ABSTRACT

VAN VOORHIS, MORIAH. Southeastern Fox Squirrel (S*ciurus niger niger*) Occurrence Throughout The Piedmont and Coastal Plain Of North Carolina. (Under the direction of Dr. Robert M. Scheller, Dr. Christopher S. DePerno, and Dr. Krishna J. Pacifici).

The southeastern fox squirrel (*Sciurus niger niger*) is a subspecies of fox squirrel that occurs throughout the Piedmont and Coastal Plain of the southeastern United States and has historically been tied to the fire-maintained longleaf pine (*Pinus palustris*) forest. Once widely distributed, the southeastern fox squirrel's populations have been declining over the past 100 years. The reason for the widespread population declines of southeastern fox squirrels is believed to be the destruction and fragmentation of habitat through fire suppression and land conversion. Destruction and fragmentation of habitat through fire suppression and land conversion reduces overall quantity of habitat on the landscape and decreases connectivity by increasing isolation and distances over which southeastern fox squirrels must travel in search of resources. The intense loss of longleaf pine forest since the 18^{th} century has resulted in ~ 10 - 20% of original southeastern fox squirrel habitat remaining intact. In response to the extreme loss of habitat, southeastern fox squirrels may move into bottomland and successional forests, pine plantations, and even urban areas. This change in the southeastern fox squirrel's occurrence results in the species habitat being uncertain at this time. Hence, the purpose of my study was to identify suitable southeastern fox squirrel habitat across North Carolina. As the population continues to decline throughout the southeast, understanding habitat use and where southeastern fox squirrels are occurring is critical to aiding in their management.

Southeastern Fox Squirrel (S*ciurus niger niger*) Occurrence Throughout the Piedmont and Coastal Plain of North Carolina

by
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TABLE OF CONTENTS

LIST OF TABLES ... 6
LIST OF FIGURES ... 7

SOUTHEASTERN FOX SQUIRREL OCCURANCE THROUGHOUT THE PIEDMONT AND COASTAL PLAIN IN NORTH CAROLINA ... 8
- Introduction ... 8
- Methods ... 11
  - Study Area ... 12
  - Species Data Collection ... 13
  - Environmental Data ... 17
  - Model Algorithms ... 20
  - Model Evaluation ... 21
- Results ... 21
- Discussion ... 27
  - Recommended Use of Models ... 28
  - Using Citizen Science for Southeastern Fox Squirrel Data ... 30
  - Southeastern Fox Squirrels as Indicators of Longleaf Pine Presence ... 31
  - Conclusion ... 32
- References Cited ... 33

LIST OF TABLES

Table 1 The breakdown of sources from citizen scientists reporting southeastern fox squirrel, *Sciurus niger niger*, sightings in the Piedmont and Coastal Plain of North Carolina from 2008 – 2022. 9

Table 2 The percentage of total area for the five most common forest types within total cell count for 34 km buffer around each southeastern fox squirrel, *Sciurus niger niger*, sightings using 2008 United States Forest Type Inventory Data Set 12

Table 3 Model performance for each of the four models used to predict southeastern fox squirrel presence 16

Table 4 Percentage of variance explained by predictor variable for each M1, M2, M3, and M4 model 17

LIST OF FIGURES

Figure 1 Southeastern fox squirrel, *Sciurus niger niger*, in North Carolina. Photograph courtesy of an anonymous study participant 4

Figure 2 Study area of the Coastal Plain and Piedmont regions of North Carolina. The sandhills sub region of the study area is identified as well. Figure created using ArcGIS, Version 9.0 (Environmental Systems Research Institute, Inc., Redlands, California) 6

Figure 3 Image of flyer that was distributed in game lands and managed lands throughout October 2021 to February 2022 in North Carolina as part of the citizen science campaign for southeastern fox squirrel location 8

Figure 4 Location of study area with 554 plotted southeastern fox squirrel, *Sciurus niger niger*, sightings from 2008 – 2022 and randomly generated pseudo absences. Figure created using ArcGIS, Version 9.0 (Environmental Systems Research Institute, Inc, Redlands, California 10

Figure 5 Workflow used M1, M2, M3, and M4 to species distribution model and map predictions for presence of southeastern fox squirrels 13

Figure 6 Predicted probability of occurrence map created using M1 random forest model. Figure created using ArcGIS, Version 9.0 (Environmental Systems Research Institute, Inc., Redlands, Calif.) 17

Figure 7 Predicted probability of occurrence map created using M2 random forest model. Figure created using ArcGIS, Version 9.0 (Environmental Systems Research Institute, Inc., Redlands, Calif.) 18

Figure 8 Predicted probability of occurrence map created using M3 random forest model. Figure created using ArcGIS, Version 9.0 (Environmental Systems Research Institute, Inc., Redlands, Calif.) 19

Figure 9 Predicted probability of occurrence map created using M4 random forest model. Figure created using ArcGIS, Version 9.0 (Environmental Systems Research Institute, Inc., Redlands, Calif.) 20

SOUTHEASTERN FOX SQUIRREL OCCURANCE THROUGHOUT THE PIEDMONT AND COASTAL PLAIN IN NORTH CAROLINA

Introduction

Once widely distributed, the southeastern fox squirrel's (*Sciurus niger niger*) populations have been gradually declining over the past 100 years (Amspacher et al. 2019, Carraway et al. 2017, Wiegel et al. 1989). These declining populations raise conservation concern as southeastern fox squirrels are an ecologically important disperser of longleaf pine seeds and beneficial fungi (Greene and McCleery 2017). Remaining populations of southeastern fox squirrels are suspected to be disconnected from one another as there are isolated patches of suitable habitat containing no southeastern fox squirrels (Carraway et al. 2017). This raises concerns for population resiliency. Habitat fragments that are connected by dispersal will possess a greater overall population and exhibit more resilience to habitat disturbance (Opdam 1991). Hence, the uninhabited patches are indicative of the population decline and indicate uncertainty regarding southeastern fox squirrel habitat range and connectivity in the region (Carraway et al. 2017).

The southeastern fox squirrel is a subspecies of fox squirrel that occurs throughout the Piedmont and Coastal Plain of the southeastern United States and has historically been tied to a habitat of fire-maintained longleaf pine (*Pinus palustris*) forest (Amspacher et al. 2019, Carraway et al. 2017) (Figure 1). Pine species appear to be a necessary component of their habitat as pine seeds account for 27.6% of the southeastern fox squirrels' diet in the fall and 39.4% of their diet in the winter (Lee et al. 2001). Further, the large size of the southeastern fox squirrel is advantageous in the longleaf pine due to the aide the size provides in handling pinecones (Weigel et al. 1989, Prince et al. 2016).

Evidence for declining southeastern fox squirrel populations consists of decreasing estimates of population densities, decreases in hunter harvest reports, and anecdotal observations (Green and McCleery 2017, Wiegel et al.1989). The reason for the widespread population declines of southeastern fox squirrels is believed to be the destruction and fragmentation of habitat through fire suppression and land conversion (Lee et al. 2008, Koprowski 2005, Brudvig et al. 2015). Habitat loss and fragmentation has caused population decline in multiple species associated with the longleaf pine ecosystem (Carraway et al. 2017, Frost 1993, Weigel et al. 1989, Perkins and Conner 2004). Destruction and fragmentation of habitat through fire suppression and land conversion reduces overall quantity of habitat on the landscape and decreases connectivity by increasing isolation and distances over which southeastern fox squirrels must travel in search of resources (Winiarski et al. 2017).

