A FRAMEWORK FOR PREDICTING THE OCCURRENCE OF RARE AMPHIBIANS: A CASE STUDY WITH THE GREEN SALAMANDER

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ABSTRACT

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Traditional species surveys are often inefficient and unsystematic. They may be greatly improved by using GIS models of predicted occurrence to determine areas where a species is likely to occur. Statistical techniques for developing predicted occurrence usually require large datasets of the species' presence and absence, which are difficult to acquire for rare and cryptic amphibians such as the Green Salamander (*Aneides aeneus*), an endangered species in Ohio. The seven known sites of Green Salamander occupancy in the state were used as training sites to develop an inductive model of predicted occurrence in three southern Ohio counties using elevation, slope, percent canopy cover, distance to water, mean annual temperature, and bedrock geology. The model predicted that 30.27 km^2 of the 4310 km^2 study area was potentially suitable habitat. Site visits to evaluate the model's performance led to the discovery of five previously unreported occupied sites. These new sites included the first report of the species from the Wayne National Forest and of the species use of sandstone habitats in Ohio. Issues with accuracy and precision of the GIS data and the Global Positioning System (GPS) resulted in two of the new sites being incorrectly categorized as occurring just outside of areas of predicted occurrence. In addition, two sites were located in areas with mean annual temperatures lower than that of the training sites. This project provides a framework for developing simple, straightforward, and easily modifiable models of predicted occurrence that can increase the efficiency of surveys, locate new populations of threatened species, and help understand the parameters limiting species distributions.

Dedicated to Nicole,

for her support, encouragement, and understanding

of my passion for wildlife and conservation.

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INTRODUCTION

Amphibian Declines and Conservation

The worldwide decline of amphibian populations has been well documented (Lannoo 1998; Phillips 1990; Wake 1991). Habitat destruction and fragmentation, disease, pollution, introduced competitors and predators, and increased ultraviolet light have all been implicated in the declines (Semlitsch & Wake 2003). One obstacle to understanding and mitigating these declines continues to be the lack of baseline data necessary to document the historic and recent distribution and occurrence of amphibian species. Furthermore, there is a growing consensus that declines are not attributable to any single cause, but are instead the result of a wide range of natural and anthropogenic factors that may interact with variable effects for different species and geographic regions (Blaustein & Kiesecker 2002; Collins & Storfer 2003; Kiesecker et al. 2001; Pechmann et al. 1991). Approaches for dealing with amphibian declines require the continued collection of baseline data, combined with the power of the latest technological tools in conservation and environmental biology.

Predicting Species Occurrence

Traditional species surveys have relied heavily on expert knowledge and opinion to identify areas likely to have habitat suitable for the species being investigated. In addition to the subjective nature of this process, individuals are restricted by the number of variables and amount of data that can be manually processed, limiting the scope and accuracy of their predictions. The common practice of surveying areas of known occupancy identified through museum and literature records can lead surveyors to omit areas of suitable habitat not previously identified. Given these limitations, traditional survey techniques may not offer the rigor necessary to fully understand a species distribution.

Geographic Information Systems (GIS) are designed to manage, manipulate, and analyze large sets of spatial data (Theobald 2003). GIS integrates data, algorithms, display, management, and people to investigate complex issues and aid in decision making. With the increasing power of computer processors and storage capacity, the application of GIS to ecology and conservation has also expanded (Corsi et al. 2000; Kushwaha & Roy 2002; Turner et al. 2003).

The use of GIS for predicting the occurrence of a species involves two basic steps (Corsi et al. 2000). First, a species' requirements are defined in terms of data layers describing the distribution of measurable and mappable variables (environmental, human, etc.). Second, these layers are combined in a model and used to produce a map of the species' potential distribution. A final step, many times overlooked, is the evaluation of the model's accuracy through field surveys or the use of an independent data set. Of course, this simplified view does not take into account the decision-making required for choosing the appropriate scale, environmental parameters, and methods of analysis. These issues have been addressed by many authors (Guisan & Zimmermann 2000; Manel et al. 1999b; Mitchell et al. 2001; Olden & Jackson 2002; Scott et al. 2002).

Judging the "suitability" of an area for a given species requires some knowledge of the factors that may affect an individual's ability to colonize, survive, and reproduce. Two general methods have been utilized to delineate these factors (Corsi et al. 2000). The first method uses a deductive model based on expert knowledge (including literature reviews) to assign suitability scores to the chosen variables. Inductive models, on the other hand, gather information from areas of known occupancy for the species, with the explicit assumption that variables at these locations represent the preferred conditions for the species. While the inductive model is in general a more objective methodology, the researcher's selection of variables to be analyzed is usually guided by *a priori* knowledge of the species (Seone et al. 2005). In addition, both the deductive and inductive models are limited to including those variables which can be easily measured, and in the case of GIS models, made available in digital format.

Recent comparisons of these two model types have shed doubt on the utility of expert opinion in habitat models. In their study of black bear (*Ursus americanus*) habitat, Cleveneger et al. (2002) developed models using three methods: (1) an expert opinion model, based on a pairwise comparison of variables by groups of individuals with expert knowledge of black bears; (2) an expert literature-based model similar to the expert opinion model, but using published literature to rank the variables; and, (3) an empirical model using an inductive approach based on radiotelemetry data. They found the expert-opinion model performed poorly compared to the other two models, caused by an overestimation of the importance of some factors by the experts, and a reliance on perception and memory instead of analyzed data.

The addition of expert input during model construction also caused a decline in the ability of a model to predict the occurrence of several bird species in Spain, compared to an inductive model (Seone et al. 2005). Inductive ("unsupervised") models outperformed deductive ("supervised") models when tested within the area used to build the model and also in a neighboring area. In at least one case, the inductive model found a bird species to have an opposite relationship with a habitat variable than was predicted by the expert in the deductive model. Given the resources required to integrate expert opinion and the lack of evidence that it improves the performance of models, the use of an inductive approach appears to be the most efficient and effective technique available.

In addition to the inductive/deductive classification, models can also be defined by their ability to represent reality, precision, and generality (Guisan & Zimmermann 2000). Depending on the goals of the study and the methods used, models are generally thought to be one of three types (Guisan & Zimmermann 2000): (1) general and precise (sacrificing reality); (2) realistic and general (sacrificing precision); or (3) precise and realistic (sacrificing generality). These types result from the fact that the complexity of nature prevents a single model from accurately predicting a species' occurrence in every aspect of time and space.

GIS models of predicted species occurrence have been developed for a wide variety of taxa, including plants (Iverson et al. 1997; Rouget et al. 2001; Skov 2000; Welk et al. 2002; Zaniewski et al. 2002), butterflies (Fleishman et al. 2003; Fleishman et al. 2002; Luoto et al. 2002; Mac Nally et al. 2003), salamanders (Diller & Wallace 1994; Gustafson et al. 2001), rattlesnakes (Browning 2000; Standora 2002), birds (Conner 2002; Kilgo et al. 2002; Lauver et al. 2002; Lenton et al. 2000; Luck 2002a, b; Manel et al. 1999a; Manel et al. 1999b; Maurer 1987; Mitchell et al. 2001; Ozesmi & Mitsch 1997; Peterson 2001; Tucker et al. 1997; Wenjun & Zijian 2000), bats (Jaberg & Guisan 2001), pocket mice (Anderson et al. 2002), jackrabbits (Knick & Dyer 1997), cougars (Riley & Malecki 2001), muskoxen (Danks & Klein 2002), reedbuck (Fabricius & Coetzee 1992), marsupials (Jackson & Claridge 1999; Pausas et al. 1995), lemurs (Smith et al. 1997), and whales (Moses & Finn 1997). In order to predict the occurrence of species, researchers have used a variety of statistical techniques to describe the species-environment relationship. Techniques have included Boolean models (Browning 2000), logistic regression (Gibson et al. 2004; Luoto et al. 2002; Minns & Moore 1995; Olden & Jackson 2002; Osborne et al. 2001; Pearce et al. 2001; Porter et al. 2000), generalized additive models (Franklin 1998; Lehmann et al. 2002; Zaniewski et al. 2002), and Mahalanobis Distance Statistic (Browning 2000; Clark et al. 1993; Conner 2002; Duncan & Dunn 2001; Knick & Dyer 1997), to name a few.

Previous attempts to develop models for predicting the occurrence of amphibians have met with mixed success. Prior to the widespread availability of GIS, Hafer (1992) examined potential habitat for the Green Salamander (*Aneides aeneus*) in the mountains of South Carolina by superimposing a grid of 0.16 km^2 squares over 7.5' topographic maps of the study area and ranking each square as to its suitability for the species. Suitable habitat was defined as meeting criteria derived from known populations of the species. Using this method, four new populations of Green Salamanders were discovered, extending the species' range 32 km to the east. Using a GIS model that incorporated the age of a forest and a number of indirect measurements of soil moisture, Gustafson et al. (2001) were able to predict salamander (family Plethodontidae) abundance and mass in a central Indiana forest. Although the model's performance was termed "modest," it served the purpose of the study, so refinements that would have improved the model's accuracy and robustness were not undertaken.

An attempt to predict the occurrence of nine anuran species across Minnesota, Wisconsin, and northern Illinois also produced mixed results (Johnson et al. 2002). The researchers found that the species had different responses to chosen local and landscape factors when assessed at different scales and that these responses differed among geographic regions. This research highlights the reality that no one model is able to make accurate predictions for even one species in every aspect of time and space, and the importance of choosing an appropriate model based primarily on the goals of the study (Guisan & Zimmermann 2000).

Many amphibian species offer a unique challenge for developing models of predicted occurrence. Determining when a cryptic species is "absent" from a site can be problematic compared to easily observed species or those which leave behind signs of their occupancy (e.g., prairie dog towns). This increased probability of "false negatives" for cryptic species can compromise the predictive power of models (Browning 2000; Clark et al. 1993). Some researchers have turned to methods that require presence-only data, including the Mahalanobis Distance Statistic (Browning 2000; Clark et al. 1993; Duncan & Dunn 2001; Standora 2002). However, this procedure requires sample sizes of areas of known occupancy of $n+1$ to construct models from n variables. Cryptic species are often also rare species, known from very few locations, making it difficult to meet the sample size requirements of many statistical methods.

The Green Salamander in Ohio

The Green Salamander (Fig. 1) is the only member of the genus *Aneides* to be found east of the Mississippi River. Its distribution corresponds with the Appalachian Mountains from extreme southwestern Pennsylvania to northern Alabama and extreme northeastern Mississippi, as shown in Figure 2 (Petranka 1998). The Green Salamander's diminutive size (80-169 mm total length) as well as its cryptic nature and nocturnal behavior allowed it to go unreported from Ohio until 1941, when it was found on limestone cliffs in Adams County (Walker & Goodpasteur 1941). To date, the Green Salamander has only been reported from three southern counties in Ohio (Fig. 3). Given its rarity and limited distribution, the Ohio Division of Wildlife lists the species as endangered in the state.

All known populations of Green Salamanders are associated with rock outcrops and cliffs in forested areas where the species lives the majority of its life within crevices in the rocks (Petranka 1998). Green Salamanders have been observed outside of these rock crevices, however, and the use of other habitats is currently being investigated. On two occasions, Lipps (2003) observed Green Salamanders inside of holes in trees contacting a rock outcrop. The use of trees has been noted before [see references in Petranka (1998)], and appears to be a habit shared by populations throughout the species' range (Jeff Humphries, Clemson University, personal communication). Some researchers have remarked on the difficulty of finding Green Salamanders in their described habitat (rock outcrops) during or immediately following precipitation (Juterbock 1986) or in mid-summer (Hafer 1992). It is possible that Green Salamanders may leave the rock face to forage at these times. Juterbock (1986) noted that previous studies of stomach contents have found invertebrates more commonly associated with trees and forest litter than rock outcrops.

Green Salamander courtship and breeding has been reported in the spring, summer, and fall (Petranka 1998). Egg-laying occurs in the early summer, with female Green Salamanders remaining with their clutch of about 20 eggs for 3-5 weeks post-hatching. Eggs are usually suspended from the roof of a rock crevice, but have also been found under the bark of decaying trees (Pope 1928).

Little is known about the population dynamics or status of Green Salamanders in Ohio. Juterbock (1986) studied two Adams County, Green Township populations through a mark-recapture survey. From 1985–1987 at Abner Hollow, he estimated the minimum number of adult salamanders on each side of Waggoner Riffle Run to be between 8 and 10. Likewise, the minimum adult population at Cave Hollow was estimated at 15–20 individuals from 1982–1984. Juterbock points out the difficulty in accurately censusing populations of Green Salamanders due to their extremely secretive nature.

While apparently suitable habitat (forested rock outcrops) occur throughout much of southern Ohio, only a few locations along the Ohio River are known to support populations of Green Salamanders. There exists no satisfactory explanation for the species' unusual distribution in Ohio (Juterbock 1989). Severe declines of this species have been documented in the Blue Ridge Escarpment of North Carolina (Corser 2001), but a lack of data prevents such an assessment in Ohio. A one year survey in Ohio located Green Salamanders at only 7 of 17 historical localities surveyed (Lipps 2003). This vulnerability, as well as the rarity and specialized habitats of the Green Salamander in the state makes it an ideal pilot species for developing predictive models.

Objectives

The objectives of this research were to investigate methods for developing and testing models of predicted occurrence for rare amphibian species, utilizing the Green Salamander in Ohio as a case study. A model of predicted occurrence has utility from both a conservation and management viewpoint, and is also well suited for testing basic assumptions about the ecological requirements of a species. Overcoming the limitations of presence-only data and low sample sizes, two attributes common with rare amphibians, were seen as central to the project. Specific research objectives included:

1) Identifying precise locations where Green Salamanders are known to occur, to serve as training data in building the model.
2) Choosing landscape habitat characteristics relevant to the biology of the Green Salamander to use as variables in building the model.
3) Developing a predictive model for the occurrence of the Green Salamander.
4) Evaluating the model's performance through standardized field surveys.
5) Suggesting management and conservation strategies for the Green Salamander in Ohio.

METHODS AND MATERIALS

Study Area

The study area for this project consisted of the 3 southern Ohio counties for which records of Green Salamanders exist: Adams, Scioto, and Lawrence, encompassing approximately 4310 km^2 (Fig. 3). These counties lie mostly in the Unglaciated Allegheny (Kanawha) Plateau of Ohio, a region characterized by moderately high to high relief, dissected plateaus, and generally rugged landscapes. The elevation ranges from 149 m-323 m above sea level.

As with all of Ohio, the age of the surface bedrock decreases on a west to east axis across the study site. In central Adams County, the bedrock is dominated by deposits of Silurian origin from 438-408 million years before present. Moving to the east, bedrock geology changes to Mississippian, Devonian, and finally Pennsylvanian origin, deposited 320-286 million years before present.

The dominant land cover/land use of the study area is forest, followed by agriculture, shrub scrub, and urban areas (Fig. 4). Agricultural use of the land is greatest in the relatively flat glaciated northwestern portion of Adams County, and the current Scioto River valley and historic Teays River valley in central and eastern Scioto County. Most of the rugged, unglaciated portions of the study area are forested. The two largest cities in the study area, Portsmouth and Ironton, are located in southern Scioto and Lawrence Counties, respectively, along the Ohio River.

While forest is the major land cover of the area today, this has not always been true. In the first half of the 1800's, iron furnaces were built in southern Ohio and northern Kentucky to take advantage of the timber, limestone, and iron ore of the region. By 1860, the iron furnaces of the region were producing more than 100,000 tons of iron annually, much of it from the 46 furnaces in operation in Ohio (Collins & Webb 1966). The operation of a single furnace required up to 4000 hectares of land every year for timber, ore, and limestone, and dwindling forest resources was a major reason for the decline of the furnaces. As a result, most of the eastern portion of the study area was clear-cut, in many places several times over the span of a century. The effects of this deforestation have been hypothesized to play a role in the distribution of the Green Salamander in Ohio (Gordon 1952).

The study area includes managed areas of 755.85 km^2 or 17.5% of the total area (Fig. 5). The largest managed areas include the United States Forest Service's Wayne National Forest, the Ohio Department of Natural Resources' Shawnee State Forest and Park, and The Nature Conservancy's Edge of Appalachia Preserve. Other smaller preserves and wildlife areas are also found in the study area.

Training Sites and Variable Selection

The most recent survey for the Green Salamander in Ohio found the species at seven locations in Adams and Lawrence Counties (Fig. 6; Lipps 2003). The selection of sites surveyed came from searches of museum collections, previous reports, and personal communications with individuals familiar with the species and the area. Where Green Salamanders were observed, the latitude and longitude of the location was recorded using a Garmin eTrex Legend® Global Positioning System (GPS; Garmin Ltd., Olathe, KS, USA). These seven locations served as the training sites for the current model, and were the first step in developing the model (Fig. 7).

A database of the training sites was developed in Excel (Microsoft Corp., Redmond, WA, USA) and imported into ArcGIS (ESRI, Redlands, CA, USA) using the "Add XY data" function and converted into a point shapefile. This shapefile was then laid over several other GIS data layers to examine the relationship of the training sites to environmental and landscape variables.

The goal of this procedure is to identify factors that have relatively little variability among the training sites in comparison to the variability over the entire study area. This procedure implicitly assumes some correlation between the needs of the Green Salamander and the layers being examined, although this correlation may be causal or simply functional (Corsi et al. 2000).

The selection of appropriate layers was guided by the current knowledge of Green Salamander biology and life history. The layers chosen reflect attributes of the landscape thought to be important to Green Salamanders, including topography, geology, land cover characteristics, distance to water, and climatic conditions. Landscape level variables were chosen due to their easy availability and complete coverage for the study area. Most of the variables considered for the model were downloaded via the internet or acquired free of charge from governmental agencies (Table 1).

Elevation is an important factor in the distribution of many organisms (Fleishman et al. 2001; Gibson et al. 2004; Jaberg & Guisan 2001; Smith et al. 1997) and is often correlated with other less easily measured variables such as temperature, precipitation, and solar radiation. Digital elevation data with a spatial resolution of 30 m was acquired from the United States Geological Survey (USGS) National Elevation Dataset (NED).

Several additional layers were developed using the elevation layer. These included slope [using the “Surface Analysis>Slope” function of Spatial Analyst Extension (ESRI 1996)], aspect (“Surface Analysis>Aspect”), and hillshade (“Surface Analysis>Hillshade”). Hillshade differs from slope in that it takes into account the azimuth and zenith of the sun (Theobald 2003), as well as the effect of adjacent hills (Iverson et al. 1997) on the amount of solar radiation reaching an area.

