LANDSCAPE SELECTION OF GREEN SALAMANDERS, *ANEIDES AENEUS*, AND A MODEL OF THEIR POTENTIAL DISTRIBUTION TO GUIDE FUTURE SURVEYS IN TENNESSEE

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Abstract.— Green salamander, *Aneides aeneus,* populations have declined in parts of their geographic range. In response to these declines, the United States Fish and Wildlife Service has been petitioned to protect the species under the Endangered Species Act. Additional information is needed on the geographic distribution and the ecological requirements of green salamanders in Tennessee to aid regulatory decision making and conservation management. The objectives of our research were to determine what environmental characteristics best predict landscape suitability for green salamanders and to create a map of the model to guide future surveys. We compiled green salamander occurrence records from the Tennessee Wildlife Resources Agency's State Wildlife Action Plan database and from researchers currently conducting research. We used maximum entropy modeling to evaluate the relative importance of environmental characteristics across the landscape and we projected the model into geographic space to map the potential distribution of green salamanders in Tennessee. Environmental variables associated with rock outcroppings, tree canopy cover, and elevation contributed most to the model. Green salamanders select areas on the landscape with rocks at the soil surface, but not necessarily bedrock, with a high percent canopy cover at moderate elevations. Rocks at the soil surface likely represent large rocks and boulders deposited on the landscape by geological processes that are not parent material. The model can be used to guide future surveys and may make surveys more efficient at locating new populations in Tennessee. Accumulating up-to-date occurrence records will enable managers to better assess the current distribution of green salamanders in Tennessee and may improve conservation efforts.

Key Words.—conservation, ecological niche modeling, habitat suitability, occurrences

World-wide amphibian populations are declining at an alarming rate. Of the approximately 5,743 species of described amphibian, an estimated 32.5% are globally threatened, endangered, or extinct. Data is insufficient to assess the conservation status of 22.5% of the world's amphibians (Stuart et al. 2004). Green salamander (*Aneides aeneus*) populations, at least in Tennessee, arguably fall into this data insufficient category due to the cryptic nature of the species and a lack of large scale research in the state.

Green salamanders are a species of plethodontid salamander that range from southern Pennsylvania to northern Mississippi, with disjunct populations occurring in southern Indiana and along the Blue Ridge Escarpment in South Carolina, North Carolina, and Georgia (Petranka 1998). Green salamanders are imperiled in 10 of the 13 states where they occur and have declined substantially in the disjunct populations along the Blue Ridge Escarpment (Corser 2001, Waldron and Humphries 2005). Declines here are partially attributed to habitat loss caused by logging of old-growth forests (Wilson 2003). Declines have also been attributed to over collecting, epidemic disease, and climate change (Corser 2001). In 2012 the United States Fish and Wildlife Service (USFWS) was petitioned to protect green salamanders under the Endangered Species Act (Center for Biological Diversity 2012). A 90-day finding conducted by the USFWS determined that listing may be warranted and the species is currently under a status review (USFWS 2019).

In Tennessee, green salamanders are primarily found in the Eastern Highland Rim, the Cumberland Plateau, the Cumberland Mountains, and the northern Ridge and Valley physiographic regions. Sandstone bluffs along the margins of the Cumberland Plateau in Tennessee appear to be particularly important landscape features for green salamanders and are where many occurrences have been documented in the state (Tennessee Wildlife Resources Agency 2005). However, type of rock (i.e. limestone, sandstone, dolomite, etc.) has been determined to not be as important as the presence of suitable crevices (Gordon and Smith 1949).

