showed high potential for WLBG. Examining a smaller study region in this area will be beneficial for land managers as more exact areas of susceptibility will be determined. This study expanded upon past studies and streamlined future removal efforts by modeling areas of potential for WLBG with higher precision in the Kanawha-New River basin of West Virginia, Virginia, and North Carolina.

Why GIS?

Geographic information systems (GIS) and multi-attribute decision making (MADM) were used to locate potential future habitat for WLBG. GIS leverages computer technology to gather, manage, and analyze data, enabling users to make smarter decisions ("What is GIS?", n.d.). Disparate spatial data are manipulated through multiple processes and then combined using map overlay to produce digital maps. These digital maps are used to help stakeholders identify problems, set priorities, and perform forecasting ("What is GIS?", n.d.). MADM is one approach within multi-criteria decision analysis along with multi-objective decision making (MODM). MODM is more applicable for problems containing numerous objectives, when a theoretically infinite number of alternatives are possible (Mendoza & Martins, 2006). Alternatively, decision makers use MADM to guide their problem solving by selecting discrete alternatives (Mendoza & Martins, 2006). Therefore, MADM was used in this study to locate finite areas of likelihood for WLBG rather than an infinite number of areas.

Project Statement

This study uses GIS and MADM to show habitat likelihood for WLBG in the Kanawha-New River basin. The final result of this project is a map of the Kanawha-New River basin that answers the question: *Where is WLBG most likely to occur in the Kanawha-New River basin as it spreads south and west?* This product can be used by environmental agencies at multiple levels of governance in preparation for imminent WLBG invasion. In areas of highest risk, public outreach efforts can be put in place and future damage to intact ecosystems can be calculated. In addition, this map will guide eradication efforts by prioritizing areas to target for WLBG. Early detection and removal of the grass is critical to halt the spread into larger regions.

METHODS

Study Region

The Kanawha-New River drainage basin is 31,658 km^2 (12,223 mi^2) in size and encompasses portions of central West Virginia, southwestern Virginia, and northwestern North Carolina (Paybins et al., 2000). The basin is formed by the Kanawha River and its tributary, the New River. Two forks of the New River, the North and South Fork, converge near the Virginia-North Carolina state boundary. The Kanawha-New River basin comprises three physiographic provinces: the Appalachian Plateau (60%), the Valley and Ridge (23%), and the Blue Ridge (17%) (Paybins et al., 2000). The basin is mountainous, with a maximum elevation of 1,500 m (4,900 ft) in the Appalachian Plateau (Paybins et al., 2000). The mouth of the Kanawha River is the lowest elevation within the basin at 170 m (560 ft) (Paybins et al., 2000). The Kanawha-New River basin is predominantly rural; only 30% of the population lives in towns larger than 10,000, with 25% living in the Charleston, WV area alone (Paybins et al., 2000). The drainage basin is 76.3% forested land, 12% hay/pasture, 6.5% developed land, 2.1% herbaceous land, 1.4% shrubland, 0.6% barren land, 0.6% open water, 0.3% cultivated crops, and 0.2% wetlands (U.S. Geological Survey, 2019).



Figure 2: Study region map depicting the location and extent of the Kanawha-New River basin.

Data Sources

Spatial data was collected from the U.S. Geological Survey (USGS), the Parameter-elevation Regressions on Independent Slopes Model (PRISM), and WorldClim (Table 1). All spatial analysis was conducted in ArcGIS Pro 2.6.2 (ESRI, 2020). Input criteria were cropped to the extent of the study region, resampled to a 500 x 500m pixel size, and projected to the North American Datum of 1983 (NAD83) Universal Transverse Mercator Zone 17N projection. Meters were used as the linear unit of measurement. Euclidean distance was calculated for each proximity criteria and slope was derived from elevation data.

Time-Integrated NDVI (TIN) datasets were averaged from 2001-2018, the available range of published data.

Table 1: Input criteria and constraint variable used in the analysis.

Input Criteria	Dataset name	Source	Published
Annual Mean Temperature[1]	PRISM 30 year normals	PRISM	2012
Annual Precipitation[2]	PRISM 30 year normals	PRISM	2012
Diurnal Range[3]	Bioclim Variables (30s)	WorldClim	2019
Land Cover[4]	NLCD 2016 Land Cover (CONUS)	USGS	2019
Roads[5, 6, 7]	National Transportation Dataset (NTD)	USGS	2020
Slope[8]	1 Arc-second Digital Elevation Models (DEMs)	USGS	2017
Streams[9]	National Hydrography Dataset Best Resolution (NHD) for Hydrologic Unit (HU) 4 - 0505	USGS	2020
Temperature Seasonality[3]	Bioclim Variables (30s)	WorldClim	2019
Time-Integrated NDVI[10]	eMODIS Phenology 2001-2018	USGS	2012-2019
Trails[5, 6, 7]	National Transportation Dataset (NTD)	USGS	2020

1) PRISM Climate Group at Oregon State University, 2012a 2) PRISM Climate Group at Oregon State University, 2012b 3) Fick & Hijmans, 2017 4) U.S. Geological Survey, 2019 5) U.S. Geological Survey, 2020a 6) U.S. Geological Survey, 2020b 7) U.S. Geological Survey, 2020c 8) U.S. Geological Survey, 2017 9) U.S. Geological Survey, National Geospatial Program, 2020 10) U.S. Geological Survey, Earth Resources Observation System (EROS), 2012-2019

Input Criteria

MADM requires the determination of input criteria that are comprehensive and exhaustive enough to solve the issue being considered (Malczewski, 2010). Bowen & Stevens (2020) and Beauchamp et al. (2013) were primarily used as sources of information for input criteria in this study. Both studies conducted ecological niche modeling, in which habitat characteristics of locations where WLBG is found are used to determine habitat preferences. These habitat preferences were then applied to broader scales to determine future habitat suitability for WLBG in the Mid-Atlantic. Jackknife testing was utilized in both studies to determine variable importance and detect bias. The two studies found some similar input criteria to be of high importance, but other variables were found to be of importance in one

study but not the other. Due to the currentness and study region used, Bowen & Stevens (2020) determined the input criteria used in this study more so than Beauchamp et al. (2013). All top contributing variables in the regional-scale model produced by Bowen & Stevens (2020) were used in this analysis.

Proximity

Distance from roads, trails, and streams were top contributing variables at a landscape scale (e.g. Shenandoah National Park, VA), but not at a regional-scale (e.g. the entire Mid-Atlantic region) (Bowen & Stevens, 2020). In an effort to increase the knowledge of future WLBG spread and to expand upon past studies, these proximity variables were included in this analysis. Transportation routes have been cited as important mechanisms for invasive species proliferation (Christen & Matlack, 2009; Pauchard & Alaback, 2004). WLBG establishes in disturbed areas and therefore, areas near roads have the highest likelihood of habitation (Bowen & Stevens, 2020). In contrast to road proximity, WLBG was found to have higher likelihood when far from trails (Bowen & Stevens, 2020). This observation supports the argument that WLBG is more frequently found in forest interior, especially when in competition with its competitor Japanese stiltgrass (Beauchamp et al., 2013). Both studies determined that WLBG was more likely to be found when closer to streams. Terrestrial plants prefer the shallow water table depth at these areas (Riis et al., 2001).