The association of Green Salamanders with rock outcrops is well documented (Petranka 1998; Walker & Goodpasteur 1941). Outcrops and cliffs are typically associated with limestone and sandstone bedrock formations in southern Ohio. A draft digital layer of bedrock units was supplied by the Ohio Department of Natural Resources (ODNR), Division of Geologic Survey. This layer was in vector format, with the bedrock units shown as polygons.

Green Salamanders are only known to live within forested areas (Petranka 1998). A digital data layer of percentage canopy cover derived from LandSat 7 ETM+ (Huang et al. 2001) was acquired from the USGS. As with the elevation layer, the spatial resolution of the canopy layer was 30 m.

While Green Salamanders do not enter water, the cliff ecosystems where they occur are often associated with waterways. Hafer (1992) included both the presence of drainage and distance to water as variables in her Green Salamander model. For this study, a digital hydrography layer was downloaded from the National Hydrography Dataset. Using the "Straight Line" distance function in the Spatial Analyst Extension of ArcGIS, a layer showing distance to water was created.

The distribution of the Green Salamander in southern Ohio suggests that the species may be limited in its northern distribution by climatic factors. To examine climatic conditions in the study area, digital layers of temperature means and extremes for 1971–2000 were acquired from the Spatial Climate Analysis Service.

In addition to the GIS data layers, unclassified LandSat 7 ETM+ images were also examined as potential data layers for the model. These images consisted of leaf-off images from December 11, 2001 from row 33, path 19, downloaded from the Ohio View consortium. Images were imported into ER Mapper 6.4 (Earth Resource Mapping, San Diego, CA, USA), processed, and exported into ArcGIS. The LandSat 7 ETM+ collects information from 6 electromagnetic bands, ranging from 0.45-2.35 µm with a spatial resolution of 30 m, and a single thermal band (10.4-12.5 µm) with 60 m resolution (Vincent 1997). GIS layers of each band separately and as a ratio (excluding the thermal band) with adjustment for atmospheric haze, as described by Vincent (1997), were developed making a total of 22 additional layers.

Model Development

The first step in model development required the conversion of all data layers into raster format. Raster data is stored as a grid of equal size squares or pixels, much like a digital image. Each pixel on the map has an associated data value. Unlike vector data that is stored as points, lines, or polygons, raster layers are easy to use in calculations and model building (Theobald 2003). The bedrock and distance to water layers were converted to raster layers with a pixel size of 30 m using the "Convert>Features to Raster" function of Spatial Analyst.

The next step was to project all of the data layers using a common datum and coordinate system. This allows for the curvature of the real-world spatial data to be displayed and analyzed on a planar surface with Cartesian coordinates (Theobald 2003). For this project, all data was projected in North American Datum 1983 (NAD83) Universal Transverse Mercator Zone 17 North (UTM 17N). The UTM system uses meters as the coordinate system.

Compilation of the attributes for each of the data layers at each of the seven training sites was automated using the "Intersect Point Tool" of Hawthe's Analysis Tool Extension for ESRI's ArcGIS (Beyer 2004). This extension collects a user-specified attribute of each of the layers at each of the training sites. This information is then appended to the table of attributes for the point layer. For this project, the value of each data layer being examined at each of the training sites was appended to the attribute table for the training sites.

The attributes of each of the layers at each training site were examined to determine factors with less variation among the training sites than the entire study area. The low variance of values for a particular attribute may indicate some correlation of the suitability of an area for the Green Salamander and a specific attribute. Conversely, attributes with an equal amount of variance at the training sites and across the entire landscape provide little utility for the model and are probably not playing an important role in determining the occurrence of the species. For the current model, attributes to be included in the model were determined by first calculating the difference of the minimum and maximum values of interval data for both the training sites and the entire study area. If the range at the training sites was less than 35% of the range of the entire landscape, then it was included in the model. Attributes with a range of values at the training sites greater than 35% of the range observed across the study area were not included. For nominal data, a similar procedure was utilized. If less than 15% of the total categories for an attribute were found at the training sites, that attribute was included in the model.

Once the attributes were selected, binary maps of suitability were produced for each attribute. These maps were produced using the "Reclassify" function of the Spatial Analyst Extension in ArcGIS. All pixels having values within the range found at the training sites were reclassified to a value of "1." Pixels falling outside of this range were reclassified to a value of "0."

The final habitat suitability model was produced using these binary maps and the "Raster Calculator" function of Spatial Analyst. All of the binary maps were summed together to produce a final map of predicted occurrence. This procedure assigned a "score" to each pixel on the map representing the number of attributes within the range found at the training sites. A pixel with values within the range of the training sites for all of the attributes received the highest score, equating to a prediction of highest suitability for the Green Salamander.

This final habitat suitability map assumed an equal importance of each attribute to the suitability of a site for the Green Salamander. To test this assumption, additional maps were produced with the suitability value of each attribute reversed, one at a time using the "Reclassify" function of Spatial Analyst. This procedure allows for the production of additional models where all but one of the model parameters is satisfied. Carrying out this procedure for all of the attributes, *n*, resulted in *n* new maps.

Model Evaluation

To evaluate the performance of the model and examine the importance of each attribute, field surveys for the Green salamander were conducted during September-October 2004. Visual encounter surveys were conducted at 92 sites for approximately 30 minutes each in a manner similar to Lipps (2003). Sites surveyed were one of two types, based on the output of the model: (1) areas where all of the attributes were within the range found at the training sites (predicted to be suitable Green salamander habitat); and, (2) areas where all but one of the attributes were within the range found at the training sites (predicted to not be suitable Green salamander habitat). For each site, Green salamanders were reported as "present" or "not detected." Model predictions were judged correct when Green salamanders were located in a pixel predicted to be suitable Green salamander habitat. Green salamanders found in areas predicted by the model to not contain suitable habitat were classified as errors of omission. Given the brevity of the surveys (30 minutes) and a probability of detection <1 for searches of all rock crevices (Hafter 1992), it was not feasible to calculate errors of commission (unsuitable habitat incorrectly classified as suitable).

To maximize the amount of time spent in the field, site visits were concentrated in the publicly owned Wayne National Forest and Shawnee State Forest or in The Nature Conservancy's Edge of Appalachia Preserve. This reduced the time required for locating and receiving permission from private landowners. These managed areas are spread throughout the study area (Fig. 5) and experience various levels of human impact, and are therefore thought to be representative of the entire study area. A shapefile of points within pixels with the highest score for each of the maps produced (the habitat suitability map and each of the maps with one of the attribute's values reversed) was uploaded to a handheld GPS unit (Garmin eTrex Legend®) using the DNR Garmin Extension for ArcView (Minnesota Department of Natural Resources), to aid in relocating the sites in the field.

Rock Composition

Across their range, Green Salamanders have been reported occurring on sandstone, granite, quartzite, and limestone cliffs and rock outcrops (Gordon & Smith 1949; Petranka 1998). In Ohio, it has been suggested that the Green Salamander is associated with limestone cliffs (Walker & Goodpasteur 1941), especially the Peebles-Lilly-Bisher formations of dolomite, and not the more numerous sandstone cliffs of southern Ohio. During field visits to validate the model, samples of rocks from cliffs were opportunistically collected in order to determine the rock type. In the lab, a subsample of the rocks was initially examined using a handheld spectrometer to determine the composition of the rocks and to develop an easy method for identifying the rock type. Based on the findings of the spectrometer, a simple acid assay was developed to determine the rock type (Robert K. Vincent, Bowling Green State University, personal communication). Two drops of one molar (3.6%) HCl were placed onto each rock sample and any reaction noted. Rocks that showed no reaction were then scraped with a sharp piece of metal, and two additional drops of acid placed on the abrasion. Rocks that reacted to the acid without scraping were determined to be limestone, while those that reacted only when scraped were determined to be dolomite. Rocks that did not react at all were determined to be sandstone.

Rock sampling locations were recorded using the handheld GPS unit, loaded into the GIS, then laid over the bedrock geology layer. Using the Hawth's Analysis Tools (Beyer 2004) "Intersect Point Tool," the geologic unit corresponding to each sampling unit was collected and analyzed, allowing for a comparison of the actual rock composition and that expected based on the reported lithology of the geologic unit.

RESULTS

Model Results

Six variables were found to meet the requirements for inclusion in the model (Table 1). Five interval scale variables — elevation (Fig. 9), slope (Fig. 10), percent canopy cover (Fig. 11), distance to water (Fig. 12), and mean annual temperature (Fig. 13) — each had a range of values at the training sites less than 35% of the range for the entire study area (Table 2). One nominal variable, bedrock type, was also included in the model (Fig. 14). Bedrock at the training sites was found to be dolomitic (Adams County), or Pennsylvanian Breathitt Formation (Lawrence County), which includes 5 of the 42 (<12%) bedrock types found across the study area (Table 3).

The range of values for these six attributes at the training sites were used to produce the Green Salamander habitat suitability model:

[(183 m>elevation<244 m) AND (slope>37%) AND (canopy>82%) AND (distance to water<325 m) AND (mean annual temperature>53.42^{o}F) AND (bedrock type = Peebles Dolomite, Lilley Formation, Bisher Formation – undivided (Splb) OR Peebles Dolomite (Sp) OR Lilley Formation (Sl) OR Bisher Formation (Sb) OR Pennsylvanian Breathitt Formation (IPb))].

For each model variable, 24.01 – 60.18% of the study area was within the range found at the training sites (Fig. 8). Combined, only 0.70% (30.27 km^2) of the study area possessed the required values for all six variables. These areas were concentrated in southeastern Adams County and western Lawrence County (Fig. 15).

The reversal of the suitability values for each variable resulted in the production of six additional maps representing areas where all but one of the six variables met the model parameters (Figs. 16-21). Depending on the variable, these reversals increased or decreased the area meeting the model requirements. For example, the reversal of the elevation criteria from (>183 m and <244 m) to (<183 m or >244 m) resulted in a reduction of the area meeting the model requirements by 25.47 km^2, while the reversal of the bedrock criteria caused an increase of 53.49 km^2 meeting the model requirements (Table 5).

Model Evaluation

To evaluate the model, a total of 92 sites throughout the study area were visited from September–October 2004 (Fig. 22). Thirty-nine of these sites were predicted to have suitable habitat for the Green Salamander, while the remaining 53 sites were predicted to be unsuitable due to the absence of one of the model variables (Table 6). Of these, five sites were found to have Green Salamanders, three in Adams County and two in Lawrence County. These sites represent new records for the species in Ohio and include the first reports of the species from within the Wayne National Forest.

Of the sites where Green salamanders were observed, one was located within a pixel predicted by the model to have suitable habitat, one was located in an area outside of the slope requirements, one outside of the canopy requirements and, two came from areas not satisfying the temperature criteria of the model (Table 6). The localities predicted by the model to be outside of the range of suitable canopy and slope were located <29 m (Easter Site, Fig. 23) and <19 m (Puntenny Run Site, Fig. 24), respectively from pixels meeting all of the model requirements (e.g., suitable habitat).

The two other sites where Green Salamanders were discovered (Mahogany and Rock Hollow) came from areas not meeting the temperature requirements of the model. The Mahogany and Rock Hollow sites had mean annual temperatures of 53.39^{o} F and 53.38^{o} F, respectively. This is 0.1° F lower than the lowest temperature found at the training sites (Table 3).

Rock Composition

A total of 38 rock samples were collected from sites visited in the study area, including at four of the five new Green Salamander localities. The rock at the two occupied Lawrence County sites was found to be sandstone, while the two occupied Adams County sites tested as dolomite and limestone. This is the first report of Green Salamanders utilizing sandstone habitats in Ohio.

The GPS coordinates collected at the rock collection points allowed for an easy comparison of the GIS bedrock layer and the actual rock observed (Table 7). Twenty-three of 24 (96%) sandstone samples were located on geologic units in the GIS expected to contain sandstone. Likewise, 5 of 6 (83%) dolomite samples, and 6 of 8 (75%) limestone samples were accurately plotted onto the GIS layer where geologic units with lithology of these types are reported to occur.

DISCUSSION

Significance of Results

The current modeling of the distribution of the Green salamander in Ohio highlights both the limitations and power of GIS models in predicting species occurrence. Further examination of two of the sites predicted by the model to be unsuitable, but where Green salamanders were observed, reveals that these errors were due to limitations in the technology and not the underlying criteria of the model. GPS points collected at the Easter and Puntenny Run sites place them into pixels not meeting the canopy and slope requirements of the model, respectively. Both of these points were <30 m from pixels classified as suitable by the model, however, and the sites appeared to meet the model criteria when examined during field surveys. In areas of rugged terrain such as southern Ohio, the effects of parallax (Vincent 1997) on GIS data and poor satellite reception on GPS accuracy could easily account for these inaccurate classifications.

Two of the five new localities were found in areas below the threshold temperature criteria used in the model. This finding suggests that temperature may not be an important factor limiting the distribution of the Green salamander in the state. Future studies may wish to remove or relax the temperature criteria to increase the accuracy of the model.

It is important to remember that areas where Green salamanders were not observed during the current study may still represent suitable habitat. These sites may currently be unoccupied or Green salamanders present at the site may have gone undetected. Hafer (1992) found that the probability of detection may be less than 1:5 (detections:visits) when all available rock crevices are examined at an occupied site. In order to fully evaluate the model's performance, more intensive searches at different times of year would be required. It would then be possible to calculate the commission error rate of the model (unsuitable habitat incorrectly classified as suitable) and would probably result in the finding of additional Green Salamander localities.

Errors of omission occur when the model incorrectly categorizes suitable habitat as unsuitable. In the current study, the model's omission error rate ranged from 0-25% for the six model variables (Table 6). As previously discussed, two of these errors are attributable to the decreased accuracy of the GIS data and GPS reception, however, and not the actual model parameters. Removing these data points from the analysis results in no commission errors for all except the mean annual temperature category.

In order for a model to be useful for conservation and management purposes, it must be able to locate additional sites where the species has not yet been reported. When examined in this way, the current model performed well, resulting in the discovery of five additional locations for the Green salamander in Ohio, a 71% increase in the number of known sites for this endangered species. For surveying purposes, the model reduced the area to be searched considerably, from 4310 km^2 (the entire study area) to an area of 30.27 km^2 that satisfied the model criteria. Given the crisis nature of conservation biology, developing more systematic and efficient methods for quickly locating rare and endangered organisms has real value for land managers, governmental regulators, and field biologists.

In addition to locating unreported sites of occupancy, the methodology presented in the current study provides an easy and efficient technique for testing the importance of environmental variables in determining the distribution of species. By reversing the values that are thought to be important in making a habitat suitable, then surveying sites where all of the model criteria except this one are met, it is possible to investigate the relative importance of each variable to the habitat suitability model. In the current study, two sites not meeting the temperature criteria of the model were found to be occupied by Green salamanders, suggesting that the role of this variable in the distribution of the species requires further scrutiny.

A significant discovery resulting from this study was the presence of Green salamanders at two sites within the Wayne National Forest. This 95,000 hectare forest is the only national forest in Ohio, and is managed for multiple uses including recreation and timber and mineral extraction. Environmental analysis conducted as part of forest management plans should now include potential impacts to Green salamanders and their habitats. Buffer zones around cliffline habitats have been implemented at other National Forests (United States Forest Service 1990), and may be appropriate within the Wayne National Forest.

Sites where Green salamanders are known to occur in Ohio are clustered into two areas. In southeastern Adams County (Green Township) the species is found throughout the Edge of Appalachia Preserve, south of State Route 125. All of these sites occur on cliffs of limestone or dolomite. In western Lawrence County (>5 km to the east) the species appears to be found on sandstone cliffs. This is the first report of Green salamanders utilizing sandstone cliffs in Ohio. The difference between the two areas may simply reflect the difference in the rock types available, or may represent real differences between populations in the two areas. The lack of Green salamanders between these two areas (Scioto County) is puzzling and deserves additional investigation.

Limitations of GIS Models

GIS models have significant limitations that cannot be ignored. One of the most obvious shortcomings in the current model is the resolution of the digital data used to produce the model. All data has an associated spatial resolution, accuracy, and precision. For much of the data used in this study, the spatial resolution was 30 m, and this was the resolution used for producing the model. A pixel of 30 m is a square with sides of 30 m, and an area of 900 m^2. The spatial resolution is a measure of the amount of heterogeneity that can be captured by the layer. Only one value can be associated with each attribute for each area of 900 m^2. While some variables are fairly homogeneous and not likely to change within an area of this size (e.g., bedrock), other variables may show considerable variation that will be masked by the spatial resolution. A small rock outcrop is likely to go unrecognized in a slope layer with 30 m spatial resolution (e.g., the Puntenny Run site, Fig. 24). Likewise, the lowered precision may cause canopy gaps over roadways and fields to be incorrectly extended beyond the actual gap into the adjacent forest. At the Easter site (Fig. 23), this appears to be what occurred. A pasture lacking canopy cover extends up to the cliffline. Although the cliffline is in fact forested, the coarse resolution of the canopy layer incorrectly classifies the location of the Green Salamander observation as having no canopy.

The limitations of resolution have been discussed by others utilizing GIS and remote sensing for predicting species occurrence. In Yellowstone National Park, satellite data was found to be useful for identifying potential areas where certain bird species may located, but vegetative and habitat data with a much higher spatial resolution was necessary to accurately determine nesting and breeding habitats (Saveraid et al. 2001). Ground-collected data in Great Britain also improved the precision of land cover classifications and predictions of bird species richness when compared to satellite data (Mack et al. 1997). However, given the costs associated with the high resolution data, the authors concluded that less expensive, low resolution data may be more suitable in some circumstances, depending on the ecological problem being addressed (Mack et al. 1997). Recently launched commercial satellites hold some promise of narrowing the “scale gap” in remotely sensed data used to produce much of the GIS data layers. The IKONOS (Space Imaging) and QuickBird (DigitalGlobe) systems offer panchromatic imagery at 1 m and 0.6-0.8 m, respectively and slightly lower resolution multispectral images (Turner et al. 2003).