Green salamanders are most often found in moist, narrow crevices, ≤2cm in width on average, along shaded rock outcroppings and on tree trunks near rock outcroppings (Gordon and Smith 1949, Wyatt 2010, Niemiller and Reynolds 2011). At Catoosa Wildlife Management area in Tennessee, the best predictor of green salamander presence was length of the crevice, which was a reflection of the size of the rock outcrop (Wyatt 2010). Green salamanders selected the longest available crevices. Also, there was a strong positive correlation between green salamander presence and slope below the rock outcropping and number saplings around the outcropping (Wyatt 2010). In plethodontid salamanders respiration is primarily cutaneous and they have high rates of evaporative water loss (Peterman et al. 2013). Plethodontid salamanders often select areas with specific microclimates to avoid desiccation (Wells 2007). Steep slopes below the outcroppings are indicative of ravine type landscapes that typically have cool, moist microclimates due to the terrain blocking insolation. Saplings around the outcroppings provide shade and further maintain a cool and moist microclimate (Wyatt 2010).

While several studies have examined selection of rock outcroppings and crevices by green salamanders, few have examined selection at a broader scale across the landscape. A species distribution model (SDM) conducted in North Carolina found that green salamanders select certain soil types, shallow soils, and areas with a high percent canopy cover at intermediate elevations (Hardman 2014). Shallow soils are indicative of exposed bedrock and the species is considered a rock crevice specialist, so this result corroborates other research (Smith et al. 2017). However, soil type, the most robust predictor of landscape suitability, did not correlate with exposed bedrock, so soil characteristics other than depth appear to be an important landscape attribute for green salamanders in North Carolina. It is unclear what these characteristics may be, and the author doesn't speculate. However, soil pH and moisture have been demonstrated to impact the distribution and abundance of *Plethodon cinereus* (Wyman and Hawksley-Lescault 1987, Sugalski and Claussen 1997). There is potential that these soil characteristics could also impact green salamanders. High percent canopy cover suggests that green salamanders are selecting forested areas with dense shade and cool microclimates (Hardman 2014).

Accurate knowledge of species occurrence is essential for conservation management and regulatory decision making. For cryptic species like green salamanders, surveys aimed at documenting new occurrences are labor intensive and require adequate funding. Species distribution modeling (SDM) is a technique that uses known occurrence records, occasionally absences, and environmental data to predict the distribution of a species in geographic space. The technique has been used successfully to guide sampling effort and can ultimately make documenting new occurrences or new populations more efficient for cryptic or rare species (Rebelo and Jones 2010; Olatz et al. 2015; Fois et al. 2018). Hardman (2014) was successful in using SDMs to find new populations of green salamanders in North Carolina and the results of our research can be used to guide future survey efforts in Tennessee and will potentially increase the efficacy of the searches. With more up-to-date occurrences and the discovery of new populations, managers and regulators will have an improved knowledge of the species' actual distribution on the landscape. This can improve their ability to identify areas on the landscape where recovery efforts will be most effective and efficient

The objectives of this research were to use species distribution modeling to determine what features on the landscape in Tennessee best predict the presence of green salamanders and to create a map of the potential distribution of green salamanders to guide future survey efforts. The potential distribution represents areas on the landscape that are environmentally suitable for the species, whereas the actual distribution depends on factors such as competition, predation, and barriers to dispersal that are not accounted for in the modeling process. Based on a SDM of green salamanders from western North Carolina and the ecology of the species, we hypothesized that soil type, percent of tree canopy cover, elevation, and depth of soil to bedrock would be the primary environmental predictors of landscape suitability for green salamanders in Tennessee (Hardman 2014).

METHODS AND MATERIALS

To model the potential distribution of green salamanders in Tennessee, we compiled occurrence records from the Tennessee Wildlife Resources Agency's State Wildlife Action Plan database and from researchers currently conducting surveys. As a precautionary measure, we excluded occurrences documented before 2004. This year was selected as a cut-off because the majority of occurrences in the database were documented in 2004 or after. Loss of forest cover can negatively impact green salamander populations (Wilson 2003), so including historic occurrences where logging has occurred would adversely affect model performance. We used recent occurrences assuming they are from extant populations. Because most occurrences between these years were documented on standardized surveys of transects, we used the SDMtoolbox (Brown et al. 2017) in ArcMap (ArcMap ver. 10.6.1, ESRI, Redlands, CA, USA) to spatially filter or thin the occurrences to minimize the risk of spatial autocorrelation problems in the model. The minimum distance allowed between occurrences was set at 500 m.