The longleaf pine ecosystem evolved a characteristic open canopy with a shifting mosaic of woodlands and grassy savannah understory that is maintained through frequent fire originated by lightning and intentional fires started by Native Americans (Engstrom 1993, Van Lear et al. 2005). This frequent fire regime of one-to-three-year burns is critical to sustain the biodiversity of the longleaf pine ecosystem (Mitchell et al. 2006, Van Lear 2005). Additionally, the frequent fire regimes prevent invasion and replacement of less fire-adapted species (Ware et al. 1993, Engstrom et al. 2001, Carroll et al. 2002, Van Lear et al. 2005). In areas of fire suppression or exclusion, hardwood encroachment and secondary regeneration create a dense understory, depriving the southeastern fox squirrel of resources and maneuverability, rendering former habitat no longer suitable (Florida FW, Wiegel 1989). Forest fragmentation and changes in land use have contributed to fire suppression throughout the southeast, with fire often excluded for decades (Frost 1993, Van Lear et al. 2005, Obrien et al. 2010).

Fire began to decline on the landscape with the introduction of European colonies in the southeastern United States (Frost 1993, Van Lear 2005). Agricultural plantations consisting of pastures and row crops prevented extensive burning in much of the southeast after the Civil War (Frost 1993, Johnson and Hale 2002, Van Lear 2005). Extensive logging throughout the latter half of the 19th century decimated the longleaf pine ecosystem (Van Lear 2005). In addition to logging, conversion to pastureland, cropland, and urban land have continued throughout the 20th century resulting in the destruction and fragmentation of the longleaf pine ecosystem for over a century (Frost 1993). By the 21st century, much of the remaining longleaf pine forest exists in isolated fragments (Van Lear 2005). The destruction and fragmentation of longleaf pine through fire suppression and land conversion has culminated in the once-dominant forest of the Piedmont and Coastal Plain being reduced to 3% of its historic range (Frost 1993, Kantola 1992).

This intense loss of longleaf pine forest has resulted in ~ 10 - 20% of original southeastern fox squirrel habitat remaining intact (Frost 1993, Kantola 1992). This loss of intact habitat is of particular concern because southeastern fox squirrels live at low densities with populations in the Coastal Plain averaging as low as 0.05 squirrels per hectare and as a result large areas of habitat are needed to support viable populations (Carraway et al. 2017, Wiegel et al. 1989). In response to the extreme loss of habitat, southeastern fox squirrels may move into bottomland and successional forests, pine plantations, and even urban areas (Weigel et al. 1989, Meehan and Jodice 2010, Greene and McCleery 2017). This change in the southeastern fox squirrel's occurrence results in the species habitat being uncertain at this time (Edwards et al. 1989).

Both longleaf pine forest and southeastern fox squirrels are relatively rare on the landscape and the southeastern fox squirrel population in the Piedmont and Coastal Plain regions of North Carolina has been historically underserved in research (Greene and McCleery 2016). Lack of empirical data has resulted in an inability to forecast how available habitat fragmentation impacts southeastern fox squirrel populations across North Carolina. In response, I used crowd sourced data and created a citizen science campaign to collect southeastern fox squirrel occurrences throughout the Piedmont and Coastal Plain of North Carolina to identify the existing and potential habitat for the southeastern fox squirrel. The objective of my study was to identify state-wide habitat amount and location. As the population continues to decline throughout the southeast, understanding habitat use and where southeastern fox squirrels are occurring is critical to aiding in their management.

Figure 1: Southeastern fox squirrel, *Sciurus niger niger*, in North Carolina, 2021. Photograph courtesy of an anonymous study participant.

Methods

I collected location data on southeastern fox squirrel sightings in North Carolina, identified parameters of interest for land managers, and developed four models to predict southeastern fox squirrel presence and habitat range throughout the Piedmont and Coastal Plain of North Carolina. I expected a selection for open woodlands given the species' association with the longleaf pine ecosystem but hypothesized that with deforestation resulting in the absence of longleaf pine, southeastern fox squirrels will select pine plantation and agricultural land in fragmented areas. Existing models in the Piedmont capture squirrel dynamics at the site level (Prince et al. 2016, Amspacher et al. 2019), however they require detail that is difficult to scale up to state-wide models. Statewide distribution models exist, (North Carolina GAP

Analysis Project 2005), however, these do not capture habitat characteristics necessary for management. This study builds on the existing literature by identifying southeastern fox squirrel habitat in North Carolina on the basis of landscape scale habitat characteristics.

Methods - Study Area

This study was conducted in the Piedmont and Coastal Plain regions of North Carolina, USA (Figure 2). The borders of this region are defined by the county outline provided by the North Carolina Department of Public Instruction (North Carolina Department of Public Instruction, 2012). This region spans from the foothills of the Appalachians to the Atlantic coast and transitions from the rolling hills of the Piedmont to the slight slope of the Coastal Plain.

The unique geography of North Carolina consisting of the Appalachian Mountains and the Atlantic Ocean shapes the weather of this landscape (Brooks, Blaes, and Hartfield 2014). North Carolina is one of the wettest locations in the southeast with statewide precipitation ranging from 34.8 - 68.4 inches (88.3 - 173.736 cm) per year (Frankson et al. 2022). Summer temperatures in the study area average 75.6 degrees Fahrenheit (24.2° C) and winter temperatures average 41.4 degrees Fahrenheit (5.2° C) (Frankson et al. 2022).

The study area is characterized as having a patchwork of agricultural land, managed woodland, fragmented forest, and urban development (South Carolina Department of Natural Resources, 2013). Oak forest is widely distributed with fragmented successional pine occurring in combination with pine-hardwood forest (South Carolina Department of Natural Resources, 2013, Frost 1993). Common pine species in this region include shortleaf (*Pinus echinata*), loblolly (*Pinus taeda*), and longleaf (*Pinus palustris*) (South Carolina Department of Natural Resources, 2013). Common hardwoods include hickory (*Carya ovat*a), and sweetgum (*Liquidambar styracilua*) as well as multiple members of the oak genus (*Quercus*). Common forest types include pine woodland, savannah grassland, and early successional forest (South Carolina Department of Natural Resources, 2013).

The study area has been predominantly used for agricultural purposes following European settlement in the 18th century (Frost 1993). Several cycles of short-rotation pine forest were used, which often provided substantial edge habitat for game species (South Carolina Department of Natural Resources, 2013, Frost 1993, Van Lear 2005). Additionally, extensive holdings were used as recreational hunting reserves and managed primarily for production of game species with timber production to offset management expenses. (South Carolina Department of Natural Resources, 2013). The sandhills region represents a subsection of the Piedmont and Coastal Plain and stretches from central North Carolina to central Georgia and is characterized as having sandy soil that is well drained. The sandhills region is important to southeastern fox squirrels because it is home to much of the remaining longleaf pine forests.