Additional limitations of precision and accuracy come from the methods used to locate specific areas in the field during the model evaluation. Handheld GPS units may be as accurate as 10 m in flat terrain with few obstructions. In the hills and valleys of southern Ohio, however, accuracy sometimes dropped to >15 m, and achieving a fix from the satellites was not always possible without moving 1-2 m away from the exact observation point. It was also difficult to assess the exact location of areas being searched in relation to the GIS model due to the limited number of reference points loaded into the GPS unit. The use of ruggedized Pocket PCs with integrated GPS hardware and GIS software (e.g., Trimble GeoExplorer™) could help alleviate some of these issues, by allowing the results of GIS models to be taken directly into the field and locations to be ground-truthed using additional maps with easily recognized landmarks (e.g., aerial photographs).

Models of predicted occurrence typically assume no effect from changes in the temporal scale. Historic land use has been incorporated into some models (Crosswhite et al. 1998), but in general, variables within the model are static. This assumption could be easily violated in areas where stochastic events occur frequently or landscapes are being rapidly altered. The use of training data collected long before the model is developed or during a different season could also decrease the predictive power of the model. For example, training data collected during a bird's migration period would not be expected to adequately predict breeding sites. In the current model, Green Salamander training sites were collected during the late summer and fall of 2002

(Lipps 2003), and model evaluation occurred during the same time of year in 2005, minimizing the probability of model error due to changes in the temporal scale.

The predictive ability of a model typically decreases as it is applied to sites further from the area utilized in its development (Guisan & Zimmermann 2000; Luoto et al. 2002; Seone et al. 2005). The current model was developed based on the observations of Green Salamanders in Ohio and the characteristics of the habitat at these sites. Cross-validation of the model in other areas of the Green Salamander's range would be useful but was outside of the scope of this project.

While models of predicted occurrence may help to answer the question of *where* a species occurs, caution must be taken when inferring causation from a model's predictions. *Why* a particular species' distribution closely tracks slope, for example, could be caused by a number of factors. Slope, elevation, or aspect may be surrogate measures of wind, soil moisture, solar radiation, or other local climatic conditions (Corsi et al. 2000; Guisan & Zimmermann 2000; Luoto et al. 2002). In southwest Finland, the slope of the land was positively correlated to the distribution of the clouded apollo butterfly (Luoto et al. 2002). The authors explained this correlation by the fact that higher slope areas are more difficult to cultivate, leading to higher quality grassland habitats correlated with areas of greater slope (Luoto et al. 2002). Although the variables used in the current model were chosen based on the reported biological requirements of the Green Salamander, it must be acknowledged that the variables may be surrogate measurements of the actual causal factors affecting the distribution of the species.

Rare Amphibians and Small Sample Sizes

The majority of predicted occurrence models that have been developed utilize statistical techniques that assume locations without presence data are areas not utilized by the species

(Cumming 2002; Jaberg & Guisan 2001; Olden & Jackson 2002; Pereira & Itami 1991; Standora 2002). This, in turn, leads to a greater probability of "false negatives"- areas incorrectly categorized as absence sites. Utilizing absence sites for rare organisms like the Green Salamander risks eliminating habitats that are potentially useful for the species. It is possible that absence sites: (1) have not been surveyed; (2) have been surveyed but the organism was missed by the surveyor; or, (3) have suitable habitat, but have yet to be colonized by the species. By using only presence data to develop the current model, the problem of false negatives is avoided. For rare and cryptic species, delineating areas matching the conditions found at the few occupied sites and avoiding the issue of absence sites, offers a valuable alternative for developing models of predicted occurrence.

Prior to the current survey, Green Salamanders were known to occur in only 7 sites in Ohio. Such a small sample size greatly limits the number of statistical techniques available for developing a model of predicted occurrence. Sample sizes of several hundred are commonly used for developing models, and large numbers are usually necessary for achieving statistical significance with the model results. Although models for rare and endangered species are likely to have the most utility for conservation and land management, by their definition, rare species are unlikely to be known from more than a few locations. This can lead to a "widening gulf" (Seone et al. 2005) between scientists who pay too much attention to statistical assumptions of models and the land managers who urgently need the information derived from the models, especially when dealing with endangered organisms. The current model provides a straightforward and effective methodology for constructing a model with a very small sample size. The increase in the number of sites known to be occupied (71% in the current study) creates feedback that can be used to further refine the model and utilize more rigorous modeling techniques in the future.

Recommendations for Future Modeling

The precision and accuracy of the current model would benefit most from an increase in the spatial resolution of the data utilized to construct the model. The 30 m resolution of the canopy layer resulted in a jagged edge effect along forested and non-forested areas. This causes roads through forested areas and the interface of agricultural and forested areas to have poorly defined edges, with their accuracy often dependent on their alignment with the pixel of the satellite image used to create the layer.

Likewise, elevation, and the data layers developed from the elevation layer (slope, aspect, and hillshade) were not as precise as desired. Small changes in elevation (slope) associated with some clifflines and rock outcrops are easily missed using the 30 m elevation layer. As the clifflines are important habitats for a variety of rare and endangered species, not just Green Salamanders, identifying these areas is seen as a priority for future modeling. The production of a slope layer with <1 m spatial resolution using stereo-pairs of aerial photographs and DEMGen (digital elevation model generating software) is currently being investigated. A future model, limited only to areas identified as clifflines, may prove to be very useful for land managers of the area (Chris Bedel, Edge of Appalachia Preserve, personal communication).

The computational simplicity of the current model allows it to be easily updated as additional Green Salamander observations are reported in Ohio. Future models should incorporate the findings of this study, by reducing the minimum annual mean temperature parameter. As the sample size of potential training sites increases, additional statistical modeling techniques should be investigated, including the modified Mahalanobis Distance Statistic, which requires presence-only data (Duncan & Dunn 2001).

It is possible that the addition of data layers describing other attributes of the Green Salamander's habitat could help to improve the current model. In South Carolina, the presence of drainage, in addition to distance to water, was used to describe areas with a high probability of having Green Salamander habitat (Hafer 1992). As more is learned about the behavior of the Green Salamander, data such as forest composition and age, tree density, and distance to nearest known occupied site may be considered for inclusion in a predictive model. A data layer of historic iron furnaces could be incorporated into the current model to examine the relationship between locations of the furnaces and Green Salamander sites. Forest clearing to fuel the furnaces in the 1800's may have extirpated some salamander populations (Gordon 1952), and one might expect that this occurred with greater frequency closer to the furnaces.

Most habitat suitability and predicted occurrence models that are developed are never validated through field surveys. Demonstrating the utility of these models is of critical importance, however, if ecologists wish to fulfill the needs of an increasing number of land managers needing distribution maps for every species (Seone et al. 2005). Moving these models off of the computer and into the field can result in substantial increases in our understanding of species distributions, status, and habitat requirements.

Implications for Management and Conservation

The Green Salamander is known only from rocky outcrops and clifflines in forested areas in southern Ohio. Many, if not all, populations of Green Salamanders have experienced clearing of the forest through timbering operations that peaked in the mid 1800's, but continue today. How Green Salamanders respond to logging is unknown. Sites where the species is extant today may have been driven to extinction by previous forest clearing, and then recolonized by adjacent sites after forest regeneration. Forest clearing would be expected to increase temperatures, surface runoff, and possibly alter the invertebrate prey base of the habitat. Observations of Green Salamanders utilizing trees add to the evidence of the importance of forests for this species.

Green Salamanders would be expected to benefit from the inclusion of buffer zones around clifflines in areas where logging is occurring. In the USFS Daniel Boone National Forest (Kentucky, USA), buffer zones of forest above and below the cliffline are used to protect the microenvironment used by many cliff dwelling species (USFS 1990). The observation of a Green Salamander along a forest edge at the Easter site gives some hope that the species may be able to tolerate at least some fragmentation. Presence, however, does not equal viability, and it would be irresponsible to make any conclusions based on the observation of a single individual at this site.

Very little is known about the behavior and life history of Green Salamanders in Ohio. While the protection of corridors of habitat is a commonly recommended management objective for endangered species (Meffe & Carroll 1997), further study of the habitat use and dispersal of the species would be very valuable in predicting the impact of different management scenarios on the viability of populations. Radiotelemetry and fluorescent tracking powder have been used to track the movements of other amphibian species (Eggert 2002) and the feasibility of using these techniques with the Green Salamander should be investigated further. Genetic analysis of individuals at different sites may help to understand the degree of isolation among sites and aid in determining barriers to their dispersal. Requests to collect genetic samples have been denied by land managers in the past due to the unknown status of the species in the area, but the use of buccal swabs for collecting samples from amphibians may offer a non-intrusive alternative (Poschadel & Moller 2004).

Juterbock (1989) stated that the Green Salamander was probably present in more sites than had been documented at the time of his writing. The current study supports his hypothesis, and suggests that even more sites are likely to be discovered with additional field work. Evaluation of the model was mostly concentrated in the managed areas found within the study area. Sites were visited only once, and private land was investigated very little. The probability of detection of Green Salamanders at an occupied site may be lower than 1:5 (detection:visits) (Hafer 1992), and additional surveys of sites where the species was not found is warranted. Privately owned property meeting the criteria of the model should also be investigated, especially along the Ohio River in western Lawrence County (Fig. 15).

Conclusions

GIS models of predicted occurrence expand the ability of researchers to investigate large geographic areas and the combination of factors that may lead to a species presence. Directing time and effort to particular areas of interest identified by the model makes for more efficient use of the limited resources available to conservation. Rare and cryptic species pose problems for developing predictive models, particularly due to low sample sizes and the inability to determine sites of absence. However, if the objective is to efficiently and systematically identify areas likely to have unreported populations, then the straightforward approach utilized in this study provides a framework that can be easily applied to other rare amphibian species.

LITERATURE CITED

Anderson, R. P., M. Gomez-Laverde, and A. T. Peterson. 2002. Geographical distributions of spiny pocket mice in South America: insights from predictive models. Global Ecology and Biogeography 11:131-141.

Beyer, H. L. 2004. Hawth's Analysis Tools for ArcGIS. Available from http://www.spatialecology.com/htools/ (accessed April 2004).

Blaustein, A. R., and J. M. Kiesecker. 2002. Complexity in conservation: Lessons from the global decline of amphibian populations. Ecology Letters 5:597-608.

Browning, D. M. 2000. A comparison of a modified form of Mahalanobis Distance Statistic and Boolean methods to devise GIS-based models of the denning habitat of the Timber Rattlesnake (*Crotalus horridus*) in northwest Arkansas. Master's Thesis. University of Arkansas, Fayetteville.

Clark, J. D., J. E. Dunn, and K. G. Smith. 1993. A multivariate model of female black bear habitat use for a geographic information system. Journal of Wildlife Management 57:519-526.

Clevenger, A. P., J. Wierzchowski, B. Chruszcz, and K. Gunson. 2002. GIS-generated, expert-based models for identifying wildlife habitat linkages and planning mitigation passages. Conservation Biology 16:503-514.

Collins, H. R., and D. K. Webb. 1966. The Hanging Rock Iron Region of Ohio. The Ohio Historical Society, Columbus, OH.

Collins, J. P., and A. Storfer. 2003. Global amphibian declines: Sorting the hypotheses. Diversity and Distributions 9:89-98.

Conner, L. M. 2002. A technique to locate isolated populations using satellite imagery. Wildlife Society Bulletin 30:1044-1049.

Corser, J. D. 2001. Decline of disjunct green salamander (*Aneides aeneus*) populations in the southern Appalachians. Biological Conservation 97:119-126.

Corsi, F., J. d. Leeuw, and A. Skidmore. 2000. Modeling Species Distributions with GIS. Pages 388-434 in L. Boitani, and T. K. Fuller, editors. Research Techniques in Animal Ecology: Controversies and Consequences. Columbia University Press, New York.

Crosswhite, D. L., S. F. Fox, D. M. Leslie, Jr., and M. S. Gregory. 1998. Distribution of the Ouachita Dusky Salamander (*Desmognathus brimleyorum*) in southeastern Oklahoma. Proceedings of the Oklahoma Academy of Science 78:49-52.

Cumming, G. S. 2002. Comparing climate and vegetation as limiting factors for species ranges of African ticks. Ecology (Washington D.C.) 83:255-268.

Danks, F. S., and D. R. Klein. 2002. Using GIS to predict potential wildlife habitat: A case study of muskoxen in northern Alaska. International Journal of Remote Sensing 23:4611-4632.

Diller, L. V., and R. L. Wallace. 1994. Distribution and habitat of *Plethodon elongatus* on managed, young growth forests in north coastal California. Journal of Herpetology 28:310-318.

Duncan, L., and J. E. Dunn. 2001. Partitioned Mahalanobis D^2 to improve GIS classification. Pages 198-126. SAS's Users Group International Conference.

Eggert, C. 2002. Use of fluorescent pigments and implantable transmitters to track a fossorial toad (*Pelobates fuscus*). Herpetological Journal 12:69-74.

ESRI 1996. Using the ArcView Spatial Analyst. Environmental Systems Research Institute, Redlands, CA.

Fabricius, C., and K. Coetzee. 1992. Geographic information systems and artificial intelligence for predicting the presence or absence of mountain reedbuck. South African Journal of Wildlife Research 22:80-86.

Fleishman, E., R. Mac Nally, and J. P. Fay. 2003. Validation tests of predictive models of butterfly occurrence based on environmental variables. Conservation Biology 17:806-817.

Fleishman, E., R. Mac Nally, J. P. Fay, and D. D. Murphy. 2001. Modeling and predicting species occurrence using broad-scale environmental variables: an example with butterflies of the great basin. Conservation Biology 15:1674-1685.

Fleishman, E., C. Ray, P. Sjogren-Gulve, C. L. Boggs, and D. D. Murphy. 2002. Assessing the roles of patch quality, area, and isolation in predicting metapopulation dynamics. Conservation Biology 16:706-716.

Franklin, J. 1998. Predicting the distribution of shrub species in southern California from climate and terrain-derived variables. Journal of Vegetation Science 9:733-748.

Gibson, L. A., B. A. Wilson, D. M. Cahill, and J. Hill. 2004. Modelling habitat suitability of the swamp antechinus (*Antechinus minimus maritimus*) in the coastal heathlands of southern Victoria, Australia. Biological Conservation 117:143-150.

Gordon, R. E. 1952. A contribution to the life history and ecology of the plethodontid salamander *Aneides aeneus* (Cope and Packard). American Midland Naturalist 47:666-701.

Gordon, R. E., and R. L. Smith. 1949. Notes on the life history of the salamander *Aneides aeneus*. Copeia 1949:173-175.

Guisan, A., and N. E. Zimmermann. 2000. Predictive habitat distribution models in ecology. Ecological Modelling 135:147-186.

Gustafson, E. J., N. L. Murphy, and T. R. Crow. 2001. Using a GIS model to assess terrestrial salamander response to alternative forest management plans. Journal of Environmental Management 63:281-292.

Hafer, M. L. A. 1992. Survey of the Green Salamander in South Carolina. Master's Thesis. Clemson University, Clemson, SC.

Huang, C., L. Yang, B. Wylie, and C. Homer. 2001. A strategy for estimating tree canopy density using LandSat 7 ETM+ and high resolution images over large areas. Third International Conference on Geospatial Information in Agriculture and Forestry, Denver, Colorado.

Iverson, L. R., M. E. Dale, C. T. Scott, and A. Prasad. 1997. A GIS-derived integrated moisture index to predict forest composition and productivity of Ohio forests (U.S.A.). Landscape Ecology 12:331-348.

Jaberg, C., and A. Guisan. 2001. Modelling the distribution of bats in relation to landscape structure in a temperate mountain environment. Journal of Applied Ecology 38:1169-1181.

Jackson, S. M., and A. Claridge. 1999. Climatic modelling of the distribution of the mahogany glider (*Petaurus gracilis*), and the squirrel glider (*P. norfolcensis*). Australian Journal of Zoology 47:47-57.

Johnson, C. M., L. B. Johnson, C. Richards, and V. Beasley. 2002. Predicting the occurrence of amphibians: An assessment of multiple-scale models. Pages 157-170 in J. M. Scott, P. J. Heglund, M. L. Morrison, J. B. Haufler, M. G. Raphael, W. A. Wall, and F. B. Samson, editors. Predicting Species Occurrences: Issues of Accuracy and Scale. Island Press, Washington, D.C.

Juterbock, J. E. 1986. The ecology of the green salamander, *Aneides aeneus*, in Ohio. I. Life History. Ohio State University, Lima, OH.

Juterbock, J. E. 1989. *Aneides aeneus* (Cope and Packard) Green Salamander. Pages 190-196 in R. A. Pfingsten, and F. L. Downs, editors. Salamanders of Ohio. Ohio Biological Survey, Columbus, OH.

Kiesecker, J. M., A. R. Blaustein, and L. K. Belden. 2001. Complex causes of amphibian population declines. Nature (London) 410:681-684.

Kilgo, J. C., D. L. Gartner, B. R. Chapman, J. B. Dunning, Jr., K. E. Franzreb, S. A. Gauthreaux, C. H. Greenberg, D. J. Levey, K. V. Miller, and S. F. Pearson. 2002. A test of an expert-based bird-habitat relationship model in South Carolina. Wildlife Society Bulletin 30:783-793.

Knick, S. T., and D. L. Dyer. 1997. Distribution of black-tailed jackrabbit habitat determined by GIS in southwestern Idaho. Journal of Wildlife Management 61:75-85.

Kushwaha, S. P. S., and P. S. Roy. 2002. Geospatial technology for wildlife habitat evaluation. Tropical Ecology 43:137-150.

Lannoo, M. J., editor. 1998. Status and Conservation of Midwestern Amphibians. University of Iowa Press, Iowa City, IA.

Lauver, C. L., W. H. Busby, and J. L. Whistler. 2002. Testing a GIS model of habitat suitability for a declining grassland bird. Environmental Management 30:88-97.

Lehmann, A., J. R. Leathwick, and J. M. Overton. 2002. Assessing New Zealand fern diversity from spatial predictions of species assemblages. Biodiversity and Conservation 11:2217-2238.

Lenton, S. M., J. E. Fa, and J. Perez Del Val. 2000. A simple non-parametric GIS model for predicting species distribution: endemic birds in Bioko Island, West Africa. Biodiversity and Conservation 9:869-885.

Lipps, G. J. 2003. A survey of the Green Salamander in Ohio. Ohio Division of Wildlife, Columbus, OH.

Luck, G. W. 2002a. The habitat requirements of the rufous treecreeper (*Climacteris rufa*). 1. Preferential habitat use demonstrated at multiple spatial scales. Biological Conservation 105:383-394.