Physical

Habitat likelihood was highest at slopes of 2 degrees and decreased as slope increased (Bowen & Stevens, 2020), likely because WLBG prefers level ground to establish its root systems (Beauchamp et al., 2013). In regards to annual mean temperature, habitat likelihood was highest near 12-13°C in Bowen & Stevens (2020) whereas Beauchamp et al. (2013) found 11.7-13.9°C to be the most suitable range for WLBG. Defined as the variation in temperature across the year, temperature seasonality is calculated by the standard deviation of monthly temperature averages (Bowen & Stevens, 2020; O'Donnell & Ignizio, 2012). Low temperature seasonality presents higher habitat likelihood for WLBG (Bowen & Stevens, 2020). Diurnal range is a measure of monthly temperature range, calculated by the following:

$$\sum_{i=1}^{i=12} (Tmax_i - Tmin_i)$$

where T = temperature (Bowen & Stevens, 2020; O'Donnell & Ignizio, 2012). The ideal range for WLBG was determined to be 8.5-10°C (Bowen & Stevens, 2020). Normalized difference vegetation index (NDVI) is a measurement of live green vegetation or photosynthetic activity. Values range from -1.0 (water, clouds, snow) to 1.0 (green vegetation). TIN is an annual measurement of NDVI, showing cumulative NDVI from the beginning to end of the growing season (Bowen & Stevens, 2020). TIN values

greater than 50 were most suitable for WLBG. TIN data were averaged to better predict WLBG invasion in the study region. Although not included as a top predictor variable in the best regional-scale model produced by Bowen & Stevens (2020), annual precipitation was still included in two other top regional-scale models. Beauchamp et al. (2013) found annual precipitation to be a moderately high variable of importance when using jackknife analysis in their habitat suitability study for WLBG in the Mid-Atlantic. The USDA (2012) predicted areas with 76-254 cm. (30-100 in.) of rainfall a year to be most suitable for WLBG. This range of precipitation was found to be completely present within the study region, so areas with the most annual precipitation were given the highest likelihood for WLBG in this study.

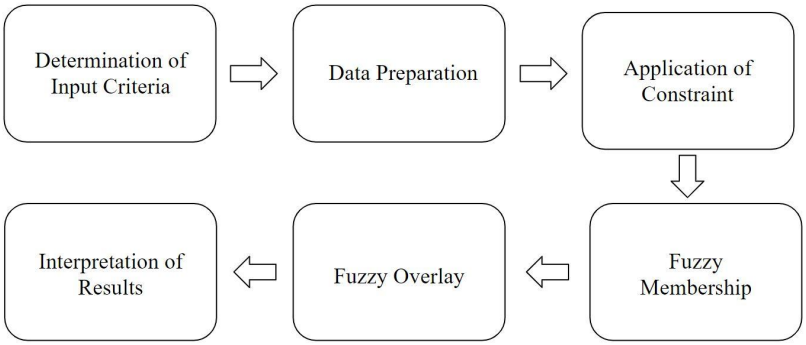


Figure 3**:** Conceptual flowchart depicting the transformation of data into information.

Constraint

MADM analyses often define a set of feasible alternatives by removing constrained areas before conducting spatial overlay (Malczewski, 1999). These areas are inherently unsuitable for the question at hand and are discarded from analysis using Boolean classification. In this study, all constraint areas were assigned null values and feasible alternatives were given a 1 (Figure 4). Other MADM GIS studies choose to assign constraint areas a value of 0; however, this would have proven problematic in the analysis for data in which 0 is a feasible alternative (e.g. 0° slope). The constraint variable was all areas coded as open water or developed (any capacity) in the 2016 National Land Cover Database (U.S. Geological Survey, 2019). Open water is defined as areas of less than 25% vegetation or soil; developed land is defined as a mixture of constructed materials and vegetation (U.S. Geological Survey, 2019). All input criteria were then multiplied by this constraint variable before analysis so that unsuitable area was removed from the input data. Removing restricted area after analysis would erroneously scale habitat likelihood values across the range of all data values rather than just the feasible alternatives. The area deemed unsuitable for WLBG in the Kanawha-New River basin was 1263.15 km^2 (3.99%).

D	F	F
D	D	A
W	A	A

⇨

N	1	1
N	N	1
N	1	1

Figure 4: Reproduction of the process used to redefine raw land cover data into feasible alternatives for WLBG. D = Developed, W = Water, F = Forest, A = Agriculture, N = Null.

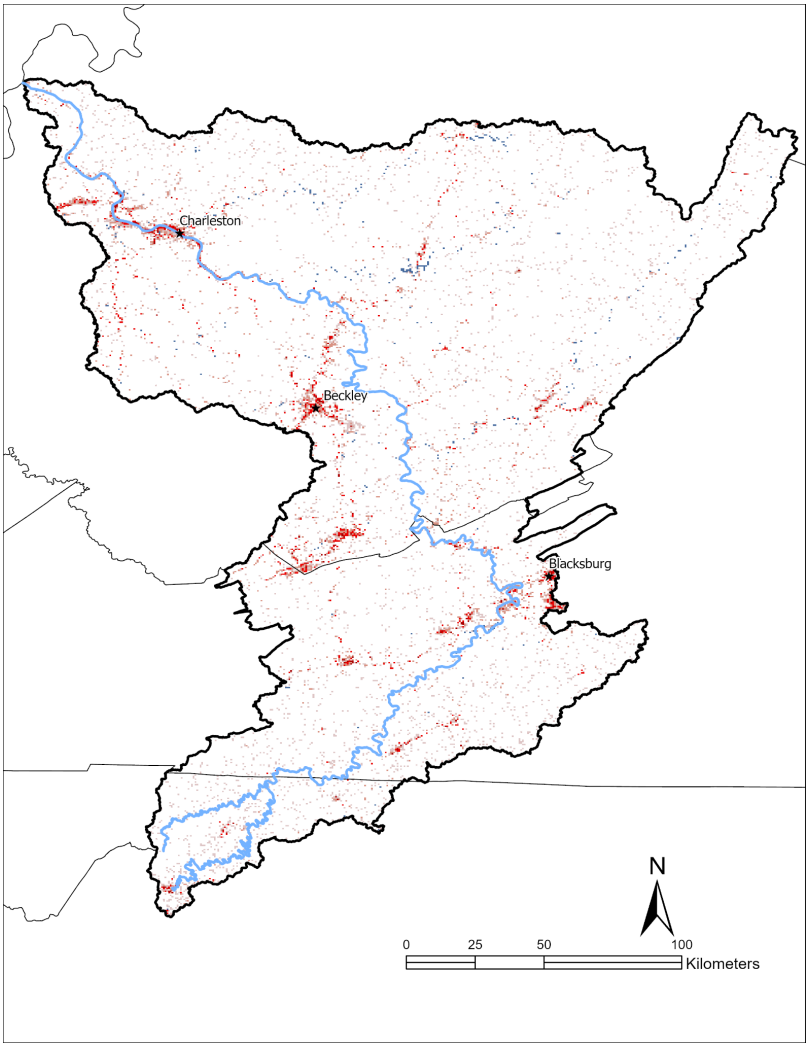


Figure 5: Constraint map used to determine feasible alternatives. Developed areas are shown in red and open water is shown in blue.

Fuzzy Logic

The three most common approaches to MADM are Boolean logic, in which data is either excluded (0) or included (1) from the results, weighted linear combination (WLC) and analytical

hierarchy process (AHP), in which data are assigned ranks and weighted based on importance (Mitchell, 2012), and fuzzy logic. Fuzzy logic was developed by Zadeh (1965) as a way to provide a natural way of dealing with scenarios in which imprecision is due to undefined criteria of membership rather than the presence of random variables. The concept is applicable to a variety of scientific fields in which non-probabilistic uncertainty is rife, including ecology and GIS (Caniani et al., 2016).