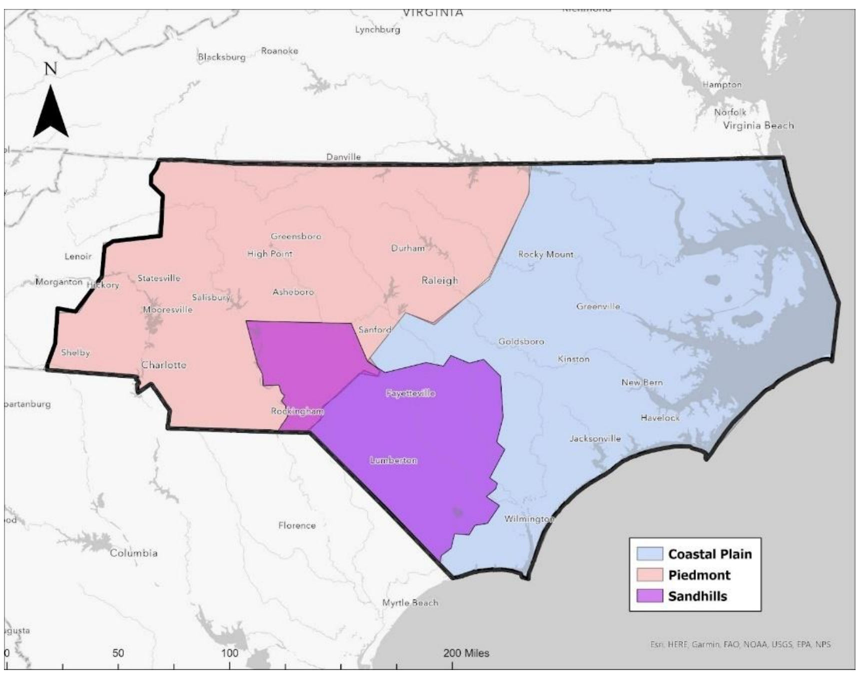

Figure 2: Study area of the coastal Plain and Piedmont regions of North Carolina. The sandhills sub region of the study area is identified as well. Figure created using ArcGIS, Version 9.0 (Environmental Systems Research Institute, Inc., Redlands, California).

Methods – Species Data Collection

To improve the current understanding of known fox squirrel habitat, southeastern fox squirrel presence data was collected through crowdsourced participation using two methods. The first was aggregating observations from the crowdsourced identification program, iNaturalist. iNaturalist is a joint initiative of the California Academy of Sciences and the National Geographic Society to allow individuals to record and share species observations (iNaturalist. Available from https://www.inaturalist.org. Accessed [2022]). The iNaturalist observations used for this study were classified as "research grade" meaning the observations are the highest quality of observation available on iNaturalist and that the observations have been reviewed and validated by community identification (Boone and Basille 2019). For observations to be considered research grade they must include the date of observation, the spatially georeferenced location, contain a picture or sound recording of the specimen, and be a naturally occurring, non-captive organism (Boone and Basille 2019). Additionally, at least two users, in addition to the submitter, must confirm the identification of the entry (Boone and Basille 2019). iNaturalist has been used in previous publications to observe the presence of elusive species as well as to determine presence of members of the genus *Sciurus* (Michonneau and Paulay 2015, Creley and Muchlinski 2017).

The second method to collect observations was sightings being submitted by the general public. Flyers were distributed by employees of The Nature Conservancy and posted on signs throughout The Nature Conservancy's affiliated game land and managed land in the Piedmont and Coastal Plain region of North Carolina. These flyers were intended for hunters and members of the public and contained information on the intent of the study, along with a request for observations of southeastern fox squirrels to be sent in along with the coordinates and a picture of the specimen (Figure 3). If not included with the initial submission, description of location and date of sighting was requested from the citizen scientist. Partnerships with state biologists, game land wardens, and land managers were established to facilitate these individuals submitting southeastern fox squirrel sightings. Hundreds of observations were submitted primarily by hunters, biologists, land managers, and state park volunteers (Table 1).

Figure 3: Image of flyer that was distributed in game lands and managed lands throughout October 2021 to February 2022 in North Carolina as part of this study's citizen science campaign for southeastern fox squirrel location.

Table 1: The breakdown of sources from citizen scientists reporting southeastern fox squirrel, *Sciurus niger niger*, sightings in the Piedmont and Coastal Plain of North Carolina from 2008 – 2022.	
Data Source	**Number of Observations**
iNaturalist	152
Biologist / Land Manager / Game Warden / Hunter	393
Other members of the public	14

All observational data collected from these methods were analyzed to ensure proper coordinates and accuracy. This was done through plotting the coordinates of the observation and confirming the data point was in the location described in the submission in addition to viewing the attached photo to confirm that the specimen was a southeastern fox squirrel. Acknowledging the difficulties in taking a photo of a southeastern fox squirrel, particularly if the encounter is while walking and the animal is startled, submissions from professional wildlife biologists / land managers and registered southeastern fox squirrel hunters were accepted without a photo attached to the submission. After ensuring the data quality, a cleaned dataset of 554 southeastern fox squirrel observations from 2008 - 2022 was used in this analysis. Because the data were heavily sampled in the sandhills region of the state, A second dataset was created where the data were spatially thinned so that there were 0.2 km or greater between any two points which resulted in 444 observations of spatially thinned data. A distance of 0.2 km was determined as previous studies in the study area averaged one southeastern fox squirrel per 0.2 square kilometer (Wiegel 1989).

The observation data used was “presence only”. To predict presence likelihood, a set of random points was generated across the study area to act as a pseudo-absence (Barbet - Massin et al. 2012). A pseudo absence is a randomly generated point acting as an absence data point that is necessary to correctly classify the condition of absence, or low probability locations in the study area (Barbet - Massin et al. 2012). The pseudo absences were randomly generated across the study area with a minimum spacing of 0.2 km between points and no overlap with existing presence sightings. In all of the following models, the amount of pseudo absence points used was equal to the amount of southeastern fox squirrel sighting points used.