Luck, G. W. 2002b. The habitat requirements of the rufous treecreeper (*Climacteris rufa*). 2. Validating predictive habitat models. Biological Conservation 105:395-403.

Luoto, M., M. Kuussaari, and T. Toivonen. 2002. Modelling butterfly distribution based on remote sensing data. Journal of Biogeography 29:1027-1037.

Mac Nally, R., E. Fleishman, J. P. Fay, and D. D. Murphy. 2003. Modelling butterfly species richness using mesoscale environmental variables: model construction and validation for mountain ranges in the Great Basin of western North America. Biological Conservation 110:21-31.

Mack, E. L., L. G. Firbank, P. E. Bellamy, S. A. Hinsley, and N. Veitch. 1997. The comparison of remotely sensed and ground-based habitat area data using species-area models. Journal of Applied Ecology 34:1222-1228.

Manel, S., J. M. Dias, S. T. Buckton, and S. J. Ormerod. 1999a. Alternative methods for predicting species distribution: An illustration with Himalayan river birds. Journal of Applied Ecology 36:734-747.

Manel, S., J.-M. Dias, and S. J. Ormerod. 1999b. Comparing discriminant analysis, neural networks and logistic regression for predicting species distributions: a case study with a Himalayan river bird. Ecological Modelling 120:337-347.

Maurer, B. A. 1987. Predicting habitat quality for grassland birds using density-habitat correlations. Journal of Wildlife Management 50:556-566.

Meffe, G. K., and C. R. Carroll. 1997. Conservation Reserves in Heterogeneous Landscapes. Pages 305-339 in G. K. Meffe, and C. R. Carroll, editors. Principles of Conservation Biology. Sinauer Associates, Inc., Sunderland, MA.

Minns, C. K., and J. E. Moore. 1995. Factors limiting the distributions of Ontario's freshwater fishes: The role of climate and other variables, and the potential impacts of climate change. Canadian Special Publication of Fisheries and Aquatic Sciences 121:137-160.

Mitchell, M. S., R. A. Lancia, and J. A. Gerwin. 2001. Using landscape-level data to predict the distribution of birds on a managed forest: Effects of scale. Ecological Applications 11:1692-1708.

Moses, E., and J. T. Finn. 1997. Using Geographic Information Systems to predict North Atlantic right whale (*Eubalaena glacialis*) habitat. Journal of Northwest Atlantic Fishery Science:37-46.

Olden, J. D., and D. A. Jackson. 2002. A comparison of statistical approaches for modelling fish species distributions. Freshwater Biology 47:1976-1995.

Osborne, P. E., J. C. Alonso, and R. G. Bryant. 2001. Modelling landscape-scale habitat use using GIS and remote sensing: a case study with great bustards. Journal of Applied Ecology 38:458-471.

Ozesmi, U., and W. J. Mitsch. 1997. A spatial habitat model for the marsh-breeding red-winged blackbird (*Agelaius phoeniceus* L.) in coastal Lake Erie wetlands. Ecological Modelling 101:139-152.

Pausas, J. G., L. W. Braithwaite, and M. P. Austin. 1995. Modelling habitat quality for arboreal marsupials in the South Coastal forests of New South Wales, Australia. Forest Ecology and Management 78:39-49.

Pearce, J., S. Ferrier, and D. Scotts. 2001. An evaluation of the predictive performance of distributional models for flora and fauna in north-east New South Wales. Journal of Environmental Management 62:171-184.

Pechmann, J. H. K., D. E. Scott, R. D. Semlitsch, J. P. Caldwell, L. J. Vitt, and J. W. Gibbons. 1991. Declining amphibian populations: The problems of separating human impacts from natural fluctuations. Science (Washington D.C.) 253:892-895.

Pereira, J. M. C., and R. M. Itami. 1991. GIS-based habitat modeling using logistic multiple regression: a study of the Mt. Graham red squirrel. Photogrammetric Engineering & Remote Sensing 57:1475-1486.

Peterson, A. T. 2001. Predicting species' geographic distributions based on ecological niche modeling. Condor 103:599-605.

Petranka, J. W. 1998. Salamanders of the United Sates and Canada. Smithsonian, Washington, D.C.

Phillips, K. 1990. Where have all the frogs and toads gone? Bioscience 40:422-424.

Pope, C. H. 1928. Some plethodontid salamanders from North Carolina and Kentucky with the description of a new race of *Leurognathus*. Amer. Mus. Noviates 306:1-19.

Porter, M. S., J. Rosenfeld, and E. A. Parkinson. 2000. Predictive models of fish species distribution in the Blackwater drainage, British Columbia. North American Journal of Fisheries Management 20:349-359.

Poschadel, J. R., and D. Moller. 2004. A versatile field method for tissue sampling on small reptiles and amphibians, applied to pond turtles, newts, frogs and toads. Conservation Genetics 5:865-867.

Riley, S. J., and R. A. Malecki. 2001. A landscape analysis of cougar distribution and abundance in Montana, USA. Environmental Management 28:317-323.

Rouget, M., D. M. Richardson, S. Lavorel, J. Vayreda, C. Gracia, and S. J. Milton. 2001. Determinants of distribution of six *Pinus* species in Catalonia, Spain. Journal of Vegetation Science 12:491-502.

Saveraid, E. H., D. M. Debinski, K. Kindscher, and M. E. Jakubauskas. 2001. A comparison of satellite data and landscape variables in predicting bird species occurrences in the Greater Yellowstone Ecosystem, USA. Landscape Ecology 16:71-83.

Scott, J. M., P. J. Heglund, M. L. Morrison, J. B. Haufler, M. G. Raphael, W. A. Wall, and F. B. Samson, editors. 2002. Predicting Species Occurrences: Issues of Accuracy and Scale. Island Press, Washington, DC.

Semlitsch, R. D., and D. B. Wake, editors. 2003. Amphibian Conservation. Smithsonian Institution, Washington, D.C.

Seone, J., J. Bustamante, and R. Diaz-Delgado. 2005. Effect of Expert Opinion on the Predictive Ability of Environmental Models of Bird Distribution. Conservation Biology 19:512-522.

Skov, F. 2000. Potential plant distribution mapping based on climatic similarity. Taxon 49:503-515.

Smith, A. P., N. Horning, and D. Moore. 1997. Regional biodiversity planning and lemur conservation with GIS in western Madagascar. Conservation Biology 11:498-512.

Standora, M. 2002. Landscape level GIS modeling of Eastern Massasauga Rattlesnake (*Sistrurus catenatus catenatus*) habitat in Michigan. Master's Thesis. Purdue University, Ft. Wayne, IN.

Swinford, E. M., G. A. Schumacher, D. L. Shrake, G. E. Larsen, and E. R. Slucher. 2005. Descriptions of geologic map units. Open-file report 98-1. Ohio Department of Natural Resources, Division of Geological Survey, Columbus, OH.

Theobald, D. M. 2003. GIS concepts and ArcGIS methods. Conservation Planning Technologies, Fort Collins, Colorado.

Tucker, K., S. P. Rushton, R. A. Sanderson, E. B. Martin, and J. Blaiklock. 1997. Modelling bird distributions: A combined GIS and Bayesian rule-based approach. Landscape Ecology 12:77-93.

Turner, W., S. Spector, N. Gardiner, M. Fladeland, E. Sterling, and M. Steininger. 2003. Remote sensing for biodiversity science and conservation. Trends in Ecology & Evolution 18:306-314.

United States Forest Service (USFS). 1990. Cliffline zone. USFS, Winchester, KY. Accessed at http://www.southernregion.fs.fed.us/boone/origprop.htm#CLIFFLINE%20ZONE (November 2002).

Vincent, R. K. 1997. Fundamentals of Geological and Environmental Remote Sensing. Prentice-Hall, Upper Sadle River, NJ.

Wake, D. B. 1991. Declining amphibian populations. Science 253:860.

Walker, C. F., and W. Goodpasteur. 1941. The green salamander, *Aneides aeneus*, in Ohio. Copeia 1941:178.

Welk, E., K. Schubert, and M. H. Hoffmann. 2002. Present and potential distribution of invasive garlic mustard (*Alliaria petiolata*) in North America. Diversity and Distributions 8:219-233.

Wenjun, L., and W. Zijian. 2000. A wintering habitat model for red crown crane. Yingyong Shengtai Xuebao 11:839-842.

Zaniewski, A. E., A. Lehmann, and J. M. Overton. 2002. Predicting species spatial distributions using presence-only data: case study of native New Zealand ferns. Ecological Modelling 157:261-280.

APPENDIX A: TABLES

Table 1. Data layers used to build the model. Layers acquired in vector format were converted to raster for analysis.

Data layer	Original format	Spatial resolution	Source
Elevation	Raster	30 m	United States Geological Survey (http://seamless.usgs.gov/)
Percent canopy cover	Raster	30 m	United States Geological Survey (http://seamless.usgs.gov/)
Hydrography	Vector		United States Geological Survey (http://seamless.usgs.gov/)
Climatic layers	Raster	0.004333 degrees	Spatial Climate Analysis Service (http://www.ocs.orst.edu/prism/)
Bedrock units	Vector		Ohio Geological Survey, Ohio Department of Natural Resources (draft version)
LandSat 7 ETM+ satellite images	Raster	30 m	OhioView (http://www.ohioview.org/)

Table 2. Values of interval scale attributes used in the model for the entire study area.

	Elevation (m)	**Slope (degrees)**	**% Canopy (percent)**	**Distance to water (m)**	**Mean annual temp. (^oF)**
Mean	246	26	59	325	53.25
Minimum	144	0	1	0	52.39
Maximum	408	75	100	2005	54.85
Max. – Min.	264	75	99	2005	2.46

Table 3. Attributes at Green Salamander locations used as training sites for the model.

Site Name	**Elevation (m)**	**Slope (degrees)**	**Canopy (percent)**	**Distance to water (m)**	**Mean annual temp. (degrees Fahrenheit)**
Cave Hollow	242	47	85	90	53.43
Horse Heaven	234	45	87	180	53.43
Abner Hollow	213	51	84	0	53.48
Alex Run	213	66	84	180	53.62
Tracy Run	202	38	85	0	53.49
Rome Hill	174	53	83	90	53.53
Sheridan	184	41	88	324	53.71
Mean	209	49	85	123	53.53
Max. – Min.	68	25	5	324	0.28
% of variation in study area	25.75	33.16	5.05	16.16	11.38
Model parameter	>173 m and <243 m	>37^{o}	>82%	<325 m	>53.42
% of study area	37.49	29.94	60.18	57.47	27.63

Table 4. Bedrock geology at known Green Salamander locations (training sites) and their prevalence in the study area.

Bedrock Unit	**Area (m^2)**	**Percentage of total study area**
Peebles Dolomite, Lilley Formation, Bisher Formation – undivided (Splb)	138,200,355	3.22
Peebles Dolomite (Sp)	33,974,758	0.79
Lilley Formation (Sl)	37,711,159	0.88
Bisher Formation (Sb)	7,679,221	0.17
Pennsylvanian Breathitt Formation (IPb)	816,924,014	19.02
Totals	1,034,489,506	24.08

Table 5. Effect of reversing suitability criteria on the amount of area satisfying the model requirements.

Variable reversed	**Change in area (km^2) classified as suitable**	**Change in percentage of study area classified as suitable**
Elevation	-25.47	-0.59
Slope	-10.32	-0.24
Canopy	-23.73	-0.55
Distance to water	-13.21	-0.30
Mean temperature	+20.38	+0.48
Bedrock	+53.49	+1.24

Table 6. Results of field surveys to evaluate the model performance.

Model criteria not satisfied	No. of sites surveyed	No. of sites occupied[a]	% commission error[b]
Elevation	12	0	0
Slope	11	1	9
Canopy	4	1	25
Distance to water	0	2	0
Mean annual temperature	15	2	13.3
Bedrock	9	0	0
None (suitable)	39	1	—

[a]Occupied sites not meeting the slope and canopy criteria of the model were <30 m from areas of predicted suitable habitat, and are most likely the result of inaccuracies of the GIS data and/or GPS reception.

[b]An error of commission occurs when a site predicted to be unsuitable is found to be occupied. Errors of omission (unsuitable sites predicted to be suitable) were not calculated due to the low probability of detection for the Green salamander.

Table 7. Rock samples collected from the study area and their relationship with the GIS bedrock layer and the presence of Green Salamanders. The GIS layer was judged “accurate” if rock compositions (determined in the lab) corresponded to the lithology of the geologic map unit on the GIS layer.

Geologic map unit	**Number of samples**	**Rock composition**	**Accurate**	**Green Salamanders present**
Conemaugh Group (IPc)	1	Sandstone	Yes	0
Pennsylvanian Breathitt Formation (IPb)	22	Sandstone	Yes	2
Ohio-Olentangy Shale undivided (Do)	1	Sandstone	No	0
Estill Shale (Se)	1	Dolomite	Yes	0
Ohio-Olentangy Shale undivided (Do)	1	Dolomite	Yes	1
Peebles Dolomite, Lilley Formation, Bisher Formation undivided (Splb)	3	Dolomite	Yes	1
Pennsylvanian Breathitt Formation (IPb)	1	Dolomite	No	0

Table 7, continued.

Geologic map unit	Number of samples	Rock composition	Accurate	Green Salamanders present
Peebles Dolomite, Lilley Formation, Bisher Formation undivided (Splb)	4	Limestone	Yes	1
Pennsylvanian Breathitt Formation (IPb)	2	Limestone	Yes	0
Sunbury Shale, Berea Sandstone, and Bedford Shale undivided (DMu)	1	Limestone	No	0
Tymochtee Dolomite, Greenfield Dolomite, and Peebles Dolomite, Lilley Formation, and Bisher Formation undivided (St-b)	1	Limestone	No	0

APPEDNDIX B: FIGURES

Figure 1. The Green Salamander, *Aneides aeneus,* in a rock crevice. Photo by Greg Lipps.

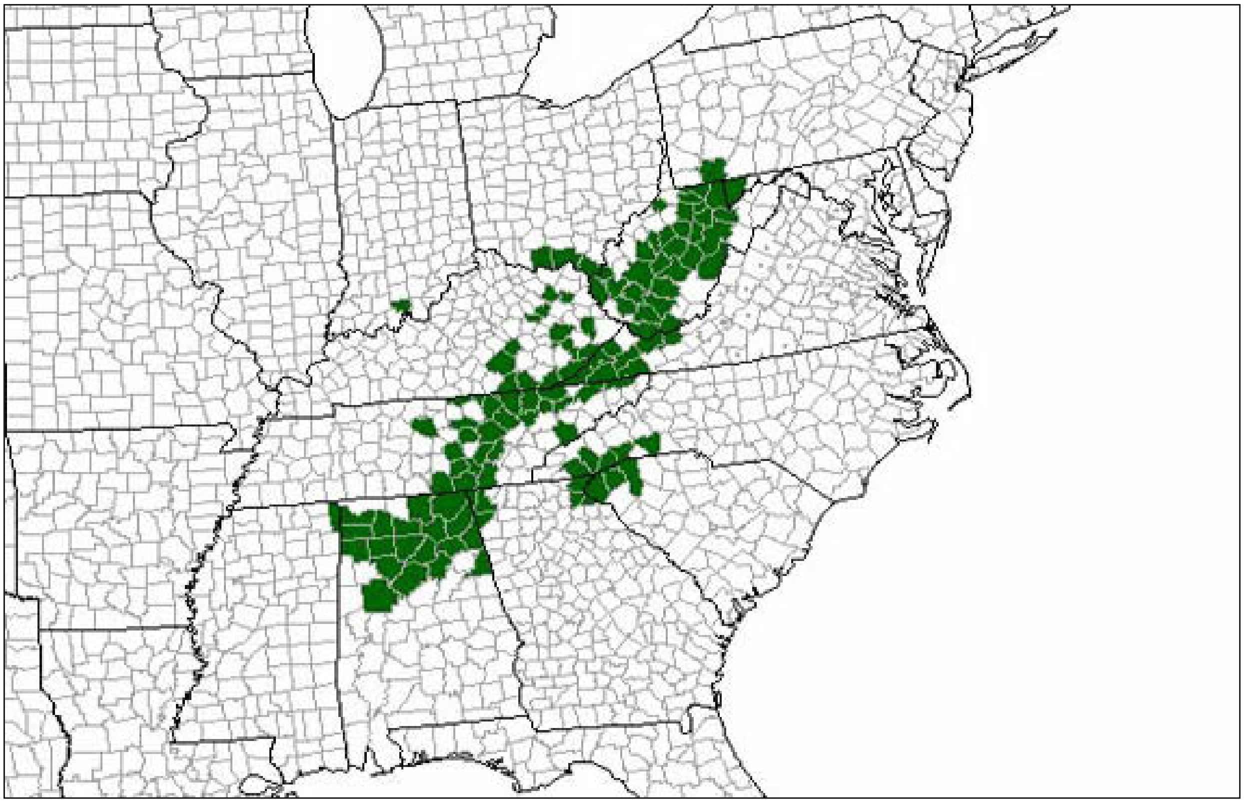

Figure 2. Distribution of the Green Salamander. From the ARMI National Atlas for Amphibian Distributions (http://www.pwrc.usgs.gov/armiatlas/).

