Species Status Assessment Report
for the
Southern Hognose Snake
(*Heterodon simus*)

Version 2.1

Photo Credit: P. Hill

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Southeast Region
Atlanta, GA

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U.S. Fish and Wildlife Service. 2024. Species status assessment report for the southern hognose snake (*Heterodon simus*), Version 2.1. October 2024. Atlanta, GA.

VERSION UPDATES

The changes from version 1.0 to version 1.1 (March 2019 – Peer Review) include minor grammatical changes as well as the removal of one record/population in South Carolina and the addition of two historical records/populations in Georgia. These changes do not significantly change the analysis for the southern hognose snake.

The changes from version 1.1 to version 2.0 (April 2019 – Federal Register) include adding Cogongrass as a threat under invasive species and *Raillietiella orientalis* as a threat under disease. We also modified the persistence model based on improvements suggested by reviewers during the Florida Pinesnake Species Status Assessment. The future scenarios were changed to reflect the best available projections into the future. We updated data including obtaining additional records of southern hognose snakes and non-target species, using the new versions of spatial data (i.e., TIGER line shapefiles of major roads, USGS National Hydrology dataset river shapefiles, sea level rise shapefiles from NOAA, and land cover shapefiles), and using the FUTURES model instead of the SLEUTH model for our predictions of urbanization in future scenarios.

The changes from version 2.0 (August 2024 – Recommenders) to version 2.1 includes the addition of further evaluation of the 3R's and some minor grammatical changes.

EXECUTIVE SUMMARY

This report summarizes the results of a Species Status Assessment completed for the southern hognose snake (*Heterodon simus*) to assess the species' overall viability. We considered what the species needs to maintain viability by characterizing the status of the species in terms of its resiliency, representation, and redundancy (3Rs). We provide a thorough assessment of ecology and individual needs of the species, followed by a description of the factors influencing viability, and then a description of the species' current condition and predicted future condition.

The southern hognose snake is the smallest of the hognose snakes and is associated with xeric longleaf pine savannah, flatwoods, and sandhills in North Carolina, South Carolina, Georgia, Florida, and west to Alabama and Mississippi. They occupy upland habitat with well-drained, sandy soils, characterized by pine-dominated or pine-oak woodland where the canopy is open with a grassy understory. The annual cycle of the southern hognose snake is characterized by seasonal peaks of activity (Tuberville et al., 2000, p. 21). Records for the species occur across all months, but there are generally two peak periods of detection, May-June and October-November. The southern hognose snake is diurnal, with peak activity occurring in the late morning to early afternoon (Beane et al., 2014, p. 173). Frogs and toads have been reported to make up the largest portion of the southern hognose snake diet, but they are also known to eat small lizards (Ashton and Ashton, 1981, p. 85; Beane et al., 1998, p. 45; Ernst and Ernst, 2003, p. 153). Specific ecological needs that are essential to the survival and reproductive success of individuals include well-drained soils, suitable vegetation structure and composition, and presence of prey.

The potential factors that could be affecting the viability of the southern hognose snake include the following: (1) habitat loss, conversion, and fragmentation from loss of longleaf pine savanna habitat; (2) road mortality; (3) invasive species, such as the red imported fire ant and feral hogs; (4) effects of climate change resulting in increased temperatures, decreased precipitation, increased severe weather such as drought, flooding, or storms, changes in wildfire frequency and intensity, decreased ability to conduct prescribed burns, and sea level rise (SLR); (5) the collection of individual snakes for the pet trade and persecution by humans; and (6) impacts that a potential disease outbreak may have on existing populations.

For the purpose of this assessment, we defined *viability* as the ability of the southern hognose snake to sustain populations in the wild over time. Using the SSA framework, we describe viability of the southern hognose snake by defining populations, estimating current condition, and predicting the future condition using the metrics of the 3Rs.

For this assessment, we defined populations as contiguous areas surrounding known southern hognose snake occurrences with habitat conducive to survival, movement, and inter-breeding

among individuals within the area. We used 2,662 species records from 1880–2023 to define 233 populations. We grouped nearby records (those within 5 km of each other) into the same population while accounting for the major movement barriers (rivers and interstates).

To describe the southern hognose snake's current condition, we assessed the species' population resiliency and the overall redundancy and representation across its current range considering the threats and conservation actions acting on the species. Each population's current persistence probability (i.e., the probability that a site is currently occupied by a southern hognose snake) was estimated and we summarized results by grouping populations into categories representing ranges of persistence probabilities. The categories we chose were unlikely or extirpated (< 50%), more likely than not on landscape (50–79%), very likely on landscape (80– 94%), and extremely likely on landscape or extant (95–100%). Although a number of populations were determined likely to currently be extant at >50 percent probability, the habitat conditions and connectivity may be impaired, resulting in lower current resiliency than the category that corresponded to their current persistence probability. To evaluate current resiliency, we assessed metrics using each population's probability of persistence, habitat suitability, and connectivity of populations across the species' range and used three categories: high, moderate, and low.