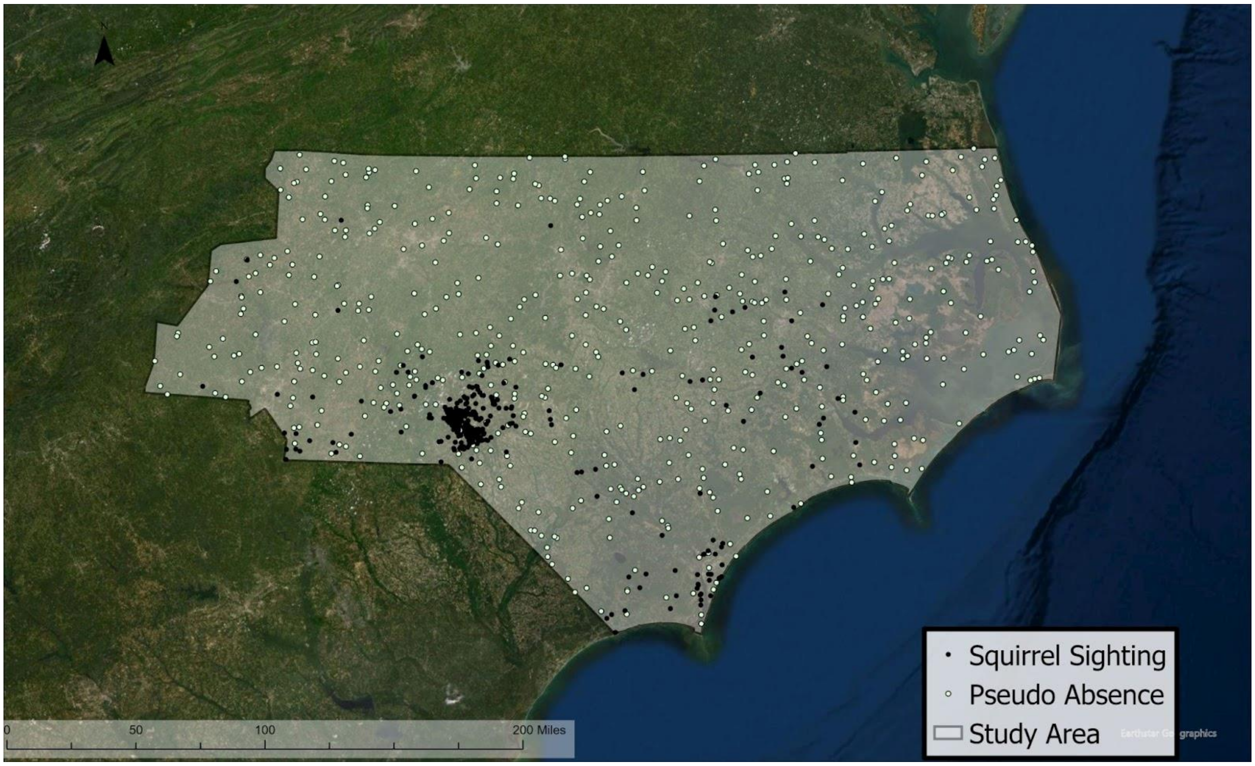

Figure 4: Location of study area with 554 plotted southeastern fox squirrel, *Sciurus niger niger*, sightings from 2008 - 2022 and 554 randomly generated pseudo absences. Figure created using ArcGIS, Version 9.0 (Environmental Systems Research Institute, Inc., Redlands, Calif.).

Methods – Environmental Data

To determine suitable habitat for the southeastern fox squirrel, environmental data was used to parameterize the species distribution model. Land cover data was used due to its ability to predict species distribution by identifying key environmental demands of the southeastern fox squirrel's habitat.

The land cover variables used were selected based on biological importance and expert opinion and recommendation. The final eight predictor variables used to classify habitat were the five dominant forest type presence variables: (1) loblolly, (2) longleaf, (3) loblolly / hardwood mix, (4) sweetgum mix, and (5) loblolly / hardwood mix forest, as well as the variables for (6) percent impervious surface, (7) agricultural land, and (8) distance from longleaf pine land cover data. All land cover data was processed through ArcGIS Pro (ArcGIS, Version 9.0, Environmental Systems Research Institute, Inc., Redlands, Calif.).

Dominant forest type data was used because southeastern fox squirrels demonstrate a strong selection for mature pine and pine-hardwood forest (Perkins and Conner 2004). The dominant forest types used in this analysis were obtained from the 2008 United States Forest Service Continental United States Forest Type dataset (United States Department of Agriculture Forest Service National Forest Type Dataset). The data was processed so that each forest type was an individual binary layer of presence. For all 554 southeastern fox squirrel sightings, a buffer of 34 km was placed around the central point. 34 kilometers represents the average maximum distance in a southeastern fox squirrel's range (Wiegel 1989). Within this buffer range, the number of cells of each forest type was summed. Forest types that were present in less than 1% of the total cell area were not used. The presence of two forest types, sweet gum / yellow poplar mix, and sweet gum / oak mix combined into one category titled "sweetgum mix". The resulting dominant forest type land cover data layers were "loblolly"," longleaf", "loblolly / hardwood mix", "sweet gum mix", and "loblolly / hardwood mix" (Table 2).

Agricultural land was used as an environmental parameter because southeastern fox squirrel habitats often border agricultural land and agricultural crops may act as an abundant food source for the southeastern fox squirrel (Derge and Yahner 2000). Additionally, a similar subspecies of fox squirrel, Sherman's Fox Squirrel *(Sciurus niger shermani)*, has been known to be present on agricultural landscapes (Green and McCleery 2017). The agricultural land data used in this analysis was taken from the 2019 National Land Cover Dataset NLCD 2019 Land Cover CONUS). I defined agricultural land as either "Hay / Pasture" or "Cultivated Cropland" by National Land Cover Dataset titles. These data were aggregated from 30m to 250m resolution resulting in a final binary presence / absence layer for agricultural land.

Table 2: The percentage of total area for the five most common forest types within total cell count for 34 km buffer around each southeastern fox squirrel, *Sciurus niger niger*, sighting using 2008 United States Forest Type Inventory Data Set.	
Dominant Forest Cover Type	Percentage of Total Area
Loblolly	38.16%
Longleaf	34.97%
Loblolly / Hardwood Mix	13.08%
Sweetgum Mix	4.49%
Loblolly / Hardwood Mix	4.36%

Percent impervious surface was used as an environmental parameter to account for the impact of road mortality, and the possibility of urban populations as is observed in Sherman's fox squirrel (Green and McCleery 2017). The impervious surface data used in this analysis was taken from the 2019 National Land Cover Dataset (NLCD 2019 Land Cover CONUS). The data was aggregated by mean cell value from 30m to 250m resolution resulting in a continuous layer with 1-100 scale cell value representing percent impervious surfaces.

I selected the distance from longleaf pine as a predictor of southeastern fox squirrel habitat because the longleaf pine pinecones are a major food source in the southeastern fox squirrels' diet (Lee et al. 2001). Distance from longleaf pine (DLP) was included to account for this proximity to the food source. The distance from longleaf pine (DLP) was classified as a variable separate from the dominant forest type longleaf data set because while dominant longleaf pine forests are only located in select parts of the state, longleaf pine as individuals are found throughout the region. The data used was sourced from the Florida Natural Areas Inventory in 2022. This data consisted of shapefiles of both known and suspected longleaf pine stands. Within ArcGIS Pro 2.8, a continuous raster measuring distance in meters from longleaf pine was created (ESRI 2011. ArcGIS Desktop: Release 10. Redlands, CA: Environmental Systems Research Institute).

Methods – Model Algorithms

Four species distribution models (hence M1, M2, M3, M4) were fitted to predict the probability of southeastern fox squirrel presence and habitat range throughout the Piedmont and Coastal Plain of North Carolina (Figure 4). The primary difference among M1, M2, and M3 models is the distance from longleaf pine parameter (DLP). The first model (M1) included the distance from longleaf pine raster for only the confirmed presence of longleaf pine. The second model (M2) included the distance from longleaf pine raster for both confirmed and suspected presence of longleaf pine. The third model (M3) excludes distance from longleaf pine from the model. The fourth model, (M4) is the same as M1 where only the confirmed presence of longleaf pine data is used for the distance from longleaf pine parameter, however the data used is all 554 un-thinned sightings instead of the 0.2 km thinned dataset of 444.