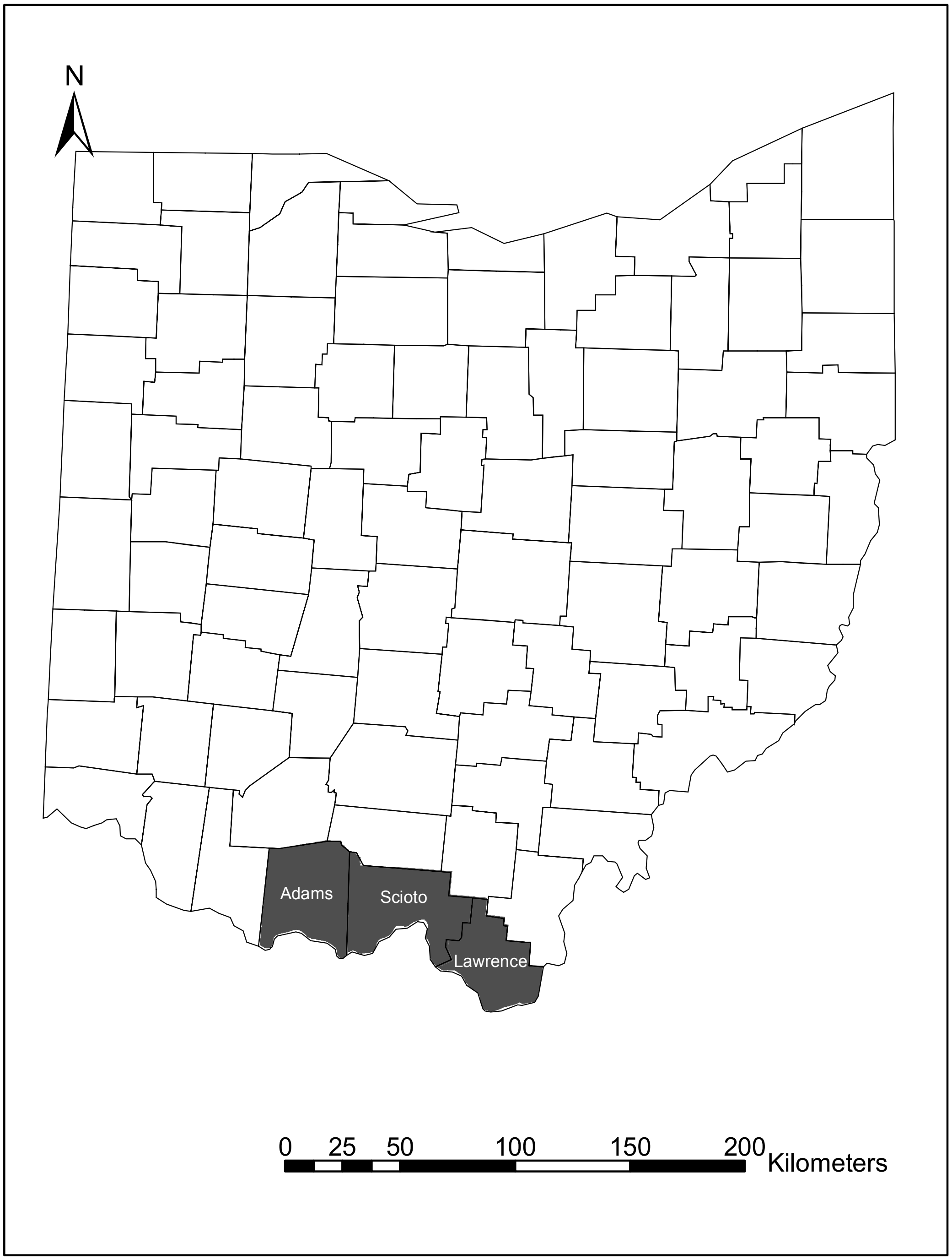

Figure 3. The location of the study area (shaded) in southern Ohio. All documented Green Salamander occurrences in Ohio are within the three shaded counties.

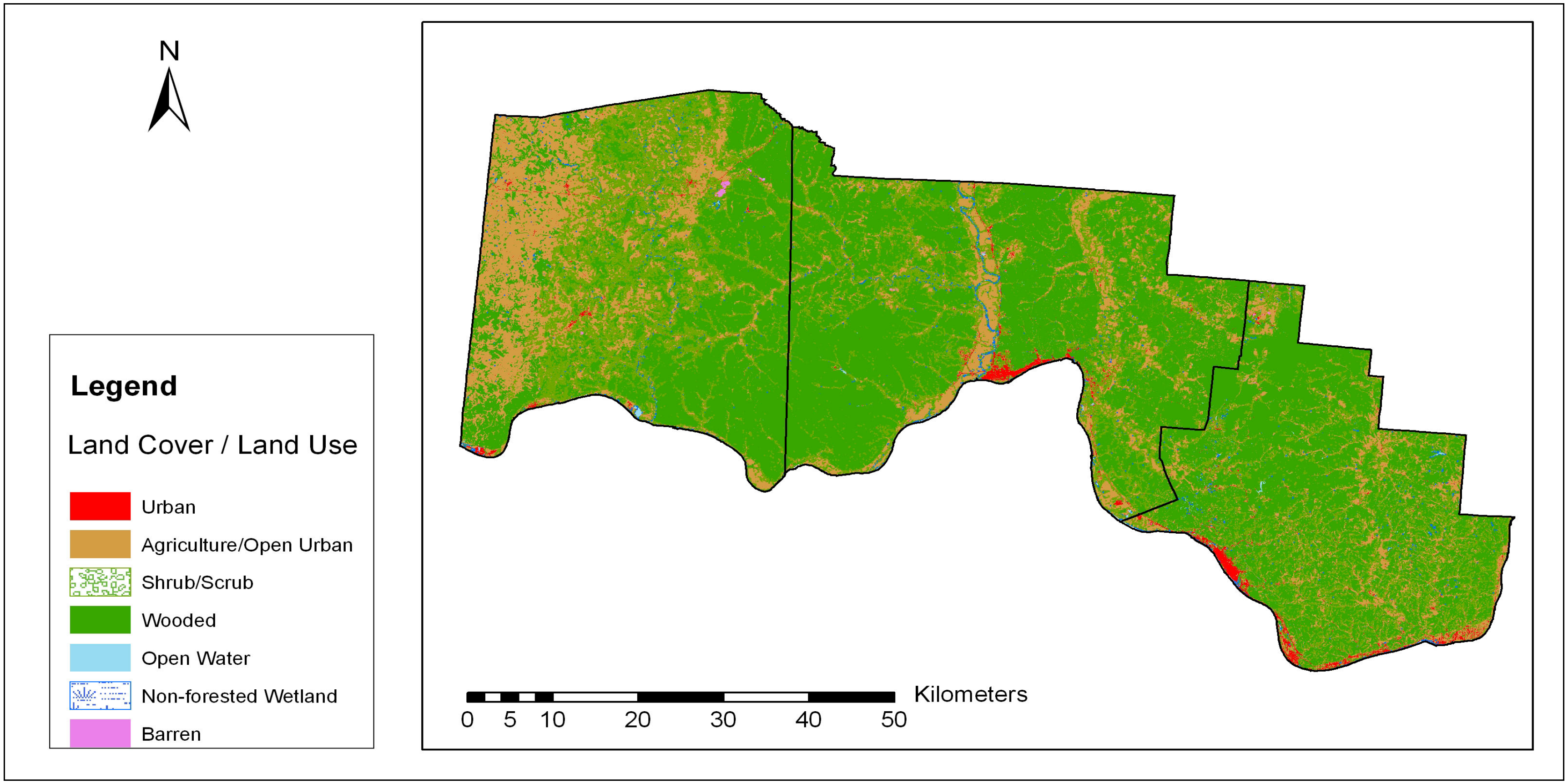

Figure 4. Land cover / land use map of the study area. Source: Ohio Department of Natural Resources (http://www.ohiodnr.com/gims) developed from 1994 LandSat images.

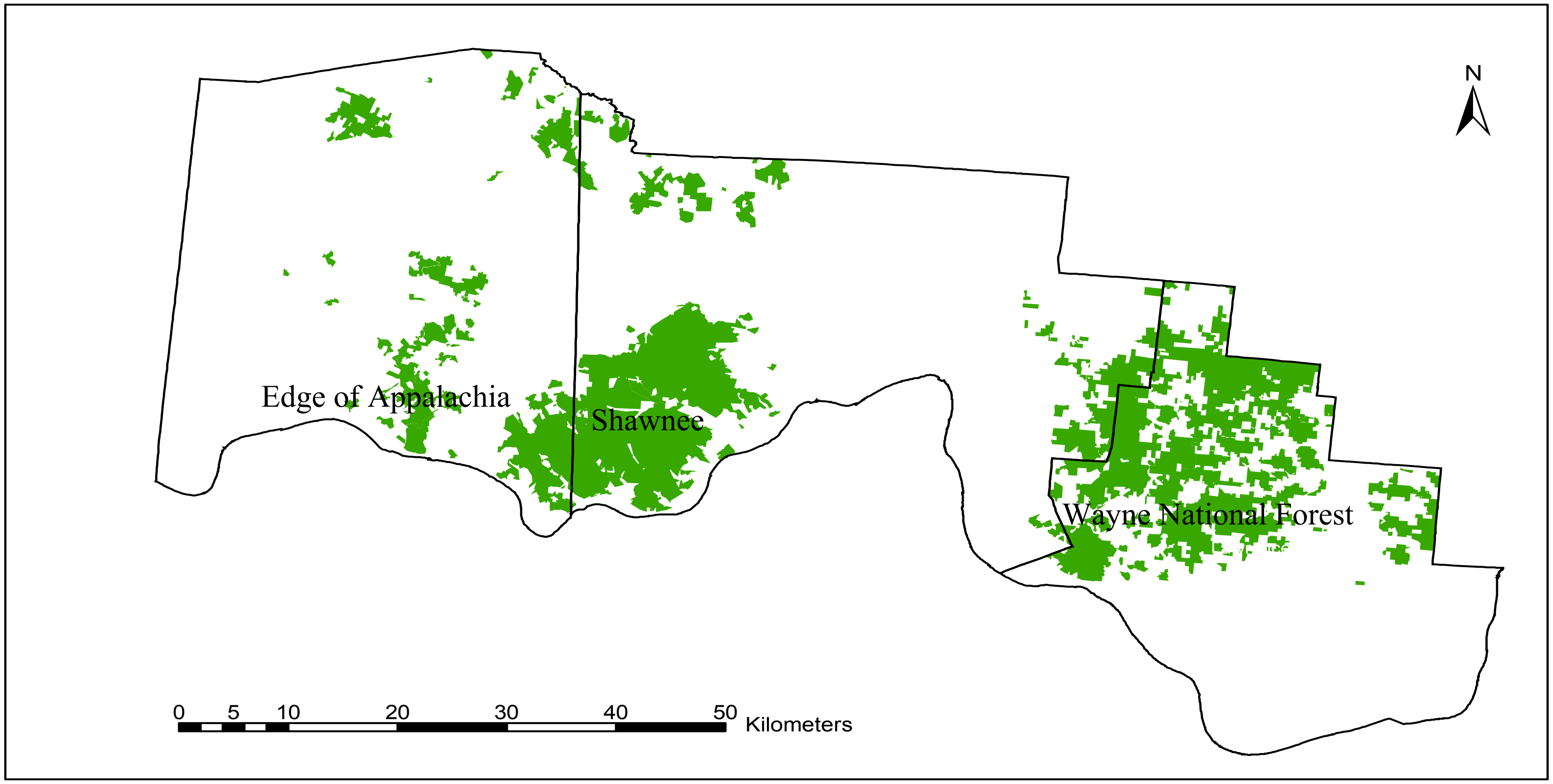

Figure 5. Properties managed for natural resources in the study area. From west to east, the three largest are the Edge of Appalachia Preserve (TNC), Shawnee State Forest and Park (ODNR), and Wayne National Forest (USFS).

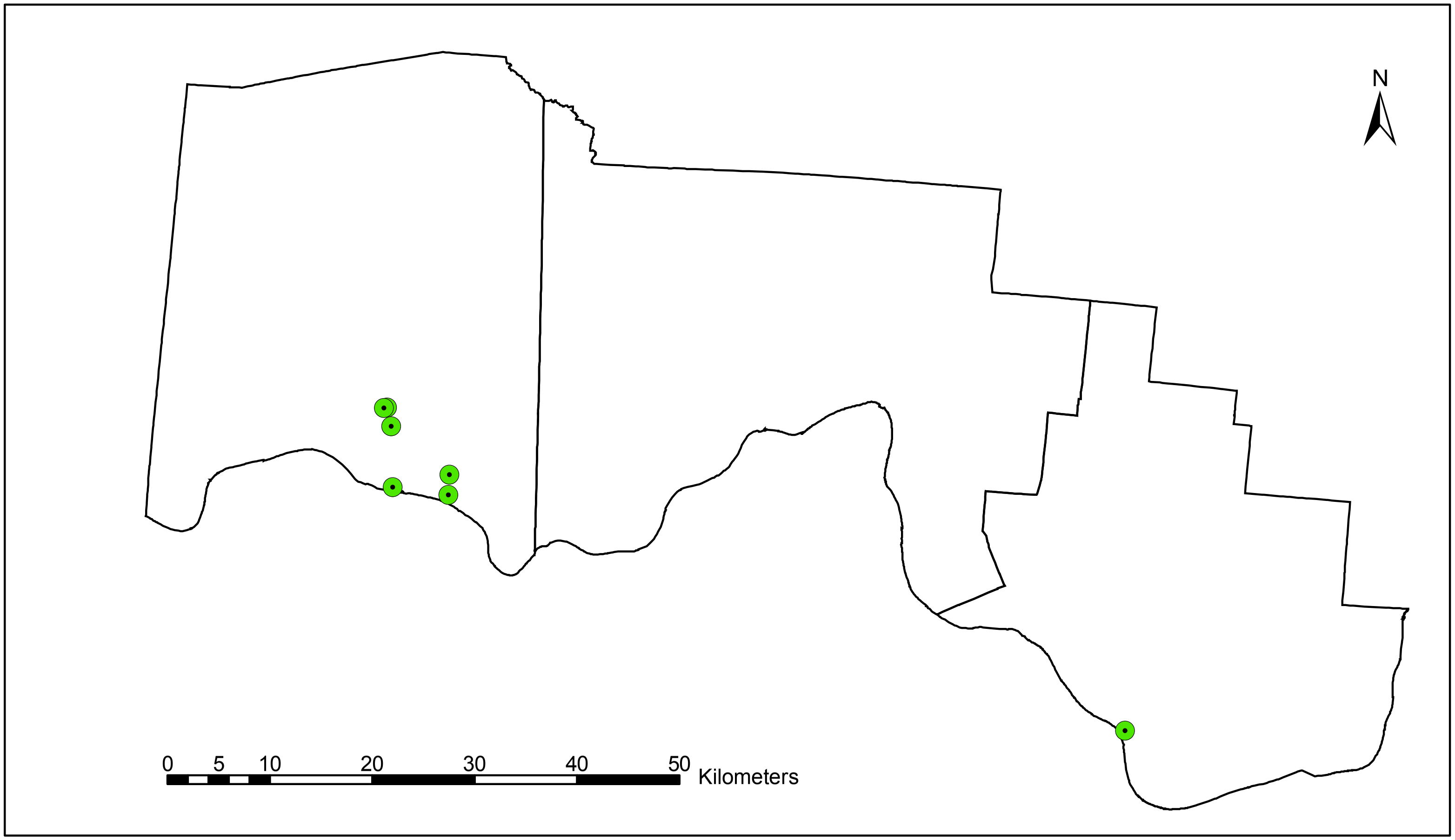

Figure 6. Location of training sites used for building the model. Green salamanders were reported at the 7 locations above by Lipps (2003).

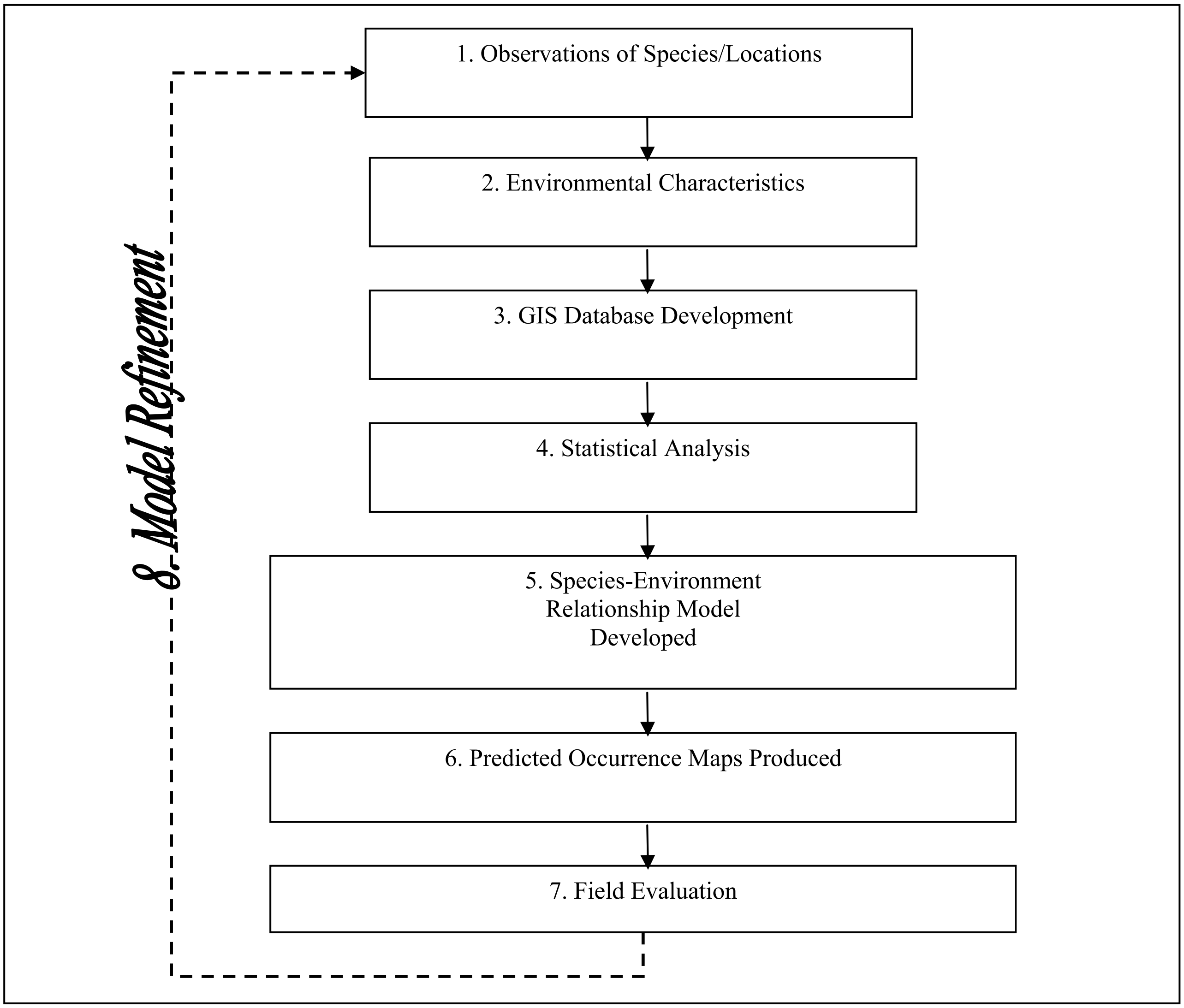

Figure 7. Procedure for predicting species occurrence. (1) Observations of a species' occurrences are used to (2) collect training data concerning environmental characteristics at the site. (3) Next, a GIS database is constructed containing this information. (4) Various statistical techniques can be used to (5) develop a model describing the species-environment relationship. This model is then applied to a given area in a GIS to produce maps of predicted occurrence (6). (7) These maps are then used to validate the model either through additional surveys at unsurveyed locations or with known locations not used to build the model. (8) Results of evaluation can be used to further refine the model.