Representation reflects the ability of a species to adapt to changing environmental conditions and can be measured by the breadth of genetic or environmental diversity within and among populations. Redundancy reflects the ability of a species to withstand catastrophic events over time by having multiple, widely distributed populations. Since we did not have species-specific genetic and ecological diversity information, we captured representation and redundancy by grouping Environmental Protection Agency (EPA) Level IV ecoregions into nine representative units, which captured different ecological settings within the species' range, and assessing the number and geographic distribution of resilient populations across and within each unit and across the entire range. To have high representation, the species must have highly resilient populations located in each of the representative units, and resilient populations should span the latitudinal and longitudinal extent of historical populations. To have high redundancy, the southern hognose snake would need to have multiple resilient populations within a representative unit and throughout its range.

Current resiliency, representation, and redundancy have decreased from historical conditions for the southern hognose snake. Range-wide, 61.8% (144/233) of southern hognose snake populations have likely become extirpated (i.e., populations with a less than 50% current persistence probability. Of the 87 extant populations, 17 populations (19.5 percent) have high resiliency, 9 populations (10.3 percent) have moderate resiliency, and 61 (70.1 percent) have low resiliency. All nine representative units have lost 37.7% –100% of their populations (i.e., including populations with a less than 50% current persistence probability). Two representative

units, the West (AL/MS) and Alabama Central units, have likely lost all their populations (Figure ES-1 and ES-2). The Atlantic Coastal Plain (GA/FL) unit was predicted to have only 1 population above a 50% probability of current persistence, only 1 population above an 80% probability, and no populations with high resiliency and 1 population with moderate resiliency. Therefore, this unit is also at a higher risk of unit-wide extirpation and indicates the potential for further loss of representation. The southern hognose snake has likely experienced a decrease in latitudinal and longitudinal variability (i.e., a range contraction), relative to its historic range extent. Although highly resilient populations are currently distributed across most (5 of 9) representative units, their distribution has become clustered. This has left multiple large geographic regions only containing populations that are likely extirpated, including southern Alabama, central Georgia, the eastern Florida Peninsula, and the northeastern end of the Coastal Plain.

Table ES-1. Number of southern hognose snake populations and their current status and resiliency (n=233). Resiliency includes only extant populations. Percent of total historical populations includes all extirpated and extant populations. The percent of extant total includes only the currently extant populations.

Population status/resiliency	Number of populations in each category	% of total	% of extant total
High Resiliency	17	7.3%	19.5%
Moderate Resiliency	9	3.8%	10.3%
Low Resiliency	61	26.2%	70.1%
Extirpated	144	61.8%	0.0%
Unknown	2	0.9%	0.0%

Figure ES-1. Southern hognose snake populations across representative units based on probability of persistence. Green populations are extremely likely to currently occur on the landscape or be extant; yellow populations are very likely; blue more likely than not; and red populations are unlikely to currently exist (i.e., considered extirpated).
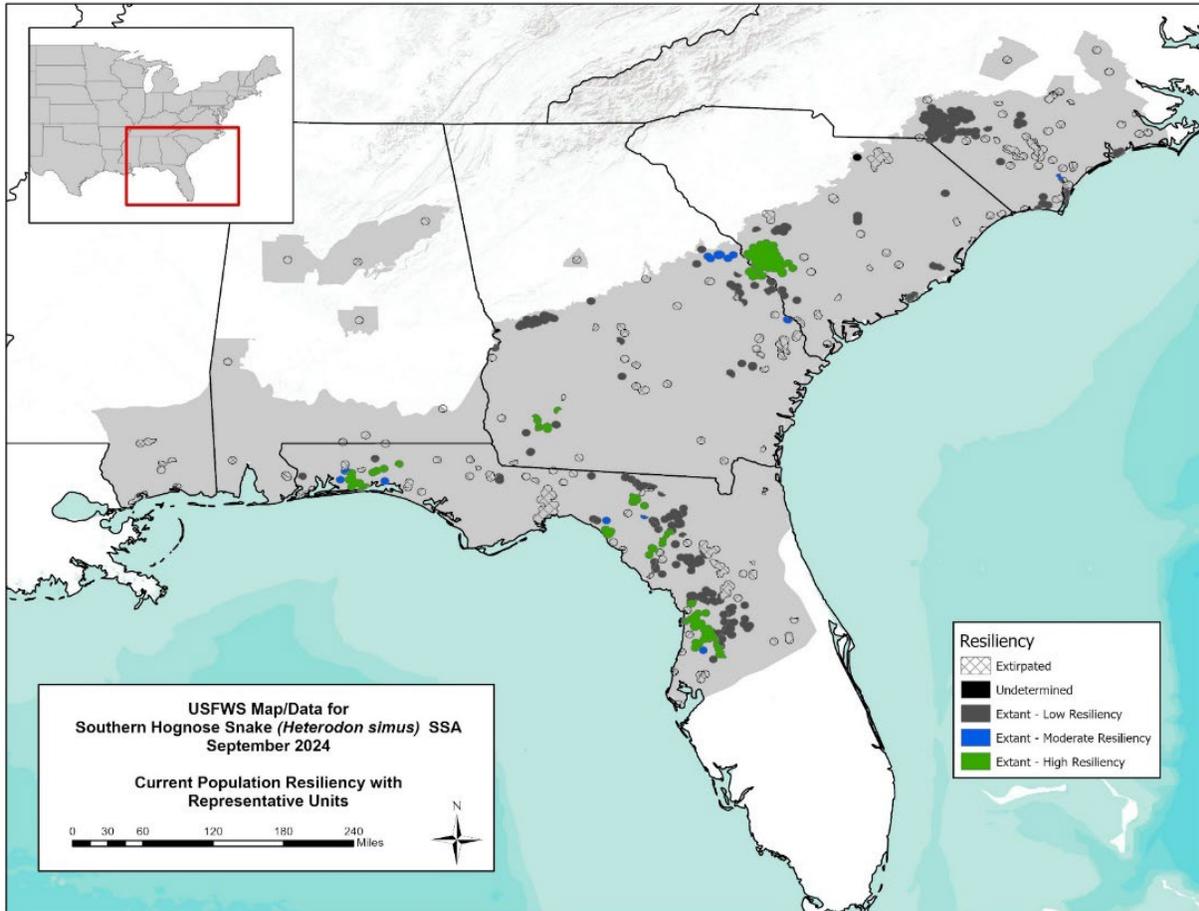
Figure ES-2. Current population resiliency showing all the populations. Populations in green (n=13) indicate those with the highest resiliency, moderate (n=4) in blue, and those that we that we consider to be extant but have low resiliency are in dark grey. Extirpated populations are hatched.