We used maximum entropy modeling with presence-only data using Maxent software (Phillips et al. 2006) to model the potential distribution of green salamanders in Tennessee. Maxent uses a machine learning algorithm to compare cells in environmental raster files with occurrence records to randomly selected cells in the background without occurrences to estimate a suitability score for each cell in the grid (Phillips 2009). We selected the logistic output that assigns each cell in the grid a value between 0 (least suitable) and 1 (most suitable). In the model occupied cells were compared with 10,000 unoccupied cells in the background.

We employed a 10-fold cross validation technique in which the occurrence records are randomly partitioned into 10 equal subsets. The model is run 10 times (folds) using a different subset of the sample in each run to test the model. In this technique each occurrence record is used to both test the model and to fit the model. The technique gives an estimate of errors in the predictive performance and fitted functions of the model (Taylor et. al 2017). Maps of the model were created using the average of the model runs.

In total, eight environmental predictor variables were used in the models and acquired as raster files with a 250 m spatial resolution. The variables are related to rock outcrop habitat and microclimate and were chosen to closely replicate the SDM in North Carolina by Hardman (2014). ArcMap was used to align the cells of each raster file and they were clipped to the extent of our study area, which is the state of Tennessee. We attained a digital elevation model at 250 m resolution and used ArcMap to derive aspect and percent slope (U.S. Geological Survey and National Geospatial-Intelligence Agency 2010). We transformed aspect to northness and eastness to make it a continuous variable by first converting degrees to radians. Then for northness we calulacted the cosine of each radian and the sine of for eastness. For northness the result is a continuous variable with 1 being north and -1 being south. For eastness the result is a continuous variable with 1 being east and -1 being west. Soil type, depth of soil to bedrock, and coarse soil fragments at the surface of the soil were acquired from the International Soil Resource and Information Center (Batjes 2012). The soil type dataset is a model of the most likely soil class from the World Reference Base for Soil Resources classification system (International Union of Soil Scientists Working Group 2015). Depth of soil to bedrock is the predicted depth (cm) of soil overlaying bedrock parent material. Coarse soil fragments is the predicted volumetric percent of rock fragments >2mm in diameter at the surface of the soil including rocks and boulders. Finally, percent tree canopy cover was downloaded for both 2004 and 2016 (Dimiceli et al. 2015). Tree canopy cover for 2016 was the most recent year available when the SDM was being created. We used ArcMap to average tree canopy cover for the two years and the resulting raster with averaged values was used in the model to match as close as possible the temporal resolution of the occurrence data. These eight variables were selected to allow us to compare our model results with the results from a SDM in North Carolina (Hardman 2014). Pearson correlations between environmental variables were acceptable ($r \leq 0.72$), so collinearity was assumed to not be an issue in the model.

We used area under the curve (AUC) statistic of the receiver operating characteristic (ROC) averaged across each model run to assess the performance of the model. An AUC of 0.5 represents a model that performs no better than random and an AUC of 1.0 represents a model with excellent predictive ability. We also examined the average omission rate, which is the percentage of localities with an occurrence that the model predicts as unsuitable. To define unsuitable, we made the model binomial (i.e. unsuitable or suitable) based on a defined suitability threshold. We examined omission rates of the test data subsets at two suitability thresholds: minimum training presence and 10 percentile training presence (Taylor et. al 2017). The minimum training threshold is the lowest suitable value assigned to a training occurrence. The 10 percentile training presence is the suitability value that excludes 10 percent of the training occurrences with the lowest suitability scores.

RESULTS

We compiled 213 green salamander occurrence records (Fig. 1). After spatially rarifying the records, we ended up with 79 occurrences to build the model. The average AUC for the test subsets of the model was 0.93

± 0.02. Based on this threshold independent measure of model performance, the model has good predictive ability. The average minimum training threshold of the training data was 0.03 and the omission rate of the test data was 0.01 ± 0.05. The average 10 percentile training presence was 0.23 and the omission rate was 0.019 ± 0.15. Overall, the omission rates are relatively low and cross-validation suggests the model has strong discriminatory power.