Unlike Boolean logic, in which a given value is a member of a set or is not, fuzzy logic calculates the likelihood of a given value having membership in the set (Mitchell, 2012). A continuous scale of 0.0 to 1.0 is utilized to represent this membership, with 1 showing full membership and 0 showing nonmembership (Lewis et al., 2014; Mitchell, 2012). Fuzzy logic avoids issues present within the WLC approach by eliminating “crisp,” or explicitly defined, boundaries between classes ("Applying fuzzy logic to overlay rasters", n.d.). WLC requires the GIS user to convert attribute data into value scores, effectively categorizing data into levels of suitability (e.g. “highly suitable” or “least suitable”) (Kainz, 2007; Malczewski, 2010). The determination of where one class ends and another begins can often be subjective, even with the use of expert opinion and published literature to guide class definitions. Fuzzy logic attempts to replicate the uncertainty of human thought and language by defining continuous possibilities rather than categories of suitability ("Applying fuzzy logic to overlay rasters", n.d.).

Fuzzy logic can be especially useful when working with quantitative data, as the difference between 10°C and 11°C, for example, may not be significant enough to warrant a class break. Fuzzy logic is also highly applicable for data-poor scenarios with ambiguous or undefined class parameters (Dias et al., 2019; Hall & Wang, 1992). The substantial amount of quantitative data used in this study as well as the lack of information on WLBG habitat preferences justified the use of fuzzy logic.

Fuzzy Membership

The first step in the fuzzy logic process is the fuzzy membership or “fuzzification” phase, in which a function is used to place data values on the continuous scale of 0 to 1. Choosing the correct function is based on the general nature of the relationship, such as whether large, small, or moderate values have high fuzzy membership (Mitchell, 2012). Functions used in this analysis included the sigmoidal, reverse sigmoidal, and Gaussian functions. A midpoint (value at which fuzzy membership = 0.5) and spread (steepness of the curve) were also chosen for each of the fuzzified criteria.

Rescaling of Curves

Bowen & Stevens (2020) produced response curves in their analysis of WLBG likelihood in the Mid-Atlantic. These curves were integral for the determination of functions, midpoints, and spreads used in this study. In some instances, Bowen & Stevens (2020) found WLBG habitat likelihood for a given input criteria to be less than 1.0. In other words, none of the values for the given input criteria had a 100% chance of being suitable for WLBG ("Fuzzy Membership [Spatial Analyst]", n.d.). For these input criteria, the final fuzzy membership curve was multiplied by the maximum membership value found by Bowen & Stevens (2020). For example, annual mean temperature was found to have 0.7 as the maximum membership value; therefore, the fuzzy membership curve was multiplied by 0.7 to rescale the function (Figure 6) .

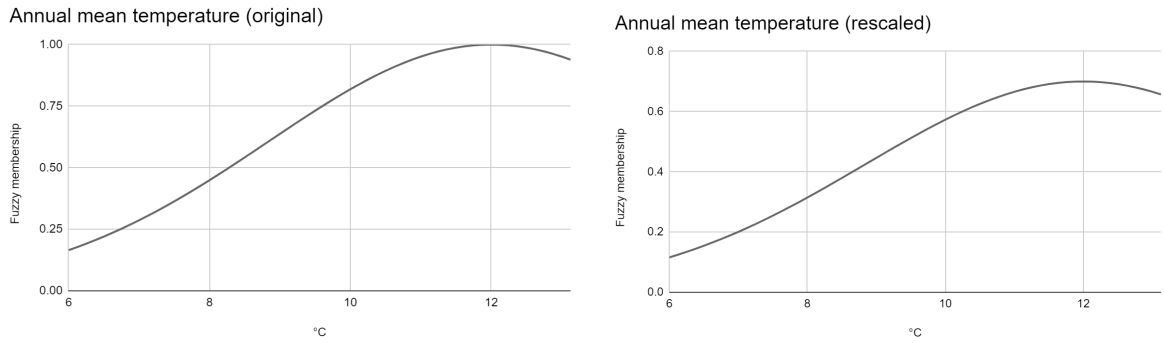


Figure 6: Original and rescaled fuzzy membership curves for annual mean temperature input criteria.

Midpoint Conversions

When rescaling the appropriate fuzzified input criteria, the original midpoints were altered. Thus, the midpoints for these criteria had to be converted to represent the chosen midpoint after the rescaling process. This conversion can be represented by the following equation:

$$\textit{Rescale factor}(x) = \textit{Old midpoint}$$

where x = the converted midpoint.

For example, Bowen & Stevens (2020) found the response curve midpoint for distance to roads to be 800 m. Since the fuzzified distance to roads input criteria was rescaled by 0.48 to reflect the relationship found by Bowen & Stevens (2020), the converted midpoint was determined to be 1666.66666667:

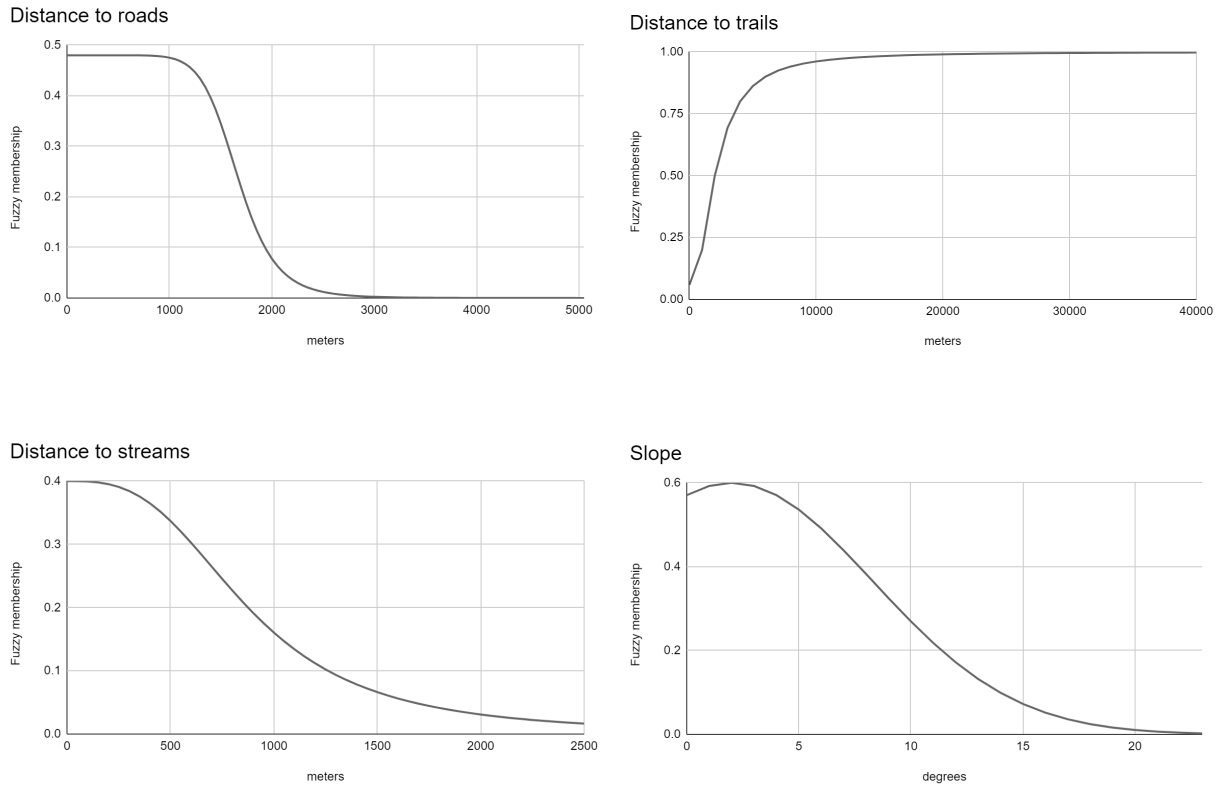
$$0.48x = 800$$

$$x = 800/0.48$$

$$x = 1666.66666667$$

This process was repeated for all fuzzified criteria that were rescaled: distance to roads, distance to streams, and TIN. Gaussian functions were not subject to this conversion process. The midpoints of these functions were not altered after rescaling since the midpoint is also the value showing maximum fuzzy membership.