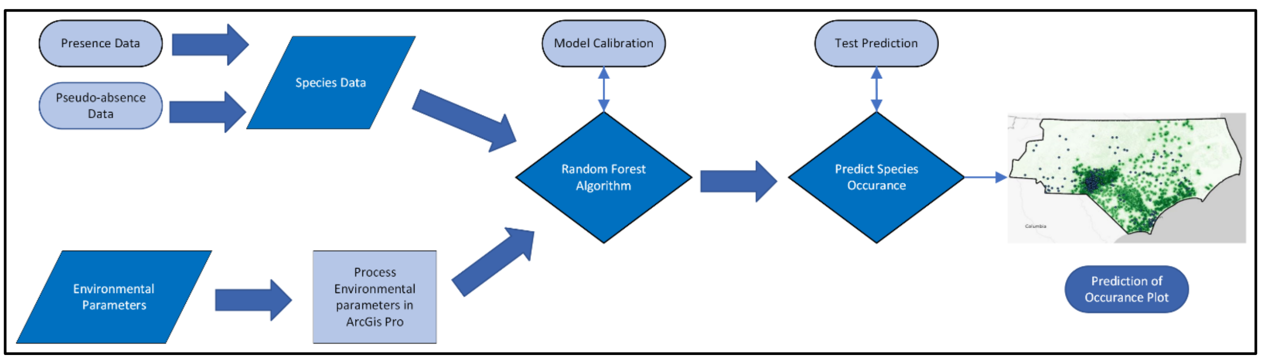

Figure 5: Workflow used to create species distribution model and map predictions for presence of southeastern fox squirrel.

To create the four species distribution models a random forest model was parameterized using the sdm package within R version 4.1.1 (Naimi, B., Araujo, M.B. 2016, R development Core Team 2021). Additionally, a logistic regression model was tested for all four models, however, the random forest consistently performed better and therefore, the general linear model was abandoned. M1, M2, M3, and M4 were tested with cross validation where each model was parameterized with 70% of the data and tested on the remaining 30%. This cross validation was repeated 100 times. Using the average parameter fit of the 100 runs, each model was then used to predict southeastern fox squirrel presence across the study area.

Methods – Model Evaluation

Because the data is collected from citizen science, frequency of occurrence is not standardized. Because predictive accuracy is affected by the frequency of occurrence of southeastern fox squirrels, Area Under the Curve (AUC) of the receiver operating characteristic (ROC) curve was used to evaluate model performance. The AUC is depicted by the curve of the true positives correctly predicted versus true negatives correctly predicted for calculated probabilities (Manel et al 2001). A model performing better than a random variable will have an AUC greater than 0.5. The closer the AUC is to 1.0, the better the agreement between the model prediction and the true observation (Manel et al 2001). AUC is more robust with respect to varied prevalence therefore it is a good parameter of evaluation for this study. In addition to AUC, model performance was evaluated using deviance, correlation, and total sum of squares (TSS) as well as plot visualization.

Results

Visual interpretation of each of the four models depicts the predicted probability of southeastern fox squirrel occurrence as highest in value in the sandhills region of North Carolina, particularly around Fort Bragg, the Cape Fear River and Wilmington (Figure 5, 6, 7, and 8). In M1, M2, and M4, there are additional high rates of probability occurring throughout the northern part of the study area in unconnected islands. When looking at all four of the generated prediction plots, the highest rates of probability occur in two broad sections - along the southern coast and in the sandhills respectively. These results indicate that the Cape Fear River is potentially acting as a corridor in the lower part of the State. The lowest probability of occurrence is in the northwestern part of the Piedmont as well as the northeastern shore of the Coastal Plain. The probability of occurrence decreases as proximity to urban areas such as the Charlotte and Raleigh metro areas increases, likely due to high rates of impervious surface. However, in models M1, M2, and M4, the Wilmington and Fayetteville metro areas were still ranked high.

In M1 the highest rates of predicted probability closely follow the established longleaf pine stands. As soon as individuals are ~2.75 kilometers away from the longleaf pine, the probability of southeastern fox squirrel occurrence decreases from 80.5% to 40.5%. The next major decrease in probability occurs 4.41km away from the longleaf pine stand with the average probability decreasing from 40.5% to 20.0%. This relationship of southeastern fox squirrels closely following the longleaf pine is detected in the analysis of variables (Table 4). Distance from longleaf pine was by far the most important variable, as 61.7% of the variance being explained by distance from longleaf pine (Table 2). The second most important variable was the dominant longleaf pine forest type accounting for 11.8% of the variance (Table 2).

M2 was very similar to M1 with the only difference being the inclusion of suspected longleaf locations included in the DLP layer. The inclusion of suspected longleaf pine made M2 perform better overall than M1. M2 has the highest AUC (0.94) and the lowest deviance (0.69) of all four of the models (Table 3). Interestingly, M2 has a higher Pearson's correlation value for the longleaf pine variable (17.0%) than M1 (11.8%) with additional slight increases in the Loblolly, and Loblolly / Hardwood mix variables (Table 4). Additionally, the southeastern fox squirrel sightings that occur in the western part of the study area are better accounted for in M2 in comparison to M1. The increased accuracy of M2 in comparison to M1 suggests that the suspected longleaf pine is present on the landscape.

M3 is very unique compared to the other models, exemplifying the effect of the distance from longleaf pine parameter. M3 had the DLP parameter excluded from the final model. M3 was created due to initial testing of the M1 placing multiple southeastern fox squirrel sightings in very low predicted probability in the northwestern portion of the study area. Excluding distance from longleaf pine from the model accounts for these sightings with higher probability. M3 largely shows the sandhills region as the highest probability of occurrence (Figure 5).

M4 was similar to M1, with the only difference being M1 using the 444 thinned data set while M4 uses the full set of 554 observations. Interestingly, when the data was not thinned, the predicted probability follows the distance from longleaf pine data slightly less. The distance from longleaf pine still explained the most variance for M4 at 58.7%, however, the second largest predictor of longleaf pine forest has decreased in value with a Pearson's correlation value of is now accounting for 10.3% of the variance instead of the 11.8% in M1 (Table 4).

Table 3: Model performance for each of the four models used to predict southeastern fox squirrel presence.

Model	Variables	AUC	Correlation	TSS	Deviance
M1	Distance LLP (confirmed), Ag land, Impervious surface, Longleaf, Loblolly, Longleaf / Oak Mix, Loblolly Hardwood Mix, and Sweetgum Mix	0.92	0.76	0.72	0.72
M2	Distance LLP (confirmed and suspected), Ag land, Impervious surface, Longleaf, Loblolly, Longleaf / Oak Mix, Loblolly Hardwood Mix, and Sweetgum Mix	0.94	0.78	0.77	0.69
M3	Ag land, Impervious surface, Longleaf, Loblolly, Longleaf / Oak Mix, Loblolly Hardwood Mix, and Sweetgum Mix	0.82	0.58	0.56	1.03
M4	Distance LLP (confirmed), Ag land, Impervious surface, Longleaf, Loblolly, Longleaf / Oak Mix, Loblolly Hardwood Mix, and Sweetgum Mix. Data not thinned.	0.92	0.75	0.73	0.74