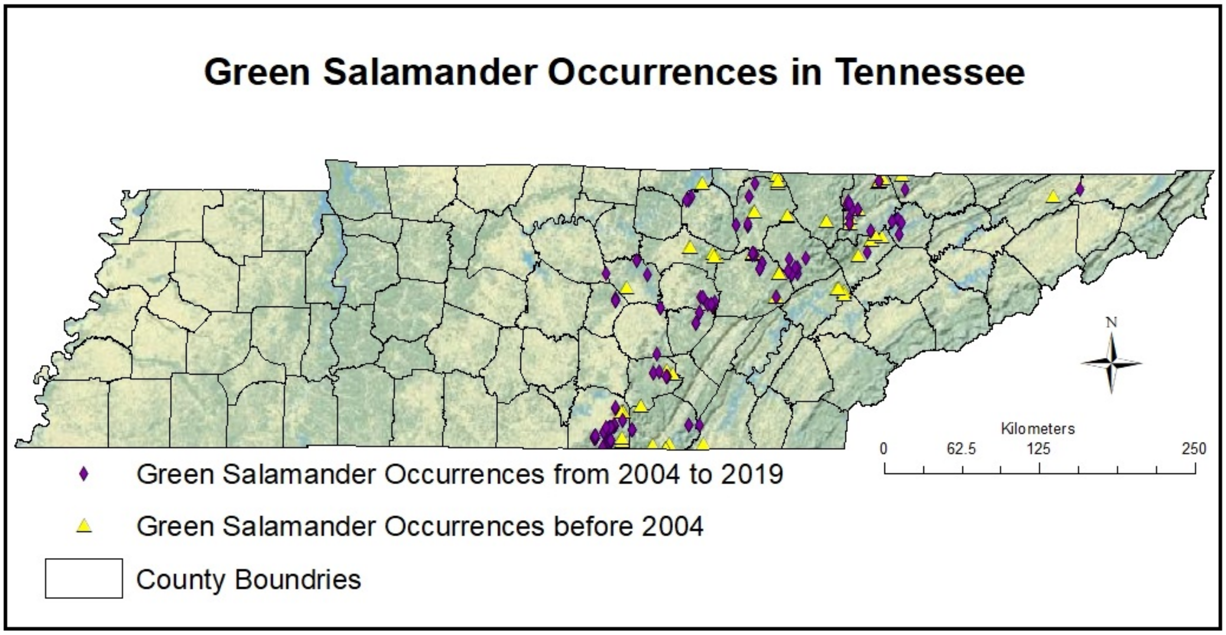


FIG. 1. Green salamander occurrence records in Tennessee from Tennessee Wildlife Resources Agency's State Wildlife Action Plan database and from researchers currently conducting research.

TABLE 1. The table displays environmental variables, and average percent contribution and standard deviation of each variable to landscape suitability for green salamanders in Tennessee across 10 cross-validated model runs.

Variable	**Percent Contribution**	**SD**
Coarse Soil Fragments	42.8	4.87
Percent Canopy Cover	16.6	4.63
Elevation	15.7	2.28
Depth of Soil to Bedrock	12.8	1.98
Soil Type	6.2	1.57
Eastness	2.4	0.46
Slope	1.8	0.56
Northness	1.6	0.39

The variable coarse soil fragments, measured in volumetric percent at the soil surface, contributes most to the model at 42.8% followed by percent canopy cover at 16.6 %. Elevation, measured in m above sea level, contributed 15.7% and depth of soil to bedrock, measured in cm, contributed 12.8% (Table 1). Landscape suitability for green salamanders has a strong positive correlation with coarse soil fragments at the soil surface up to approximately 15% coarse fragments by volume and then suitability drops slightly or plateaus (Fig. 2). Tree canopy cover also has a positive relationship with suitability up to approximately 68% then suitability drops substantially. This drop in suitability likely reflects availability. Only 2.5% of the cells in the dataset have over 77.6% tree canopy cover