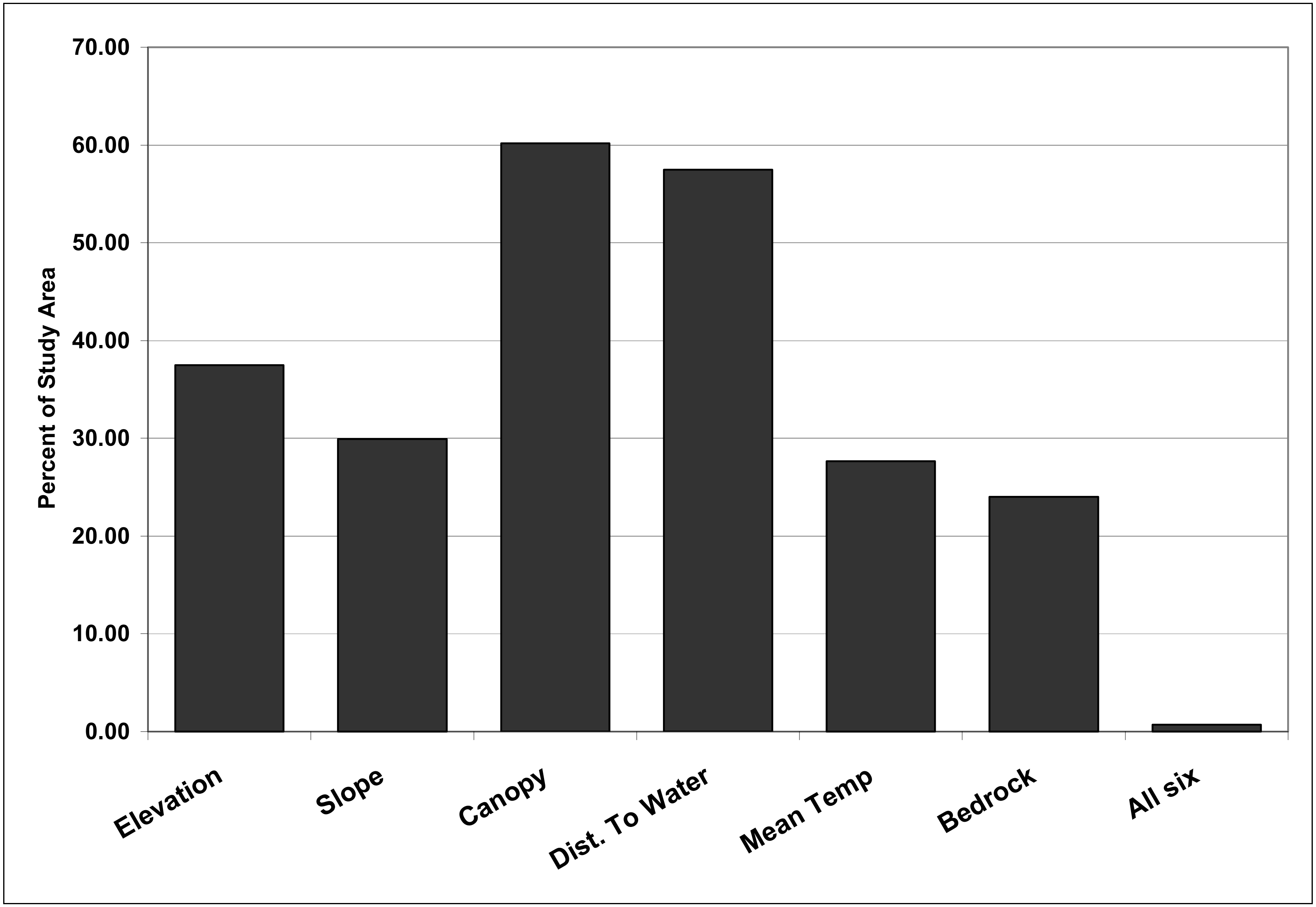

Figure 8. Percentage of study area meeting the criteria for each of the model parameters and for all six environmental parameters.

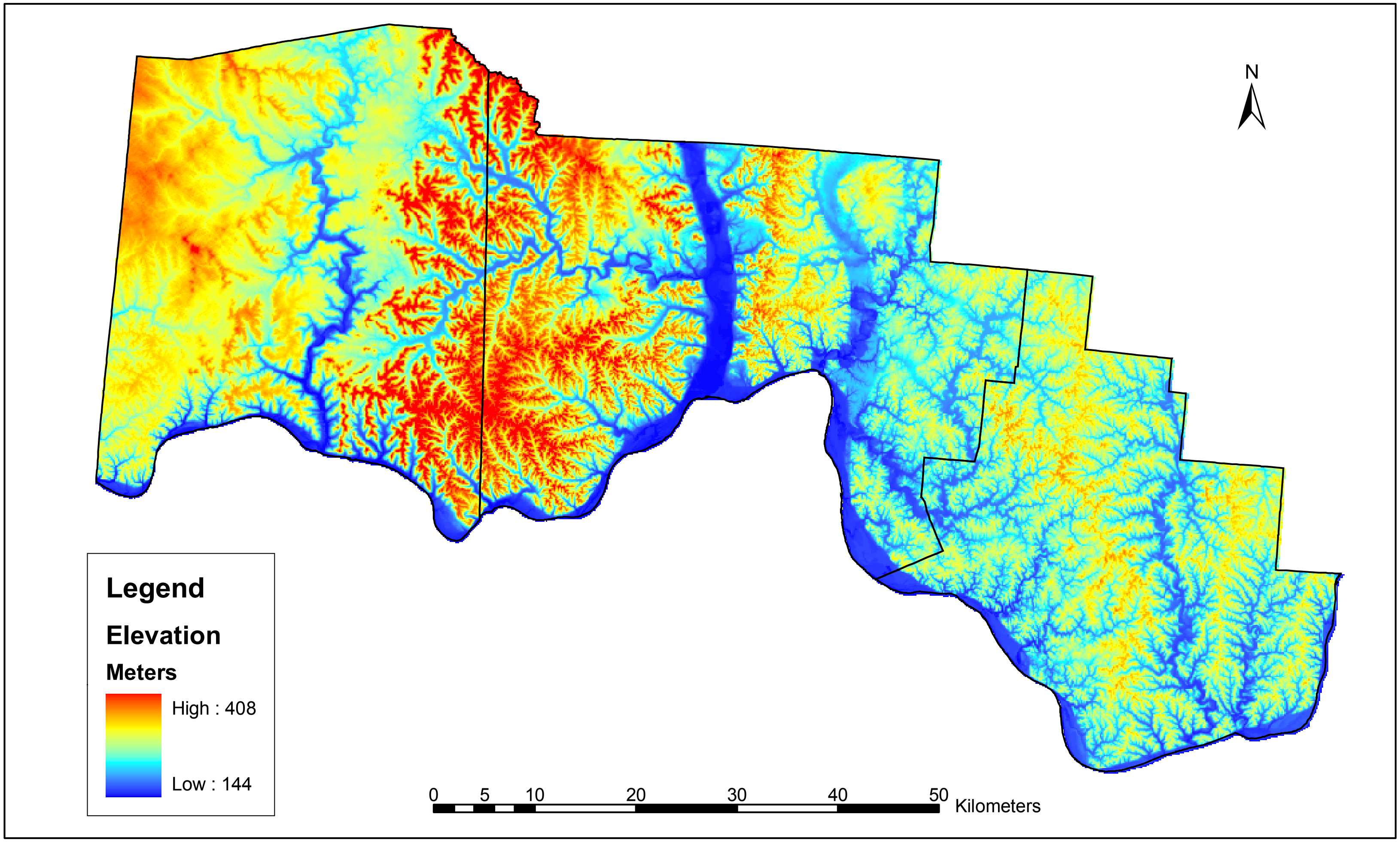

Figure 9. Elevation, in meters, of the study area.

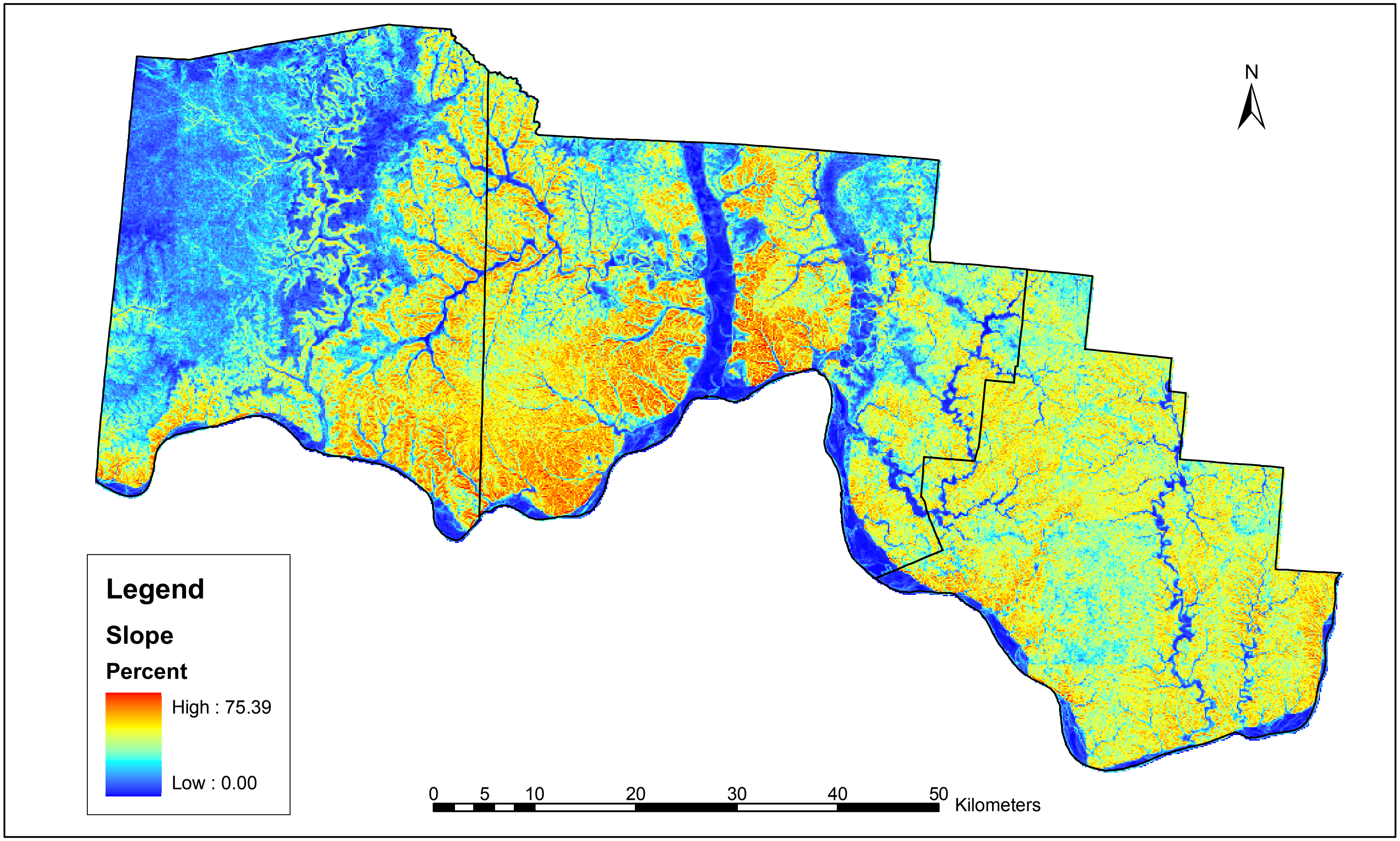

Figure 10. Slope, as percent, of the study area.

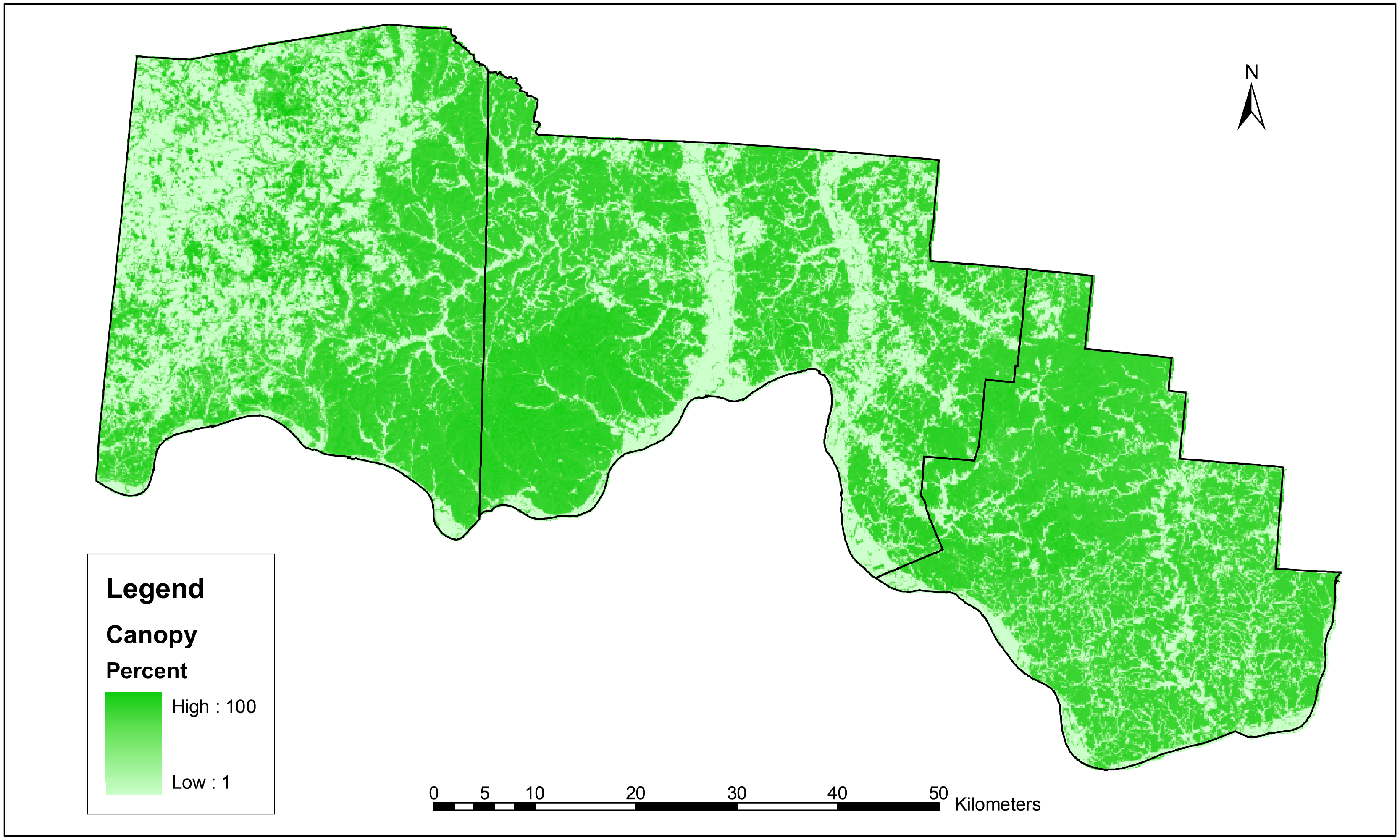

Figure 11. Canopy, as percent cover, of the study area.

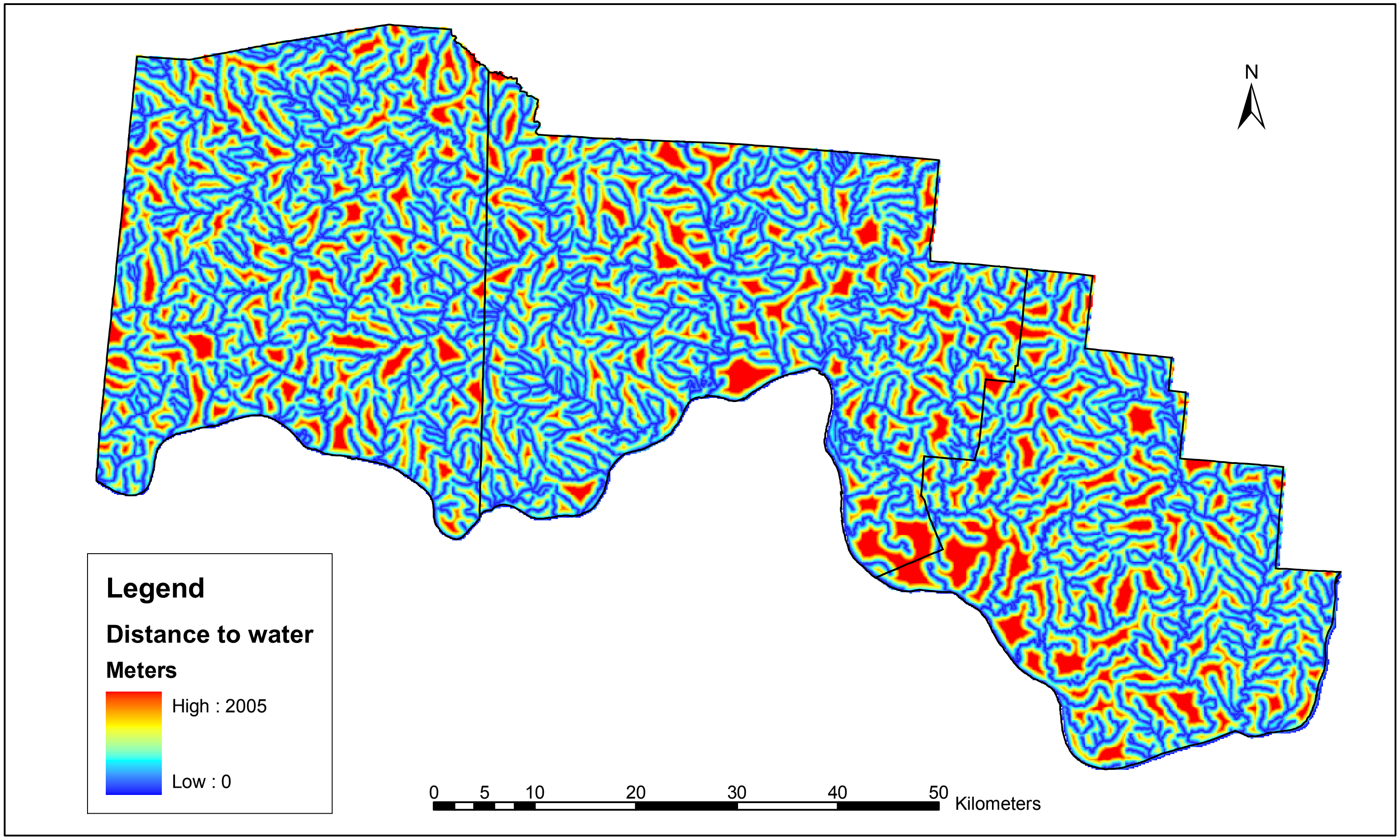

Figure 12. Distance to water, in meters, of the study area.