Table 4: Percentage of variance explained by predictor variable for each M1, M2, M3, and M4 model				
Environmental Parameter	M1	M2	M3	M4
Percent Impervious	1.0%	0.9%	1.9%	0.8%
Sweetgum Mix	0.2%	0.4%	1.0%	0.3%
Longleaf	11.8%	17%	73.3%	10.3%
Loblolly	1.6%	2.1%	16.8%	1.5%
Distance From Longleaf (DLP)	61.7%	61.9%	N/A	58.7%
Loblolly / Hardwood Mix	0.4%	0.7%	4.6%	0.7%
Longleaf / Oak Mix	0.4%	0.6%	7.0%	0.5%
Agricultural Land	1.9%	1.3%	9.2%	2.9%

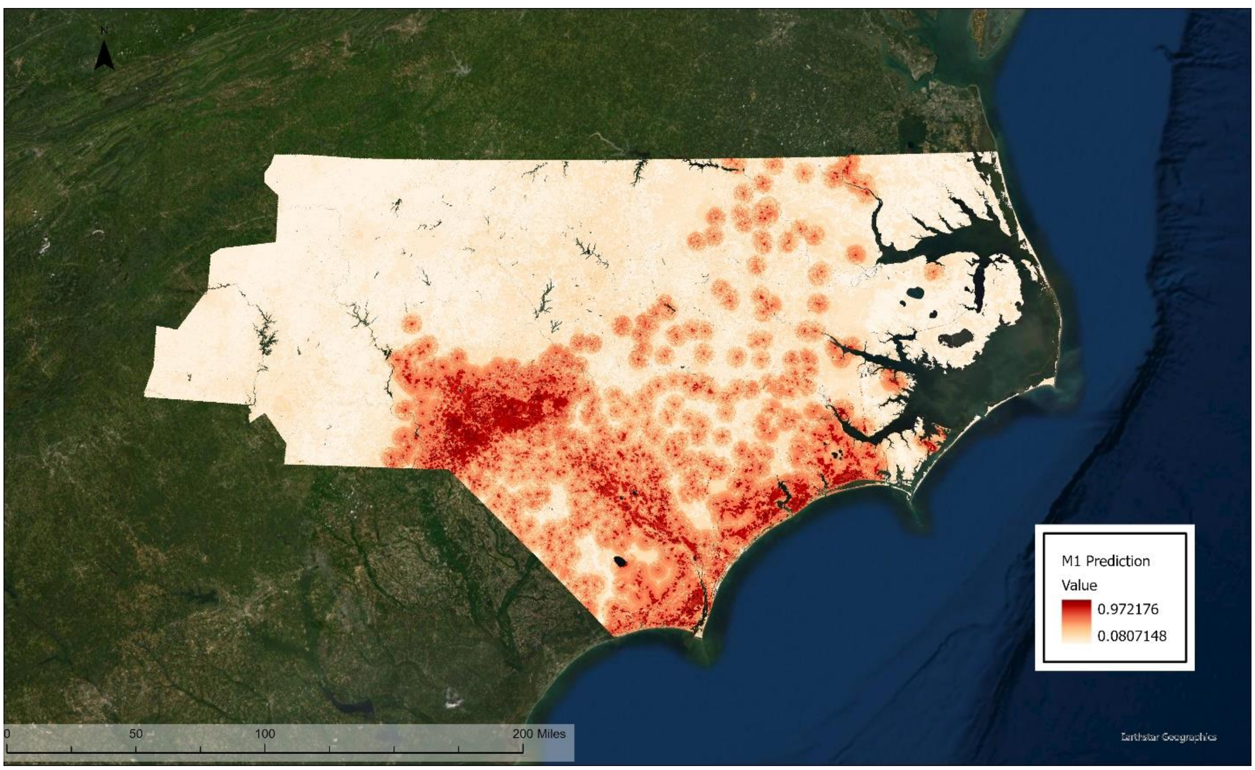

Figure 6: Predicted probability of occurrence map using M1 random forest model. Figure created using ArcGIS, Version 9.0 (Environmental Systems Research Institute, Inc., Redlands, Calif.).

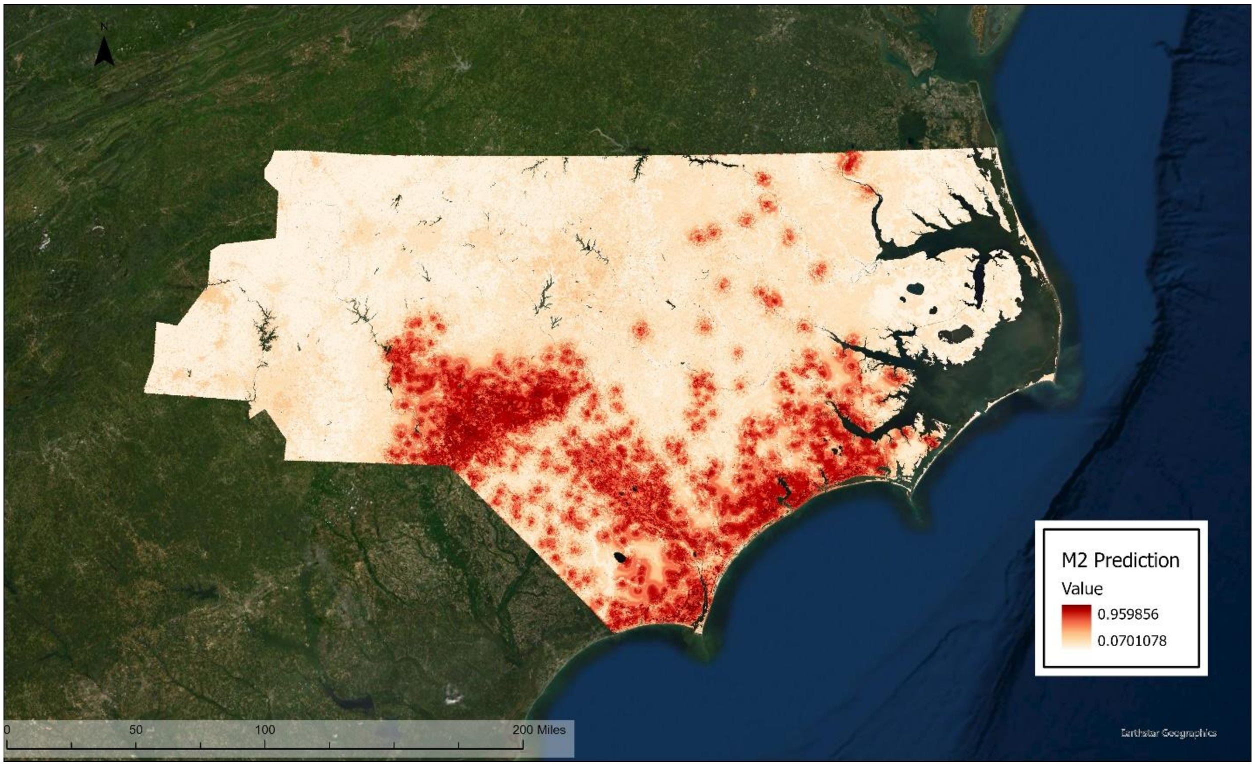

Figure 7: Predicted probability of occurrence map using M2 random forest model. Figure created using ArcGIS, Version 9.0 (Environmental Systems Research Institute, Inc., Redlands, Calif.).