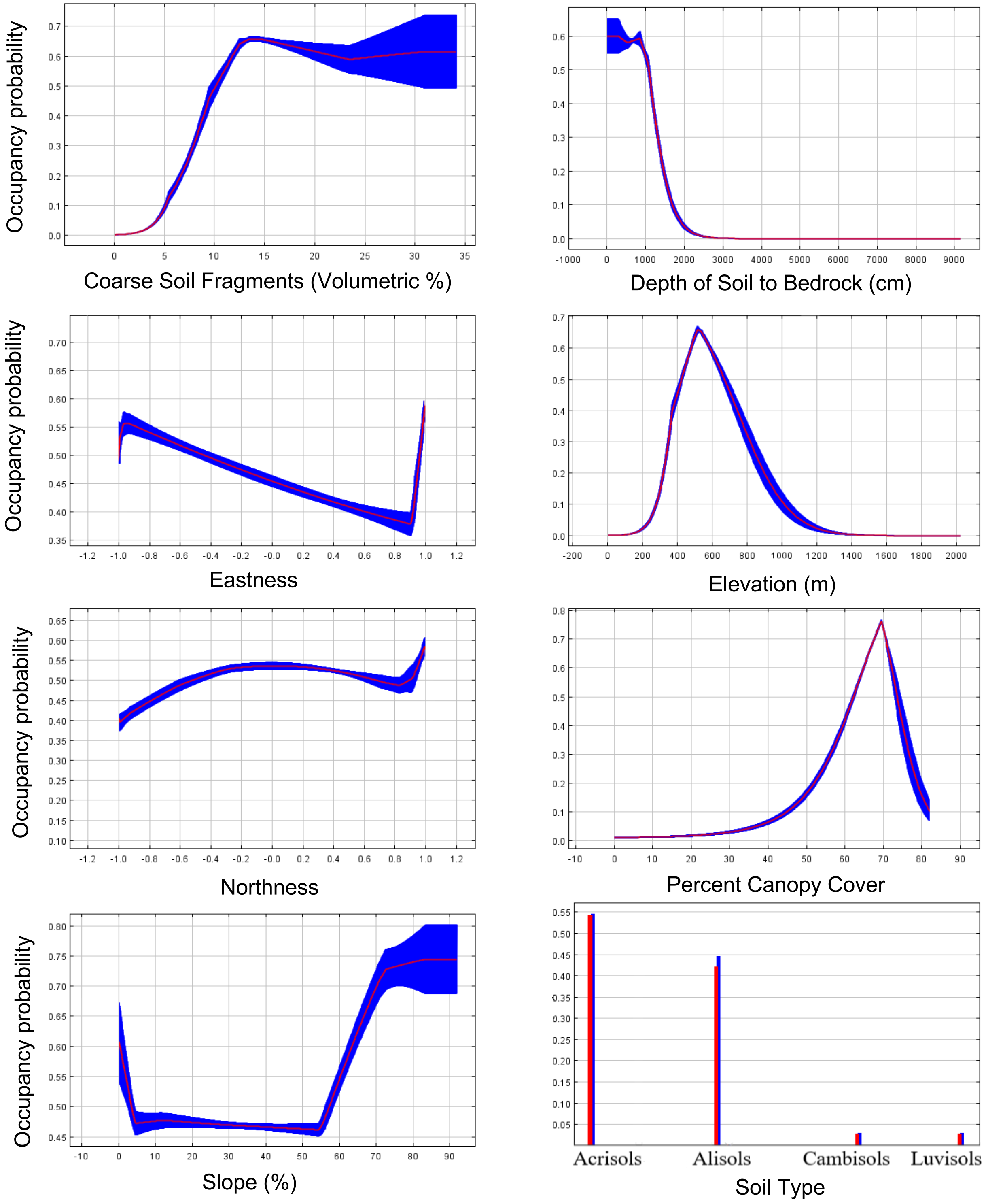
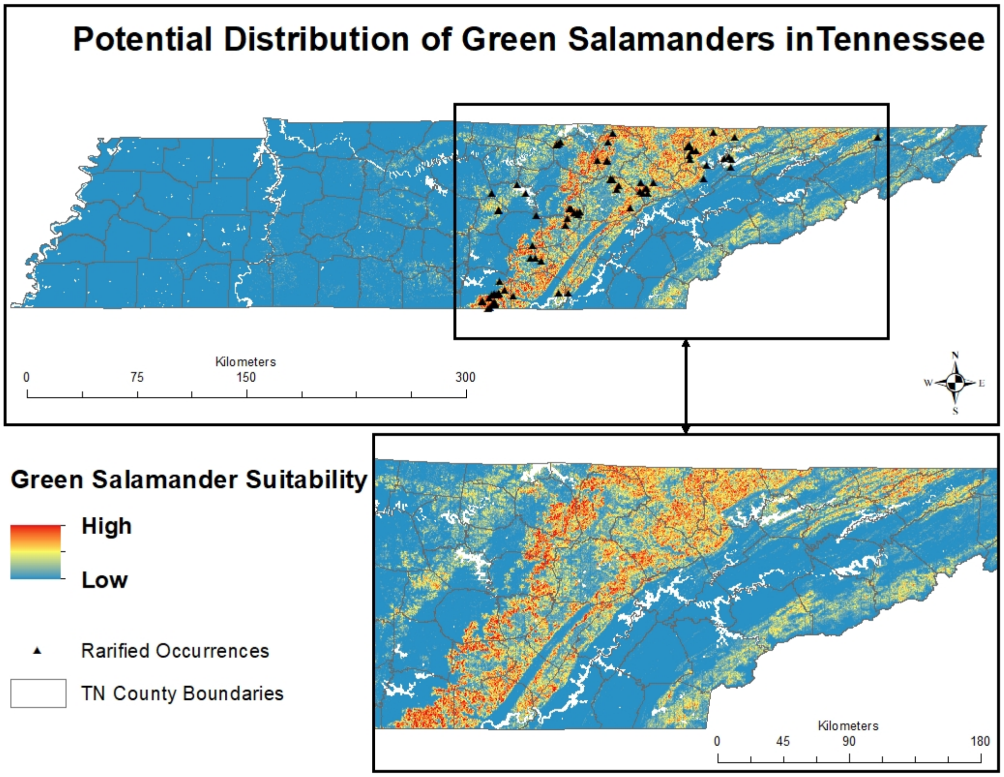