The final fuzzy membership curves produced in the analysis are shown below (Figure 7):



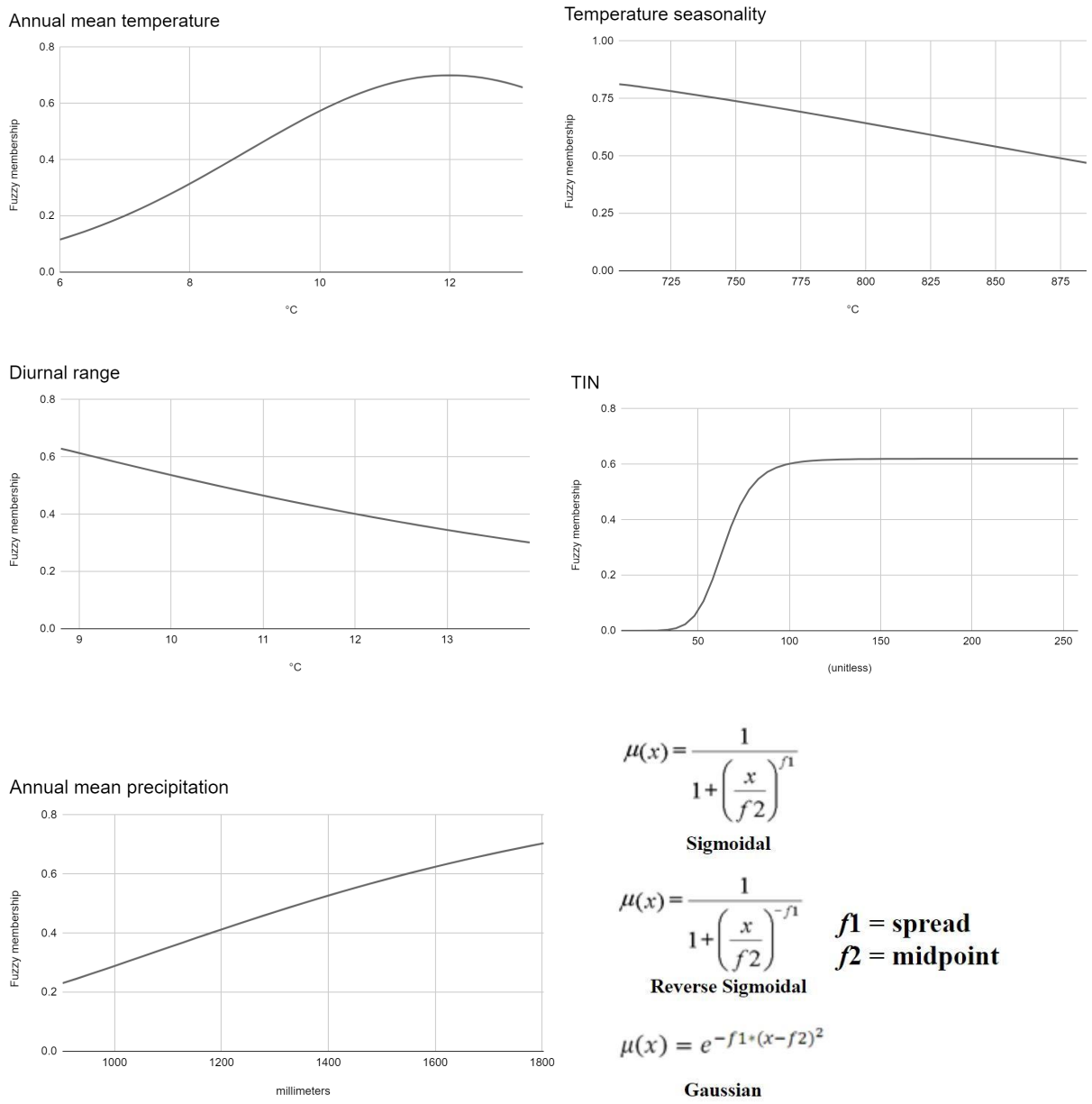


Figure 7: Fuzzy membership curves for each input criteria. Appropriate equations are supplied (“FuzzyGaussian”, n.d.; “FuzzyLarge”, n.d.; “FuzzySmall”, n.d.).

Table 2: Input criteria with function types, spread and midpoint values, and rescale factors used.

Input Criteria	Function	Spread	Midpoint	Rescale Factor
Distance to Roads (m)	Reverse Sigmoidal	9	1666.66666667	0.48
Distance to Trails (m)	Sigmoidal	2	2000	N/A
Distance to Streams (m)	Reverse Sigmoidal	3	875	0.4
Slope (°)	Gaussian	0.0125	2	0.6
Annual Mean Temperature (°C)	Gaussian	0.05	12	0.7
Temperature Seasonality (°C)	Reverse Sigmoidal	7	870	N/A
Diurnal Range (°C)	Reverse Sigmoidal	3	10.5	N/A
TIN (unitless)	Sigmoidal	8	64.5161290323	0.62
Annual Mean Precipitation (mm)	Sigmoidal	3	1350.3699951171875	N/A

The resulting fuzzy membership maps are shown below (Figure 8):