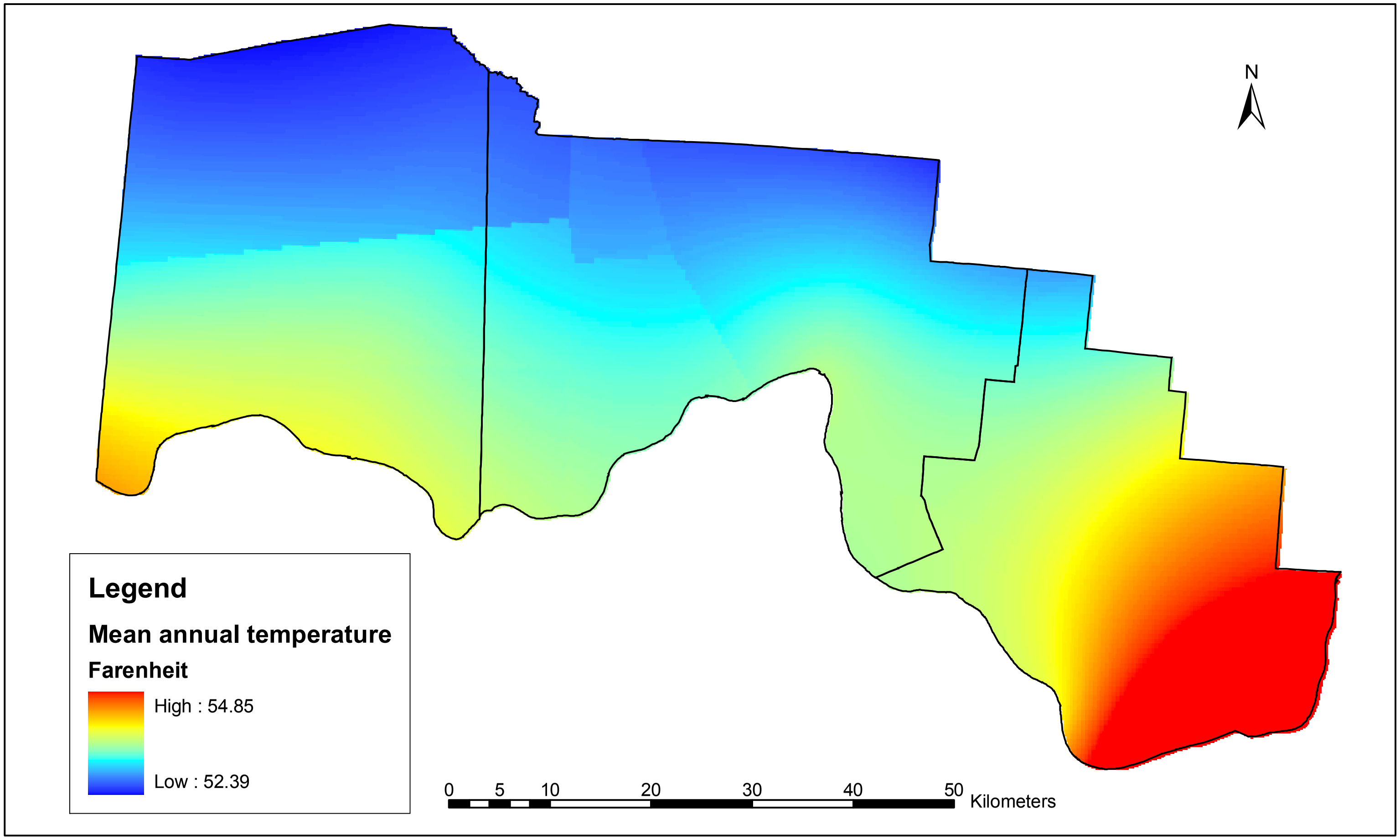

Figure 13. Mean annual temperature, in degrees Fahrenheit, of the study area.

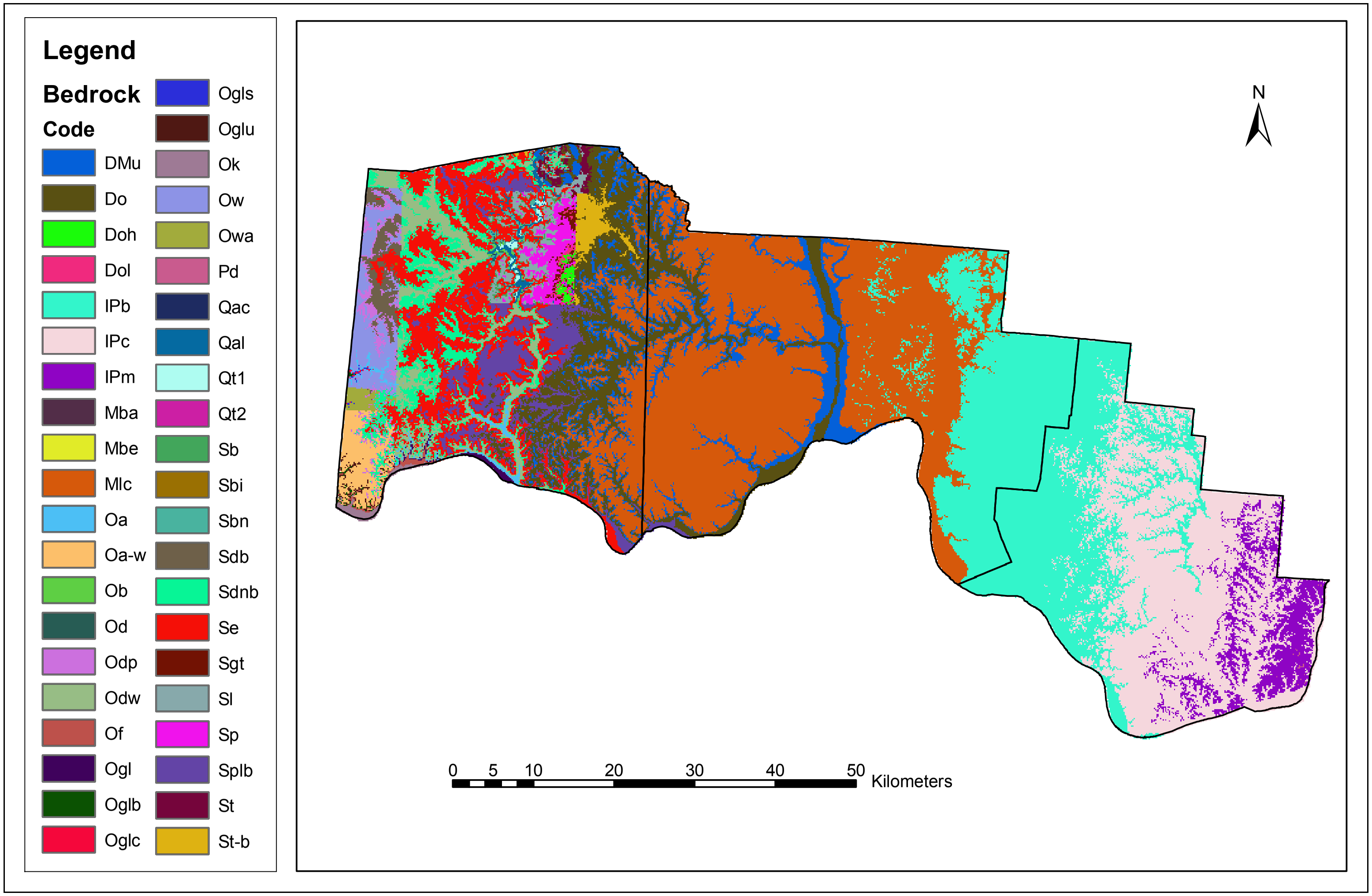

Figure 14. Bedrock geology of the study area. Green Salamander training sites were located on IPb: Pennsylvania Breathitt Formation; Splb: Peebles Dolomite, Lilley Formation, Bisher Formation undivided; Sp: Peebles Dolomite; Sl: Lilley Formation; and, Sb: Bisher Formation. Geologic map unit codes from Swindford et al. (2005).

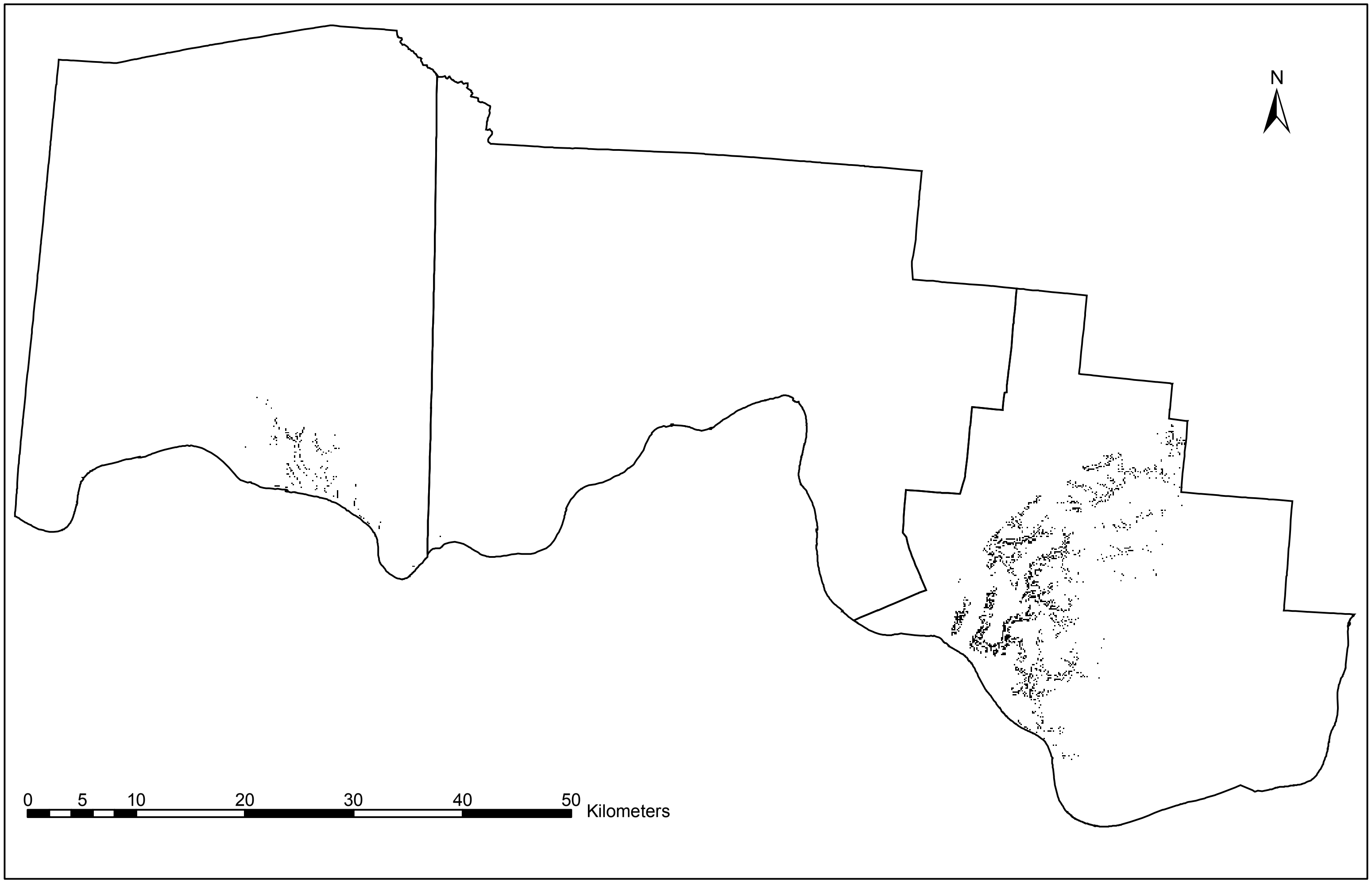

Figure 15. Map showing areas satisfying the requirements of all six variables in the model.

Figure 16. Map showing areas satisfying all of the model parameters, except elevation.

Figure 17. Map showing areas satisfying all of the model parameters, except slope.

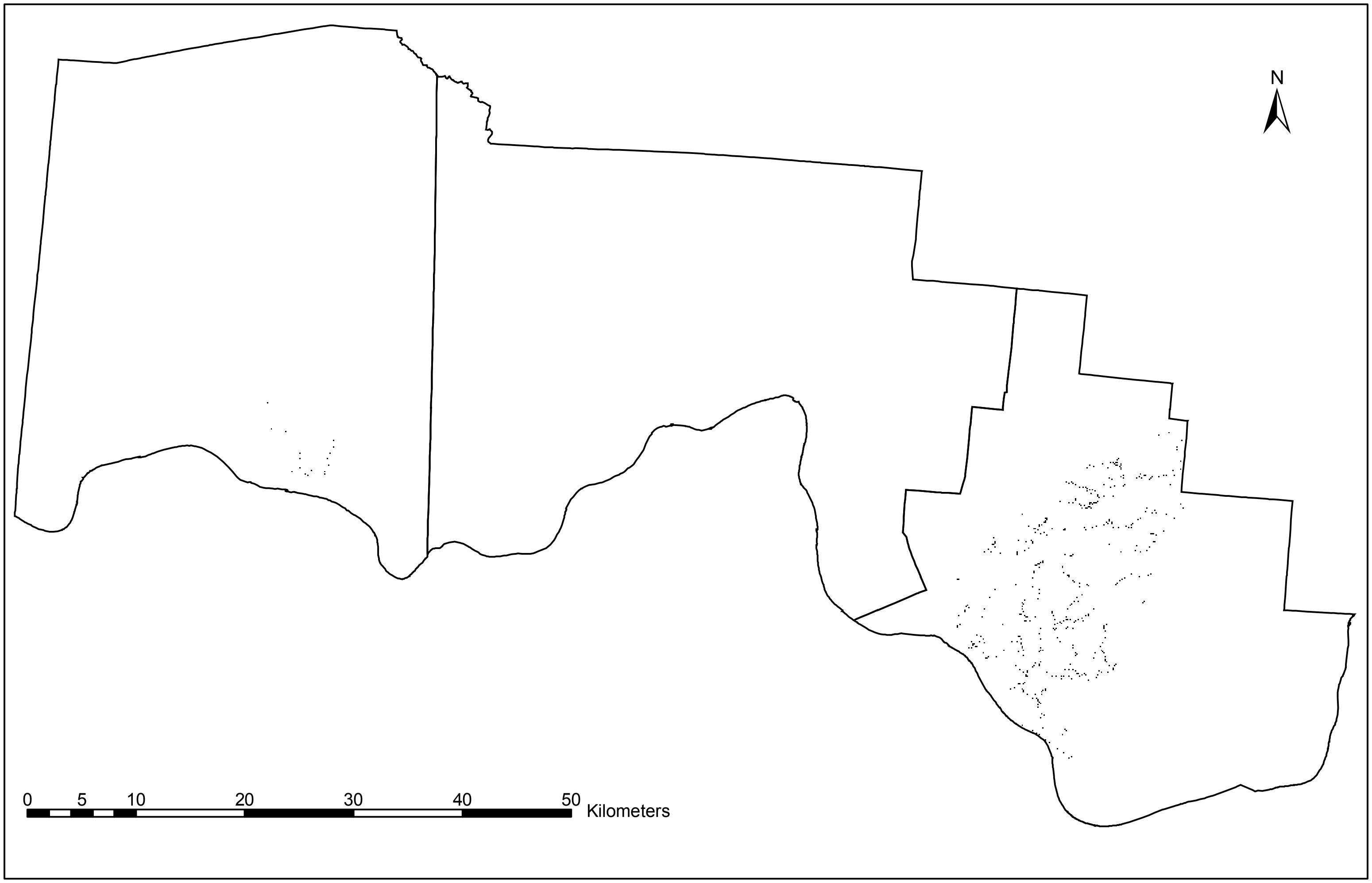

Figure 18. Map showing areas satisfying all of the model parameters, except canopy cover.