FIGURE 2. Graphs showing the response of landscape suitability (y-axis) for green salamanders to changes in values of each response variable (x-axis) in the absence of other variables. The red line in the response curve represents the average from 10-fold cross-validation and the blue area is ± 1 SD.

and the maximum is 82%. Landscape suitability peaks at approximately 500 m in elevation. The elevation of the Cumberland Plateau ranges between 457 m and 549 m and sandstone bluffs generally line the margins of the plateau (Tennessee Wildlife Resources Agency 2005). Many of the occurrences in Tennessee are along the margins of the Cumberland Plateau (Fig. 2) and the relative of importance of elevation suggests this is an important landscape feature for green salamanders. However, the variables elevation and coarse soil fragments had the strongest correlation of the environmental variables (r= 0.72), so the importance of elevation may have a slight influence from this correlation. Depth of soil to bedrock has a strong negative correlation with suitability. Suitability is highest between approximately 0 cm and 300 cm soil depth to bedrock and drops precipitously with deeper soils. Surprisingly, soil type contributed relatively little to the model at 6.2%.

The Cumberland Plateau and the Cumberland Mountains physiographic regions had the largest area of high suitability based on the model results (Fig. 3). The western margin of the Cumberland Plateau is characterized by expansive sandstone bluffs and this area was identified as highly suitable generally from the southern border to the northern border of Tennessee. The northern reaches of the Ridge and Valley physiographic region also have areas with high environmental suitability. Somewhat surprisingly, even with a complete lack of occurrence records, areas along the Blue Ridge Mountains were identified as suitable.

FIG. 3. The results of a species distribution model with landscape suitability for green salamanders displayed as a continuous field projected into geographic space with the occurrences records used to build the model.