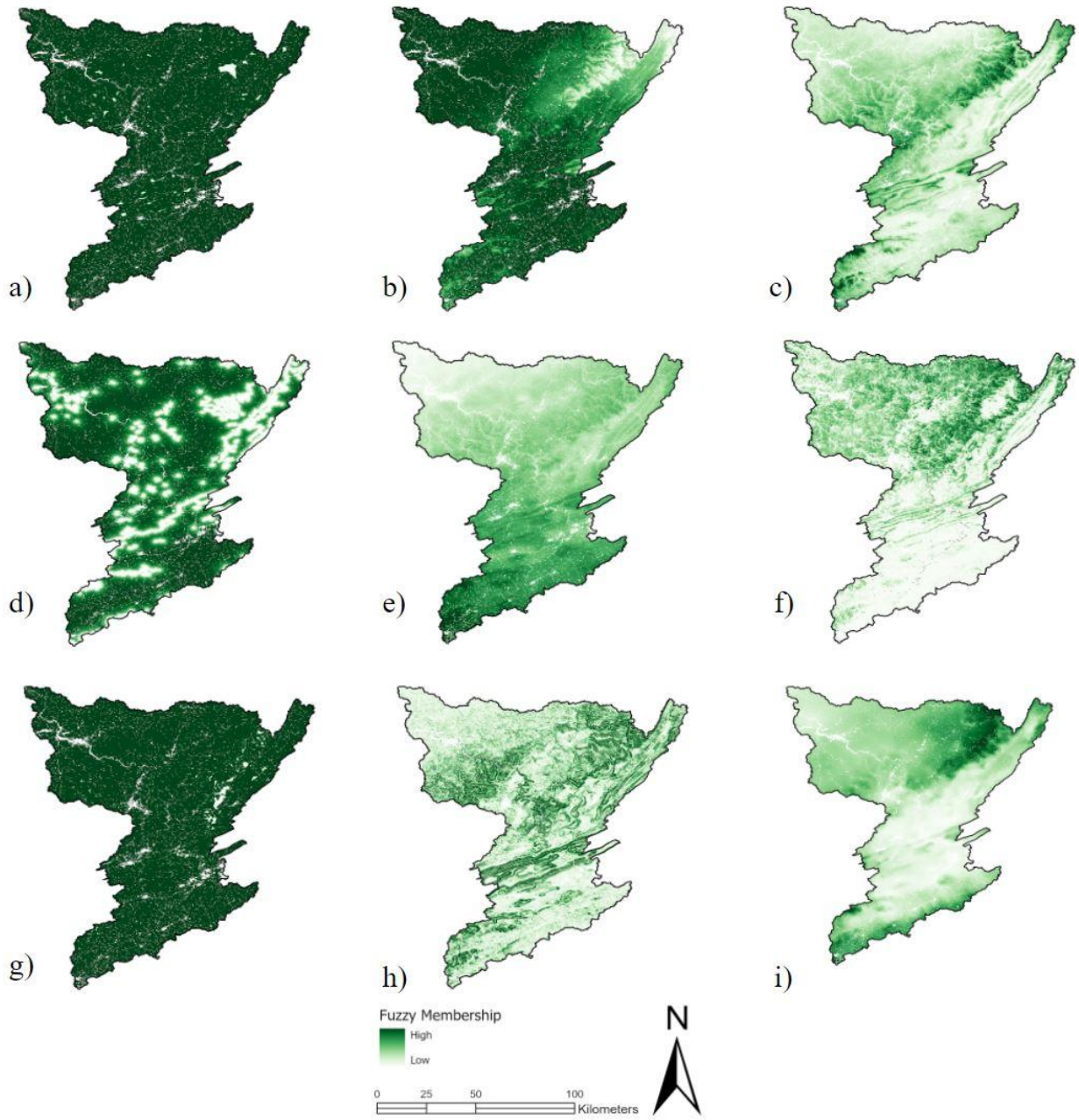


Figure 8: Fuzzified input criteria used in the analysis: a) distance to roads, b) annual mean temperature, c) diurnal range, d) distance to trails, e) temperature seasonality, f) TIN, g) distance to streams, h) slope, and i) annual mean precipitation. Darker shades of green indicate higher fuzzy membership.

Fuzzy overlay

All fuzzified criteria were overlaid to produce a final result following the fuzzy membership process. A variety of logical and mathematical operators are available to combine the fuzzified criteria. For example, the fuzzy Sum operator adds values together, creating an increasing effect (Mitchell, 2012); conversely, the fuzzy Product operator multiplies values, resulting in a decreasing effect (Mitchell 2012).

The fuzzy Gamma operator combines the effects of fuzzy Sum and fuzzy Product. A Gamma value (γ) is chosen between 0 and 1, with γ=1 producing the same result as fuzzy Sum and γ=0 producing the same result as fuzzy Product (Figure 9).

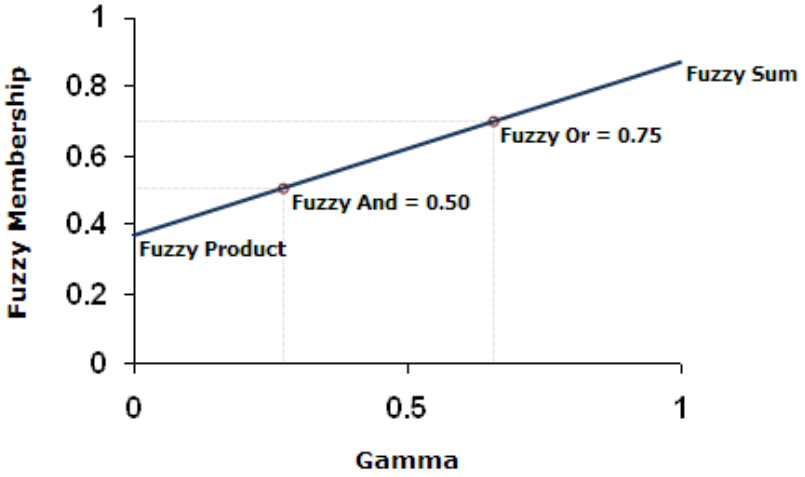


Figure 9: Graphical representation of the fuzzy Gamma operator as it compares to the other operators. From "How Fuzzy Overlay Works", n.d.

The function for fuzzy Gamma is as follows ("How Fuzzy Overlay Works", n.d.):

$$\mu(x) = (\text{FuzzySum})^{\gamma} * (\text{FuzzyProduct})^{1-\gamma}$$

For this study, fuzzy Gamma was used with γ=0.9. This value is commonly used in fuzzy logic spatial analysis literature as it establishes relationships between multiple input criteria, creating the most realistic result ("How Fuzzy Overlay Works", n.d.; Lewis et al., 2014).

0.9	0.6	0.4
0	0.1	0.2
0	N	0.8

INPUT 1

0.1	1	0
0.3	1	0
0.3	0.8	0.5

INPUT 2

0.7	0.9	0.4
0.8	0.6	0.2
0.8	0.5	0.2

INPUT 3

0.97	1	0.64
0.86	1	0.36
0.86	N	0.92

SUM

0.06	0.5	0
0	0.06	0
0	N	0.08

PRODUCT

0.73	0.93	0
0	0.75	0
0	N	0.72

GAMMA = 0.9

Figure 10: Conceptual representation of three fuzzy overlay operators. N=null values.

RESULTS

The final habitat likelihood map for WLBG in the Kanawha-New River basin is shown below (Figure 11):

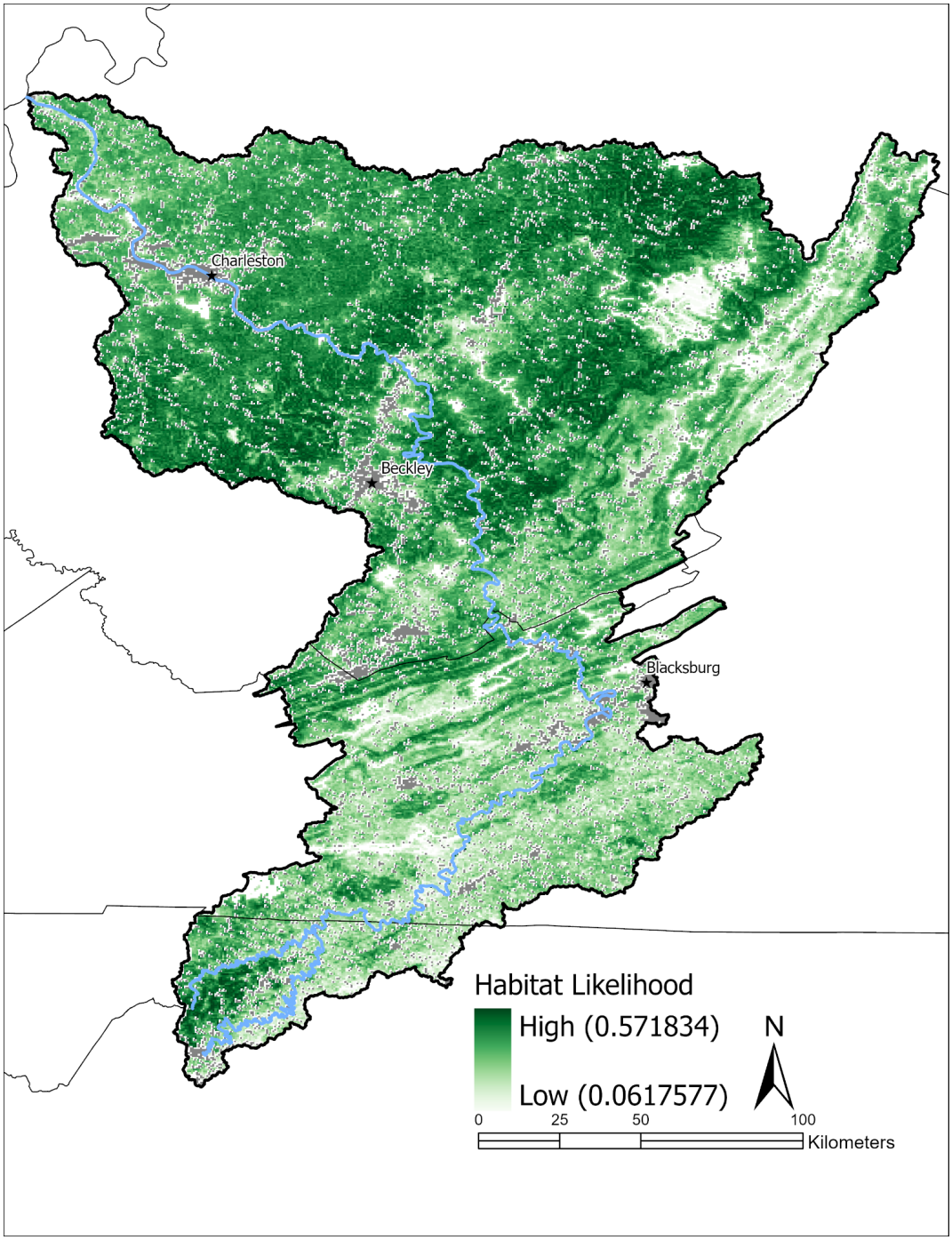


Figure 11: Final results for WLBG likelihood in the Kanawha-New River basin using fuzzy logic. Restricted areas are shown in gray.