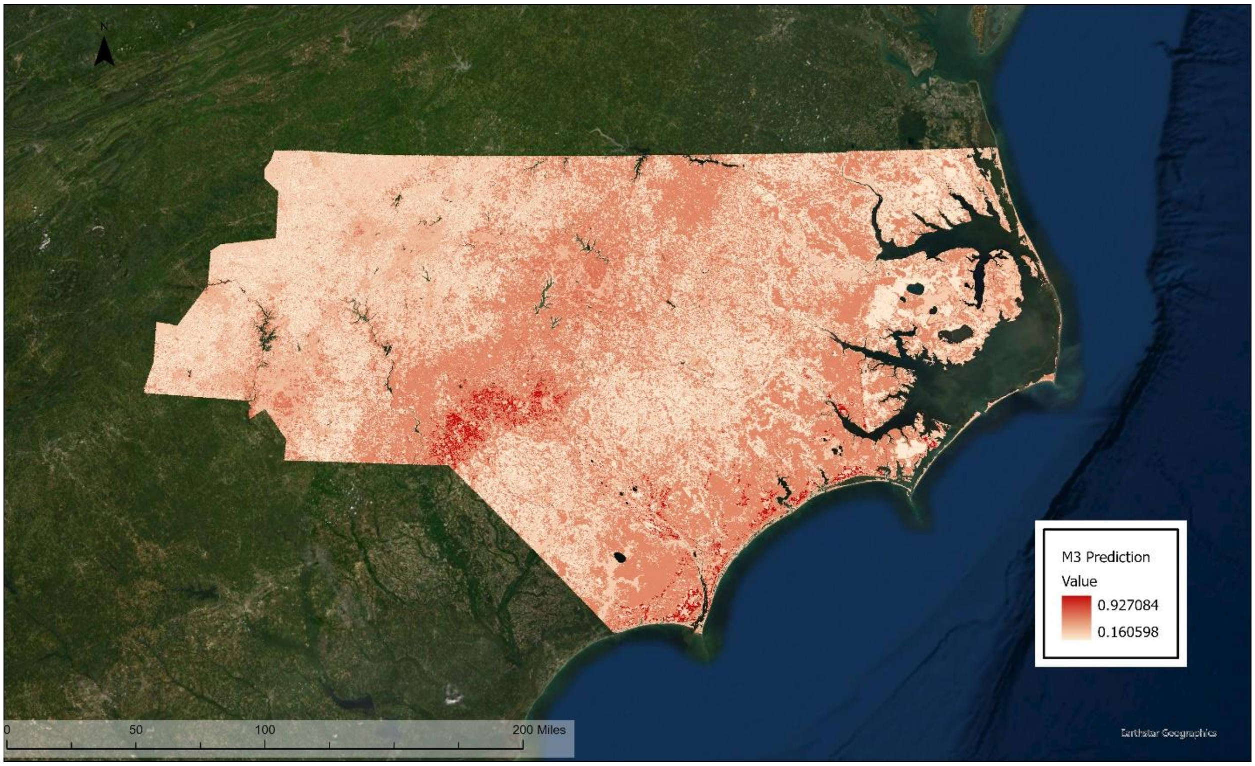

Figure 8: Predicted probability of occurrence map using M3 random forest model. Figure created using ArcGIS, Version 9.0 (Environmental Systems Research Institute, Inc., Redlands, Calif.).

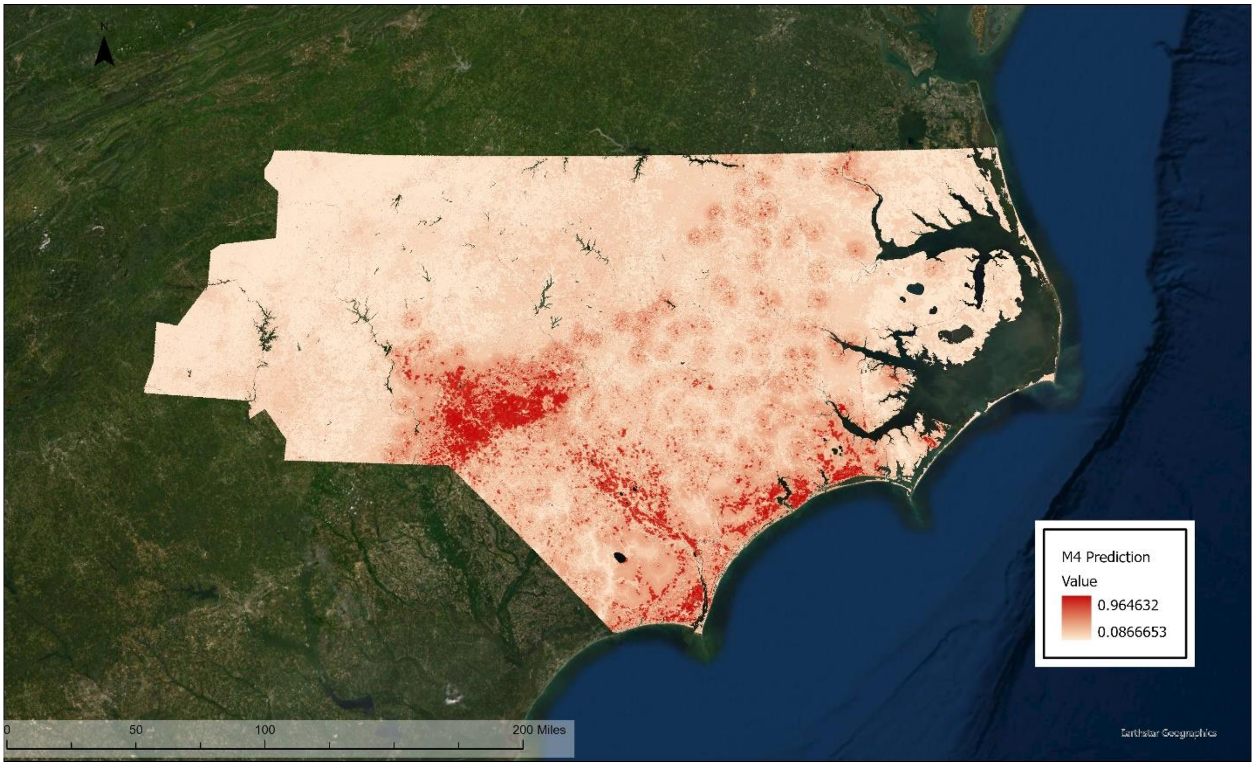

Figure 9: Predicted probability of occurrence map using M4 random forest model. Figure created using ArcGIS, Version 9.0 (Environmental Systems Research Institute, Inc., Redlands, Calif.).

DISCUSSION

The potential location occupied by southeastern fox squirrels is of interest in many monitoring programs to track the population and determine areas for conservation actions or restoration. I provided four models that can be used by management in aiding this goal. Additionally, I demonstrated the usefulness of citizen science in collecting southeastern fox squirrel data and as such can provide recommendations for future citizen science efforts. Finally, I estimated the relationships among southeastern fox squirrels, longleaf pine, and their relationship to the landscape.