DISCUSSION

Our model of the potential distribution of green salamanders in Tennessee indicates that areas with rocks at the soil surface, not necessarily bedrock, and a high amount of tree canopy cover at moderate elevations are important landscape features for the species in Tennessee. Model results support our hypothesis that tree canopy cover and elevation would be important variables in the model. However, contrary to our hypothesis, depth of soil to bedrock and soil type contributed less to the model than expected and coarse soil fragments contributed more than expected.

In a SDM for green salamanders in North Carolina, soil category was the greatest contributing environmental variable, contributing more than depth of soil to bedrock. Hardman (2014) suggests that soil attributes other than depth may be important in their study area but doesn't speculate what the attributes could be. These soil attributes were possibly less important in Tennessee due to the abundance and connectivity of rock outcroppings along the Cumberland Plateau that are generally lacking along the Blue Ridge Escarpment. It should be noted that our model and the North Carolina model used different soil category datasets from different sources and this could explain why soil type contributed less in our model. Additionally, Hardman (2014) didn't include coarse soil fragments at the soil surface and inclusion of this variable in the model could have decreased the contribution of soil category. Hardman (2014) speculated that depth of soil to bedrock would be a more important variable along the Cumberland Plateau where expansive bluff lines are abundant and we found little evidence for this in our model. The presence of coarse soil fragments on the soil surface was a more robust predictor of suitability.

An expansive area along the Blue Ridge Mountains in Tennessee was identified as suitable in our model. The last green salamander occurrence in this physiographic region in Tennessee was documented in the Great Smoky Mountains National Park in 1929 (Neimiller and Reynolds 2011). Green Salamanders have declined dramatically in the near-by disjunct populations of the Blue Ridge Escarpment in North Carolina, South Carolina, and Georgia (Corser 2001). If populations of green salamanders did exist in the Blue Ridge Mountains of Tennessee historically, it's likely that dramatic declines occurred here as well. Of course, our model does not account for biotic interactions (i.e. competition and predation) and the species may have never been abundant in the Blue Ridge Mountains because of these interactions. Still, this model could direct future green salamander surveys in the Blue Ridge Mountains of Tennessee and help to determine if populations are extant in this physiographic region.

Several areas in Tennessee are highly suitable for green salamanders but lack occurrences records in Tennessee's State Wildlife Action Plan Database. Notably, Putnam and Overton Counties along the western escarpment of the Cumberland Plateau, Bledsoe County on either side of the Sequatchie Valley, and the boarder of Hancock and Hawkins Counties in the Ridge and Valley physiographic region have large areas of high suitability. Most of these areas are privately owned and have likely never been systematically surveyed. Based on the results of the model and our knowledge of the landscape in these areas, we speculate that green salamander populations occur in these geographic areas. Standardized surveys are needed for a more complete assessment of the actual distribution of green salamanders in Tennessee.

Forest canopy cover is an important variable in landscape selection of green salamanders and this result provides further evidences that green salamander conservation in Tennessee should focus on protecting forests surrounding rock outcrops (Wyatt 2010).

Forests regulate temperature and humidity regimes around the rock outcrops and trees in close proximity to outcrops may be additionally important for foraging during rain events (Smith et al. 2017). In Tennessee these features are particularly important along the margins of the Cumberland Plateau, the Cumberland Mountains, and northern Ridge and Valley physiographic regions in Tennessee where the landscape is most suitable for the species. A 100 m forest buffer has been suggested to protect rock outcroppings from solar radiation (Petranka 1998). Research is needed to demonstrate if this buffer size is adequate and how fragmentation of forests around and between outcroppings impacts green salamander populations.

Acknowledgments.—This research was funded by the Tennessee Wildlife Resources Agency through the State Wildlife Grants program. We thank Dr. Matthew Niemiller from the University of Alabama- Huntsville and Dr. Becky Hardman from the University of Tennessee- Knoxville for their help in the field and contributions to the larger objectives of the project. Additionally, we thank Dr. Kristen Cecala and anonymous reviewers who improved the manuscript by providing comments on previous versions.

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