Areas of highest habitat likelihood are located in the north-central portion of the study region in the Allegheny Plateau physiographic region near Charleston, WV. Other areas of high susceptibility include narrow bands along ridgelines in the central and southwestern portions of the study region near the WV-VA border. Large pockets of unsuitability are seen in the northeastern and northwestern areas of the study region as well as small clusters in the south-central portion. The southern portion of the Kanawha-New River basin generally shows less habitat likelihood for WLBG than the northern portion.

The results of fuzzy overlay show generally low fuzzy membership throughout the Kanawha-New River basin (Table 3). No areas in the study region show total fuzzy membership (1.0) or very high fuzzy membership (0.75-1.0). The highest fuzzy membership value found in the results (0.57) represents only moderate membership. Given the low standard deviation, most areas in the study region show fuzzy values that are close to 0.39, or low membership.

Table 3: Results of fuzzy overlay.

Max	0.57
Min	0.06
Mean	0.39
Standard Deviation	0.07

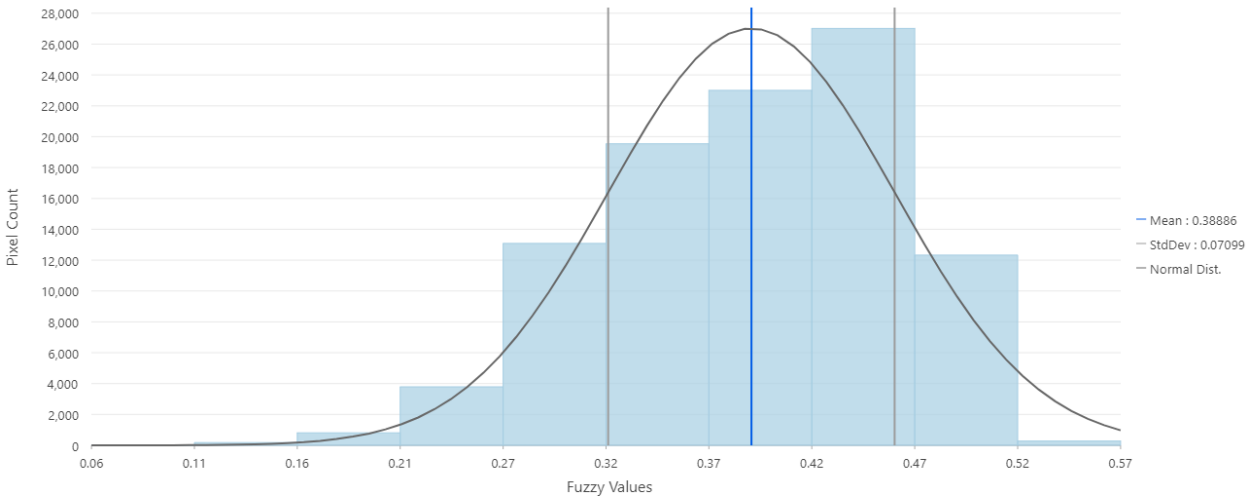


Figure 12: Histogram depicting the results of fuzzy overlay.

Fuzzy values were binned using equal interval classification to further aid conceptualization (Table 4). Doing so revealed that approximately half of the Kanawha-New River basin shows 0.37-0.47

fuzzy membership. By extension, about 85% of the study region shows less than 0.5 fuzzy membership. Roughly 4% of the basin was constrained area and was not included in binning.

Table 4: Results of binning fuzzy overlay values into equal intervals.

Ranges	Total Area (km^2)	Percentage of Study Region (%)
0.47-0.57	3,830.62	12.10
0.37-0.47	15,199.01	48.01
0.27-0.37	9,912.12	31.31
0.16-0.27	1,399.28	4.42
0.06-0.16	56.98	0.18

DISCUSSION

Interpretation of Results

Results of this study show generally low habitat likelihood for WLBG in the Kanawha-New River basin. The most suitable areas for WLBG only possess moderate membership (0.57), meaning that these locations are not optimal for the grass. It was impossible for any area to show high membership (0.75-1.0) as not every input variable reached these membership values. Due to these membership values, WLBG may not be as serious of a threat to the study region than previously thought. However, these results should be interpreted with caution. Fuzzy membership curves were rescaled and converted in an effort to replicate response curves presented by Bowen & Stevens (2020). This caused some variables to fail to reach maximum membership. For example, the fuzzy membership curve for distance to roads was adjusted to have a maximum membership of 0.4, based on the curve presented in Bowen & Stevens (2020). In fuzzy overlay, these restrictive adjusted variables influenced the results by decreasing the final membership value at a given location. Had fuzzy curves not been adjusted and maximum fuzzy membership values reached 1.0 for all variables, the final fuzzy overlay result may have shown greater habitat likelihood in more areas.

Contiguous areas of high habitat likelihood are seen in the central portion of the study region between Charleston and Beckley. This is cause for concern, as unintentional introduction of WLBG into new habitat through human vectors (e.g. hiking) is theoretically higher near urban areas than other rural

localities in the study region. WLBG is known to be able to disperse over long distances via its viscous awns that can remain attached to the disperser for long durations (Kepner & Beauchamp, 2020). Additionally, current presence point data for the grass shows isolated confirmed sightings in the Eastern Shore of Maryland (EDDMapS, 2021). It is then possible for WLBG to be dispersed over a long distance from current habitat into the Kanawha-New River basin and establish an isolated colony in the suitable locations determined in this study.

The portion of the study region in North Carolina shows relatively high likelihood for WLBG, specifically near the North Fork of the New River. Fuzzified input criteria maps all generally show high membership in this area. Ridgelines along the VA-WV state border show high habitat likelihood as well. Fuzzified input criteria maps show particularly high membership here for slope, diurnal range, and TIN (Figure 8).

The large pocket of unsuitability in the northeastern study region can be attributed to the presence of trail networks. In the analysis, areas needed to be ~5,000 km away from trails to achieve high membership. As a result, these dense trail networks caused the area to exhibit low habitat likelihood.

Recommendations

Areas showing highest habitat likelihood in this study should be ground-truthed by land managers to perform early detection and eradication. Discovering and eliminating WLBG before it becomes established in a habitat is critical in the fight against continued spread (Bowen et al., 2020). Portions of the northeastern study region with high likelihood may be prioritized, as these areas are closest to current presence points (EDDMapS , 2021). This eliminates any potential short distance spread via natural vectors, e.g. viscously awned fruits dispersed by animals (Kepner & Beauchamp, 2020). High likelihood areas in the central study region may also be targeted to eliminate early establishment and spread via humans over long distances (Kepner & Beauchamp, 2020). Although rural, land managers may choose to focus on the portion of the basin in North Carolina as WLBG could establish itself in this area first before spreading further south.