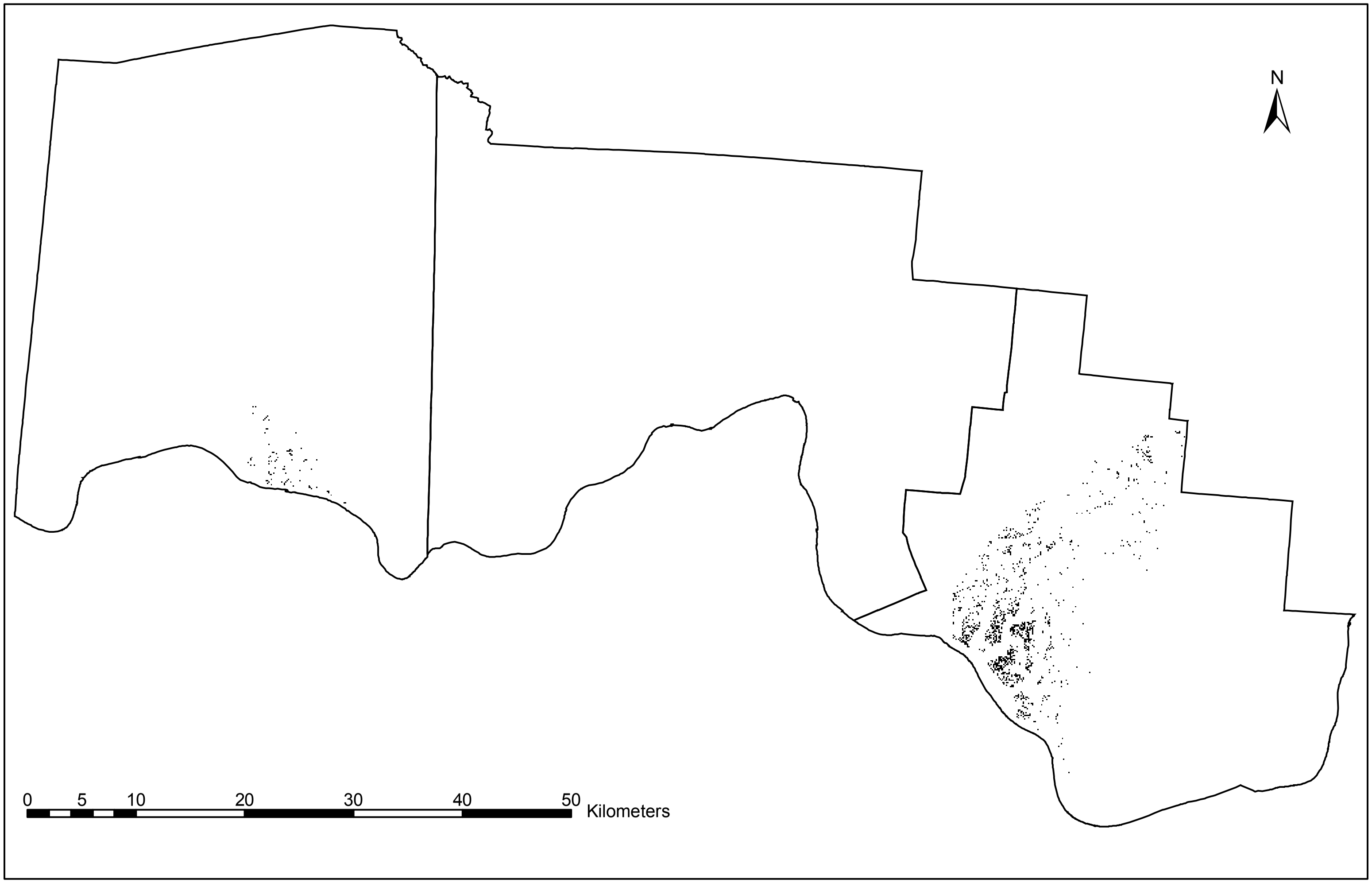

Figure 19. Map showing areas satisfying all the model parameters, except distance to water.

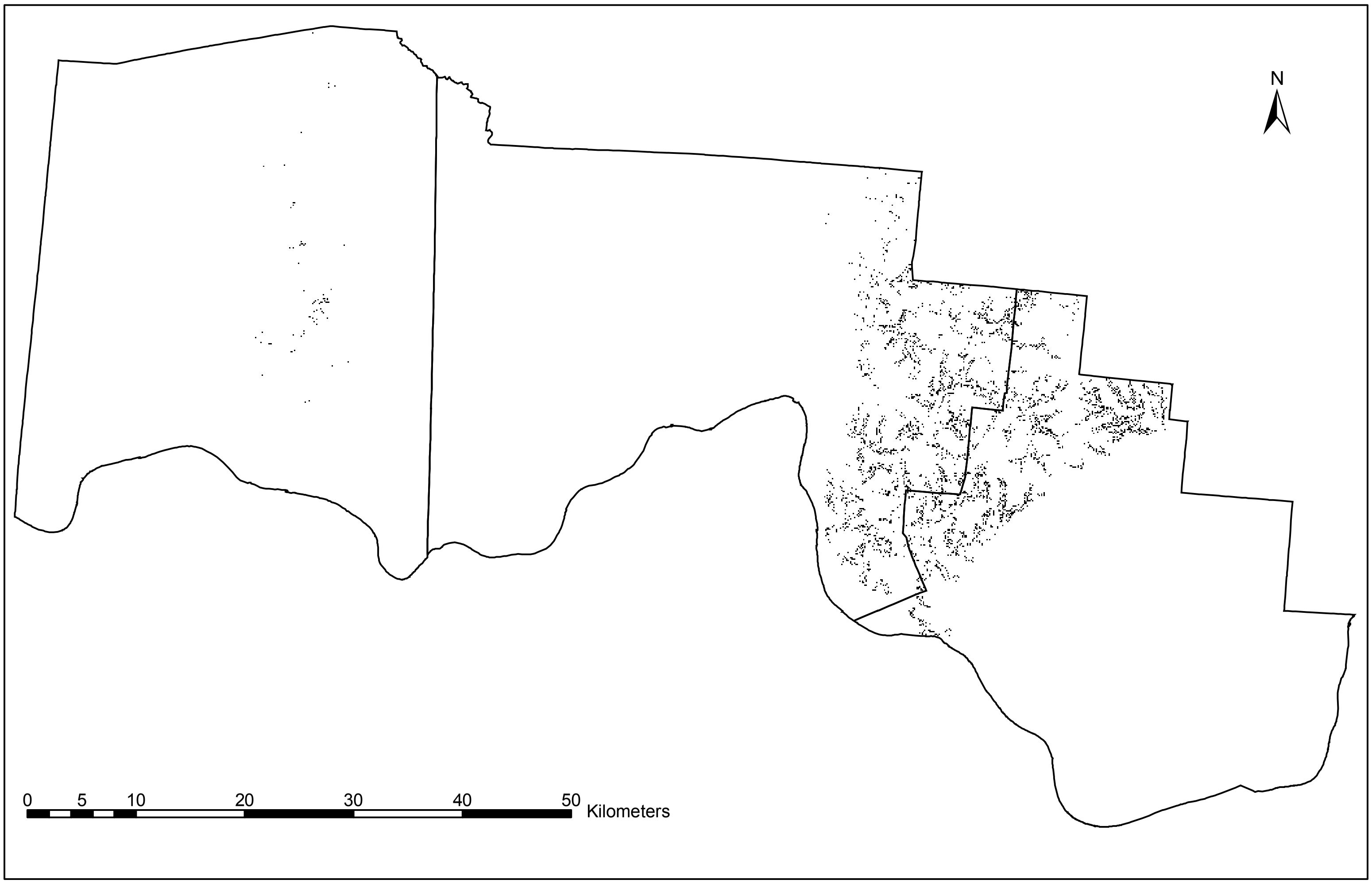

Figure 20. Map showing areas satisfying all of the model parameters, except mean annual temperature.

Figure 21. Map showing areas satisfying all of the model parameters, except bedrock type.

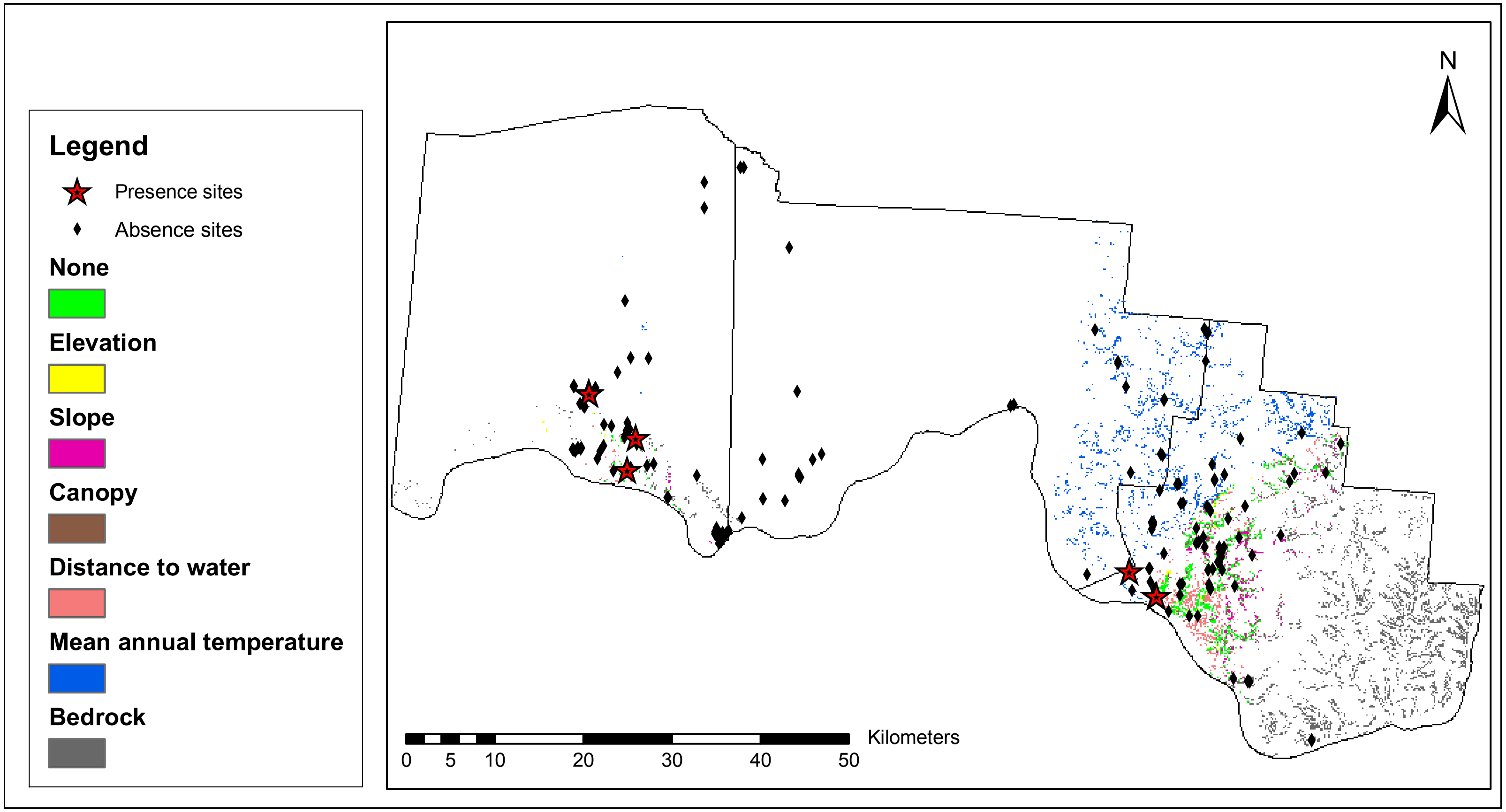

Figure 22. Results of field surveys to evaluate the model performance. Sites where Green Salamanders were observed are indicated with a star. Legend categories indicate which model parameters were not satisfied (e.g., None = all model parameters satisfied; Elevation = elevation parameter not satisfied).

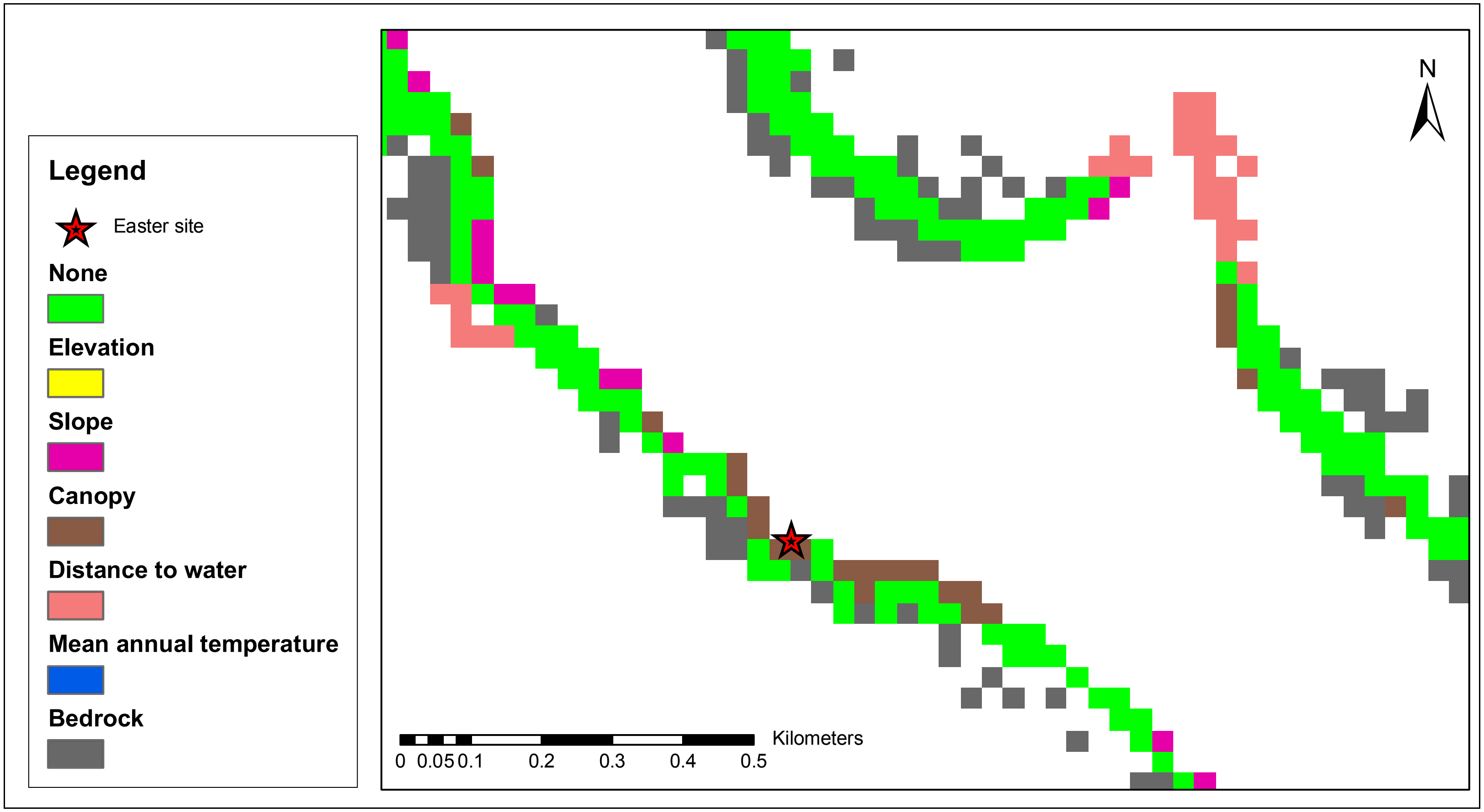

Figure 23. Easter site, Green Township, Adams County, Ohio. Location of GPS coordinates places the site in a pixel not meeting the canopy requirement of the model.

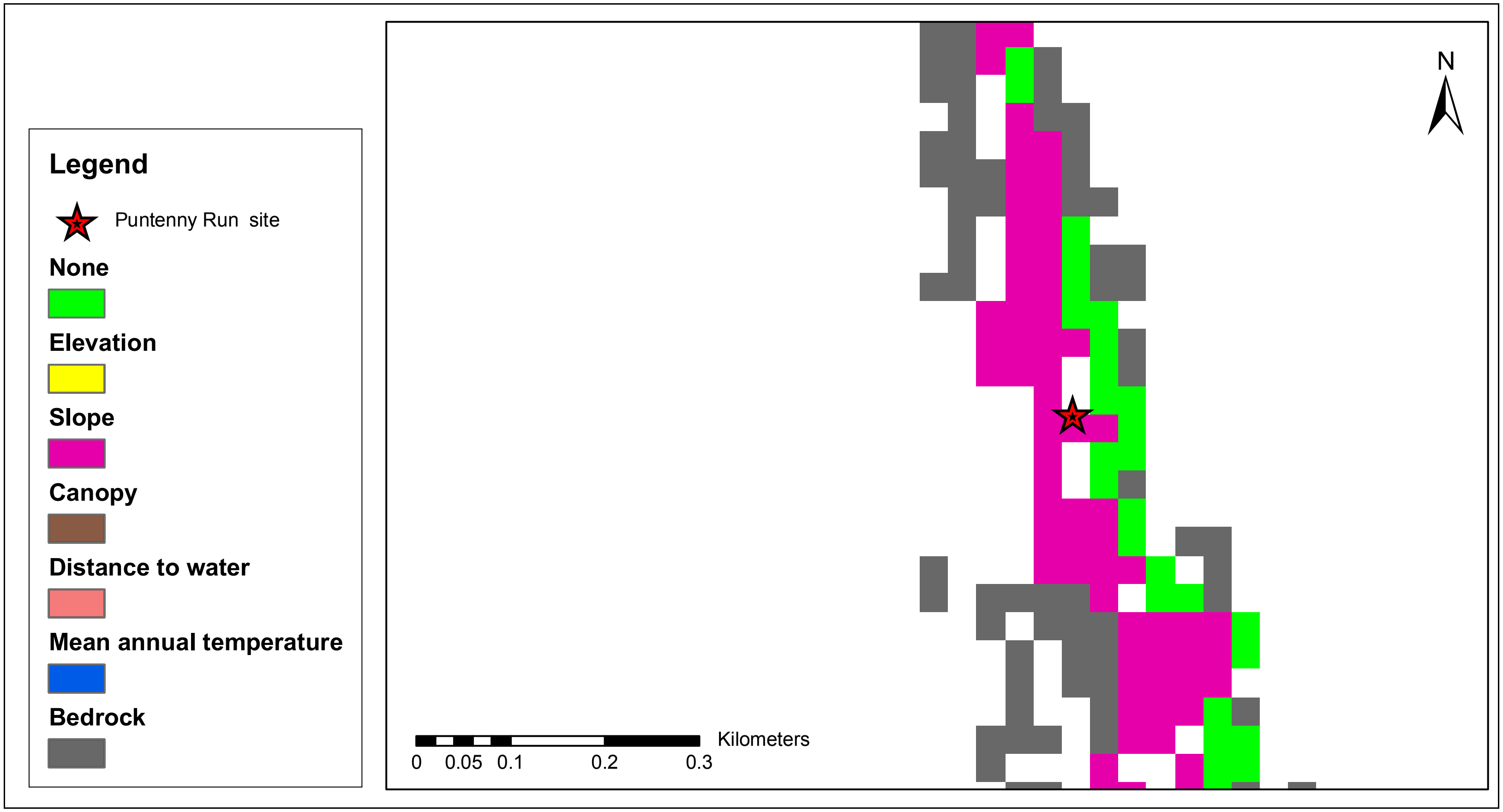

Figure 24. Puntenny Run site, Green Township, Adams County, Ohio. The GPS coordinates collected at the site places it within a pixel predicted to have a lower slope than required to satisfy the model.