Discussion – Recommended use of models

The results indicate that across all models, southeastern fox squirrel occurrence is concentrated to specific geographic areas in the southeastern part of North Carolina with high probabilities consistently occurring in the sandhills region and along the southern coast. Overall, the probability of occurrence of southeastern fox squirrels declines and fragments towards the northeast and northwest of the sandhills in North Carolina. The majority of areas in the northwestern part of the study area do not meet the environmental demands of the southeastern fox squirrel's habitat and have a low probability of southeastern fox squirrel occurrence, particularly in models M1 and M4.

The four models provided can be useful for different aspects of management depending on their intended use. M3 (exclusion of DLP) provides a more generalist view of habitat for the southeastern fox squirrel. M3 has a lower AUC (0.82) than the other models, however M3 predicts larger amounts of potential habitat and better captures the probability of outliers in central NC when compared to the other models (Figure 4, Figure 5, Figure 6, Figure 7). Because the outliers in central NC have high DLP values and are not located in longleaf pine forest, these western sightings of southeastern fox squirrels could be individuals existing in alternative habitats in response to the extreme fragmentation of the longleaf pine. M3 may be most useful in scenarios where managers are looking for locations to restore the longleaf pine ecosystem or identifying outliers in habitat.

Models M1, M2 and M4 were all high performing models with the most important variable being DLP, representing the relationship between southeastern fox squirrels and longleaf pine stands. The highest rates of predicted probability for both M1, M2, and M4 closely follow the longleaf pine stands represented by the DLP layer. The three models are very similar with M2 performing slightly better. M1 performs the worst when accounting for the southeastern fox squirrels occurring in the northwestern section of the study area. The difference between M1 and M4 is the use of the 0.2km thinned data in M1 versus the un-thinned data in M4. The effect of this difference is seen in the importance of both the DLP variable and the longleaf pine forest variable. DLP is slightly more important in M1 with 61.7% of variance explained by DLP, compared to 58.7% in M4. Longleaf pine forest is more important for M1 compared to M4 (11.8% and 10% respectively). M1, M2, and M4 all depict a strong pattern of high rates of probability occurring in isolated fragments. Because M1, M2 and M4 are all high performing models with high rates of prediction, all three of these models could be directly useful for southeastern fox squirrel conservation. M1(thinned data) accounts for the oversampling in the sandhills region better than M4, but M4 better emphasizes the relationship between southeastern fox squirrels and the longleaf pine forest in congruence with DLP. M2 addresses both of these issues by emphasizing the forest type relationship with longleaf pine while still closely following the DLP layer and the inclusion of suspected areas of longleaf pine. This combination is especially promising for southeastern fox squirrel management due to the balance between the highest performing variable (DLP) and the importance of the southeastern fox squirrels' historic habitat (Longleaf Forest).

Within M1, M2, and M4 the predicted probability occurs primarily in islands around known longleaf pine stands. The phenomenon where the probability of occurrence decreases by 60% at 5 km distance from the longleaf pine stand may be explained by the distribution of southeastern fox squirrels. The average maximum dispersal distance of southeastern fox squirrels between habitat patches is 6km (Meehan and Jodice 2010). The decrease in occurrence probability at 5km may be accounting for the dispersal distance. M4 was created to ensure that this effect was not an artifact of the spatial thinning used on the data in M1. I suspect M1, M2, and M4 are creating this pattern of radial dispersion due to southeastern fox squirrel observations in this region occurring in highly fragmented habitat (as compared to the sandhill region's more continuous habitat). Future research should determine if the southeastern fox squirrels present in the fragmented habitat in the northern part of the state are dispersing out from the longleaf pine stands.

Discussion – Using Citizen Science for Southeastern Fox Squirrel Data

In general, there was a positive response from the community when requesting southeastern fox squirrel location sightings. Citizen science was particularly successful due to southeastern fox squirrels being the largest species of tree squirrel native to the United States and having a variety of color forms, the most common of which is a black body with a white face (Carraway et al 2017). These physical character traits make them easily identifiable for citizen scientists and visually distinctive from the other *Sciuridae* species in the study area, the common gray squirrel (*Sciurus carolinensis)*. Furthermore, the southeastern fox squirrel exists at high enough populations in certain areas to be allowed as a game animal which results in a large population of hunters in the public that are familiar with the identification and location of southeastern fox squirrels. My citizen science campaign was successful with over 407 of the 555 observations used in this analysis submitted by citizen scientists within an eight-month window. Citizen science is an effective, low cost, high coverage method of gathering locational data for the southeastern fox squirrel over a large spatial temporal scale.

Although there was immense response from the community with at least one submission sent in every day for the entire duration of the campaign, there were challenges. First, a large amount of data was submitted that was unable to be used (criteria listed in the methods). Second, acquiring this information from the hunter community was difficult until trust with the hunting community had to be established. Once established, it was the hunters that knew more remote locations of suspected southeastern fox squirrel sightings and were a large source of information for where the species occurred throughout the state. In future studies, more explicit data requests should be made on public notifications in addition to further relations being formed with the southeastern fox squirrel hunters.

Discussion – Southeastern Fox Squirrels as Indicators of Longleaf Pine Presence

The inclusion of the suspected longleaf pine in M2 made the model more accurate than M1(only confirmed longleaf pine presence in DLP) with a 0.02 increase in the AUC and a 0.0.3 decrease in the deviance. Additionally, the variance explained by the DLP in M1 (confirmed only in DLP) is 61.7% and the inclusion of suspected LLP in M2 slightly increases the variance explained by DLP to 61.9%. While the difference is slight, it should be acknowledged that the inclusion of suspected longleaf pine on the landscape improved the performance of an already high performing model. This suggests that the suspected longleaf pine is present on the landscape. If the suspected longleaf pine was not present, it is likely that its inclusion would decrease the performance of M2, not increase.

Additionally, the southeastern fox squirrel is known to rely on the longleaf pine for a food source and when the distance from longleaf pine (DLP) parameter was left out of the model, in M3, the longleaf pine forest type became the most influential parameter, emphasizing the importance of longleaf pine in predicting the presence of southeastern fox squirrels. To support this idea, an alternate model was created predicting the presence of longleaf pine using distance from southeastern fox squirrel sighting as the variable. This model performed better than a random variable presenting southeastern fox squirrels as a potential predictor of longleaf pine occurrence as well. The potential ability of crowd sourced southeastern fox squirrel location data to predict longleaf pine presence on the landscape is an area of future research. Using the relationship between the southeastern fox squirrel and the longleaf pine could be a useful tool for land managers attempting to identify undocumented fragments of longleaf pine on the landscape.

Discussion - Conclusion

In conclusion, I created four models to identify potential southeastern fox squirrel habitat in the Piedmont and Coastal Plain of North Carolina. These models can aid in the management of the southeastern fox squirrel populations. The probability of occurrence I provided imparts credible, defensible, and repeatable information for generating hypotheses and assessing the usefulness of management strategies to aid in the restoration of the declining population of southeastern fox squirrels. The southeastern fox squirrel is just one of many species reliant on the longleaf pine ecosystem. Nearly two thirds of all species that are recognized as declining, threatened or endangered in the southeastern United States are associated with the longleaf pine ecosystem (Mitchel 2006). The southeastern fox squirrel is declining primarily due to habitat loss and fragmentation therefore a recovery plan focused on habitat restoration and protection is critical.

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