Potential areas of interest for early eradication and removal of WLBG by land managers are shown below (Figure 12):

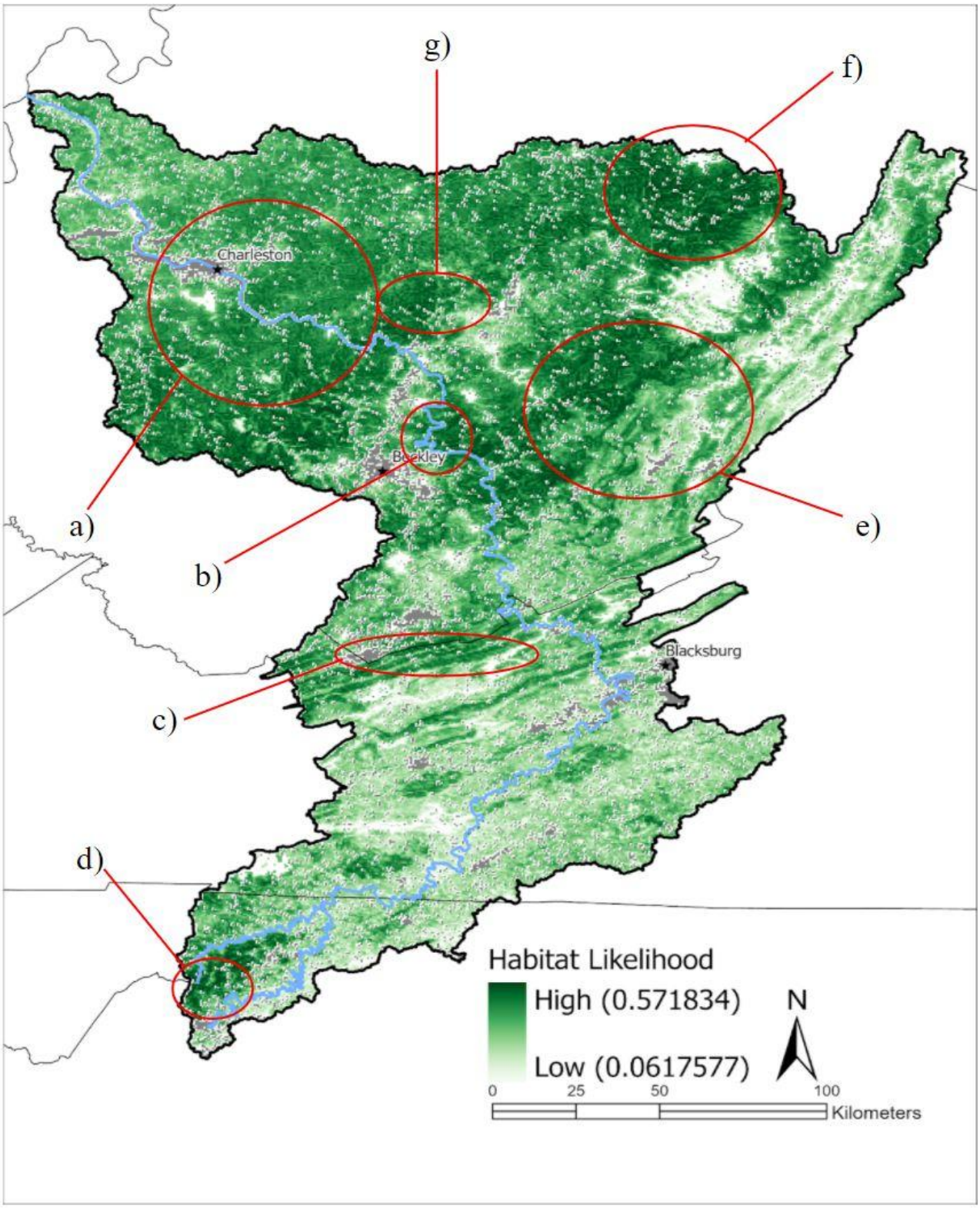


Figure 13a: Prioritized areas for investigation of WLBG within the Kanawha-New River basin: a) Charleston Metropolitan Area, b) New River Gorge National Park, c) East River/Buckhorn/Wolf Creek Mountains, d) Elk Knob State Park, e) Greenbrier County, f) Webster County, and g) Gauley River National Recreation Area.

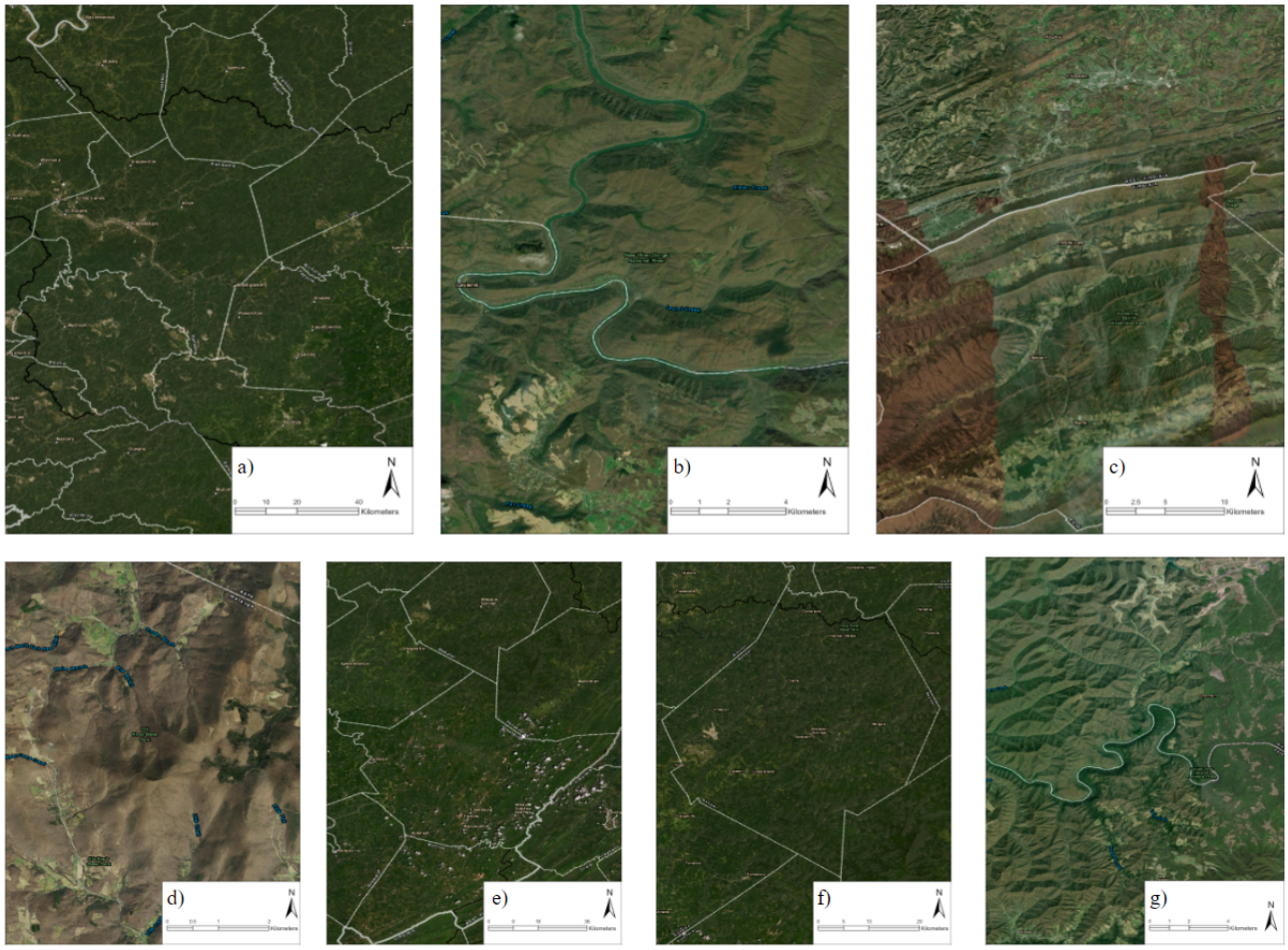


Figure 13b: Satellite imagery of prioritized areas for investigation of WLBG in the Kanawha-New River basin.

Table 5: Description of prioritized areas pictured above.

Name	Size	Location
Charleston Metropolitan Area	4,550 km^2	Kanawha, Boone, and Clay Counties, WV
New River Gorge National Park	294.64 km^2	Northeast of Beckley, WV
East River, Buckhorn, and Wolf Creek Mountains	~250 km^2	VA/WV border; Bland/Giles Counties, VA
Elk Knob State Park	17.90 km^2	South of N. Fork New River, NC
Greenbrier County	2,650 km^2	Southeastern WV
Webster County	1,440 km^2	Central WV
Gauley River National Recreation Area	46.57 km^2	East of Charleston, WV

These selected areas should be evaluated periodically for WLBG emergence by land managers. This effort can be active at multiple levels of government in a variety of organizations, including the U.S.

Forest Service, Wavyleaf Basketgrass Task Force, West Virginia Division of Forestry, Virginia Department of Conservation and Recreation, North Carolina Wildlife Resources Commission, etc. Multiple personnel will be needed to thoroughly survey each site over several days. Detection efforts can begin at any well-traveled roadways, trails, footpaths, forestry roads, etc. and continue into interior forested areas via bushwhacking. The inclusion of citizen science applications that track WLBG spread, like EDDMapS and Project Wavyleaf through Towson University, can alleviate the burden of surveying these geographically vast areas (Project Wavyleaf, 2014). Following any new sightings by the public, land managers can confirm these reports and take necessary eradication measures via hand-pulling or herbicide application. Random and/or systematic monitoring systems can be put in place, with observation points dispersed throughout high, medium, and low suitability areas to evaluate the accuracy of this model. Preemptive action is needed by officials to prepare for the imminent arrival of WLBG, including development of action plans, consultation with experts, and education on removal and eradication methods. Ideally, highly susceptible areas should be intensely evaluated in mid- to late-summer, with any localized clusters of WLBG sprayed with Clethodim or hand-pulled. Investigation should continue later into the growing season, with Glyphosate applied to any large populations.

Simultaneously, educational outreach should be established by appropriate organizations to inform the public about the issue. Signage should be posted in recreational lands with background information and images of WLBG provided to warn visitors. Informing the public in this manner may result in the first confirmed reports of WLBG in the region. The National Park Service can begin outreach efforts in the New River Gorge National Park, with information on the habitat preferences and distribution methods of the grass supplied. Visitors to parks, gamelands, recreational lands, etc. in the region can be instructed to examine and clean their clothing upon departure to prevent anthropogenic spread of the grass to novel habitat. The public can be pointed towards aforementioned citizen science services in an effort to map any new sightings. Educational outreach and public involvement proved to be beneficial when controlling initial emergence of other invasive species, e.g. the zebra mussel, as the public were the first to report this species in new waters (Strayer, 2009).

Limitations & Future Study

Bowen & Stevens (2020) noticed a contradictory relationship between WLBG habitat preferences in regards to distance to roads and distance to trails; the grass was more likely to be found closer to roads but further from trails. Presence points used in their study for model calibration were collected close to roads, potentially influencing this relationship (Bowen & Stevens, 2020).

Response curves generated by Bowen & Stevens (2020) were replicated in this study as precisely as possible. However, the software used was unable to generate fuzzy membership curves to completely match these response curves, e.g. logarithmic curves. In such instances, fuzzy curves generated in the software were manipulated to closely resemble the response curves. Additionally, Bowen & Stevens (2020) found a substantial extrapolation risk in southwestern VA. As a result, the results from this portion of the study region should be interpreted with caution.

Invasive species are known to exhibit phenotypic plasticity and can rapidly evolve to change habitat preferences over time (Sakai et al., 2001). Variables included when performing invasive species modeling for WLBG in the future may need to be adjusted once the grass becomes more established in the Mid-Atlantic. This creates a temporal component when investigating the WLBG invasion that must be considered in any following study. Future study of WLBG in this region may also consider examining a smaller area of interest at a finer scale. Using higher resolution data instead of the 500 x 500m data used in this study would provide more precise estimates of habitat likelihood for WLBG. The pixel size chosen for this study was particularly problematic for proximity variables, as one pixel would cover a wide range of fuzzy membership values (Figure 14). A study using smaller pixel size would also aid land managers in their surveying efforts by highlighting less vast areas of high likelihood.

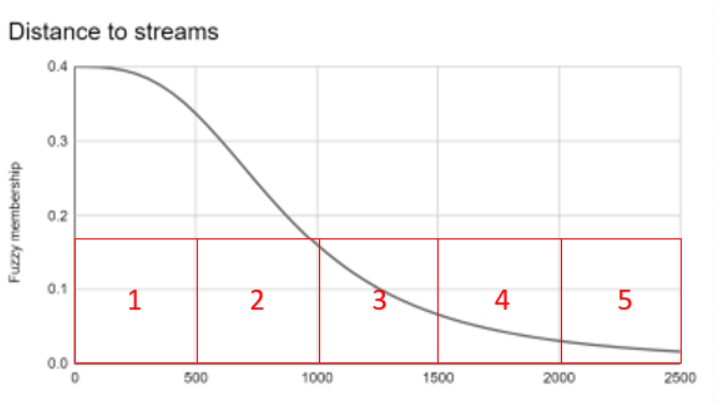


Figure 14: Pixel size superimposed over the fuzzy membership curve for distance to streams.

Related Literature

This study complements the findings of Bowen & Stevens (2020), albeit with different methods. Modeling the future spread of WLBG using GIS and fuzzy logic appears to show the grass as less of a threat in the Kanawha-New River basin than Bowen & Stevens (2020) did in their analysis of the Mid-Atlantic. The USDA (2012) created a general habitat likelihood map for the entire U.S. and showed 30% of the country to be suitable for WLBG. Moore (2011) used the Invasive Species Forecasting System

from NASA to predict WLBG habitat in the central Mid-Atlantic. Beauchamp et al. (2013) used Maxent to show areas susceptible to WLBG in the greater Washington, D.C. area. This study provides alternative insight into the WLBG problem and examines an area in which WLBG is not yet established to show potential for future invasion.

Additionally, this study has presented the practicality of fuzzy logic-based GIS studies for invasive species management. Fuzzy logic and/or GIS have been demonstrated to be viable methodologies in calculating economic costs of invasives, in guiding decision making for European House Borer spread in Western Australia, and in predicting invasive species spread in Greece (Demertzis et al., 2018; Eiswerth & Van Kooten, 2002; Liu et al., 2010). These methods could be applied to other emerging invasive vegetation threatening the Mid-Atlantic, including European privet, bush honeysuckle, water hyacinth, or large flower primrose willow (Potomac Highlands CWPMA, n.d.; Heffernan et al., 2014).

WLBG is causing ecological and economic damage in the Mid-Atlantic. Although not currently in the Kanawha-New River basin, WLBG will soon inhabit this region given its current geographical location and distribution patterns. This study provides insight into areas most prone to WLBG invasion in order to alert appropriate land managers. Early preparedness and knowledge of potential spread is critical in the fight against the grass and in the preservation of ecosystem health throughout the region for generations to come.

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