In evaluating future conditions for the southern hognose snake, we developed a simulation model that predicted population persistence through 2080 using current persistence and habitat conditions under six scenarios. We used the same metrics from the current conditions analysis to characterize future resiliency, representation, and redundancy, which we summarized in 2040, 2060, and 2080. Because the simulation model accounted for year-to-year variation and uncertainty, predictions varied each time we ran the model. Therefore, we additionally characterized future conditions by calculating the mean (the most likely prediction) and 95% confidence intervals for the number of persisting populations in each representative unit and range-wide each year through 2080. All six scenarios yielded nearly identical predictions of the number and percentage of resilient populations. These patterns were seen across all future time horizons (2040, 2060, and 2080). To simplify the reporting of our results since there was so little difference between the scenarios, we only show the results for the Low Urbanization/RCP 4.5 (best case) and High Urbanization/RCP 8.5 (worst case).

Our analysis shows that future resiliency, representation, and redundancy, is predicted to decrease from current conditions for the southern hognose snake under all scenarios. By 2040, there are 13 populations that are considered to have high resiliency. By 2080, only 2 populations exhibit the highest degree of resiliency and 14 are considered to be moderately resilient. In the future, there is a high risk of the species being extirpated from three additional representative units (current conditions indicate that it is very likely already extirpated from two units) and moderate risk of reduced representation in three other units. The remaining representative unit showed a decline in the number of resilient populations. Under all scenarios we see a reduction in the number of resilient populations within each of the units, as well as across the range of the species.

This assessment shows that there have been range-wide declines for this species from its historical to current conditions, which has previously been suggested in the literature (Tuberville et al., 2000, entire). Our analysis indicates that future resiliency, representation, and redundancy, as measured by future population persistence, for the southern hognose snake is predicted to further decline from current conditions under all scenarios considered.

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CHAPTER 1 – INTRODUCTION

The southern hognose snake (*Heterodon simus*) is a species associated with xeric longleaf pine (*Pinus palustris*) savanna, flatwoods, and sandhills in North Carolina, South Carolina, Georgia, Florida, and west to Alabama and Mississippi. We, the U.S. Fish and Wildlife Service (Service), were petitioned to list the southern hognose snake as endangered or threatened under the Endangered Species Act of 1973, as amended (16 U.S.C. 1531-1543) (ESA), in July 2012 as a part of the Petition to List 53 Amphibians and Reptiles in the United States by the Center for Biological Diversity (Center for Biological Diversity, 2012, pp. 156–163). On July 1, 2015, the Service published a 90-day finding that the petition presented substantial scientific or commercial information indicating that listing may be warranted for 30 species, including the southern hognose snake (80 FR 37568, July 1, 2015). A review of the status of the species was initiated to determine if the petitioned action is warranted. Based on the status review, the Service issued a 12-month finding, of not warranted for the southern hognose snake on October 7, 2019 (84 FR 53336). The Service is revisiting the 12-month finding decision and updating the Species Status Assessment (SSA) and will issue a new 12-month finding for the species. We conducted an SSA to compile the best available data regarding the species' biology and factors that influence the species' viability. The southern hognose snake SSA Report is a summary of the information assembled and reviewed by the Service and incorporates the best scientific and commercial data available. This SSA Report documents the results of the comprehensive status review for the southern hognose snake and serves as the biological underpinning of the Service's forthcoming decision (12-month finding) on whether the species warrants protection under the ESA.

The SSA framework (Figure 1-1; USFWS, 2016, entire) is intended to be an in-depth review of the species' biology and threats, an evaluation of its biological status, and an assessment of the resources and conditions needed to maintain long-term viability. The intent is for the SSA Report to be easily updated as new information becomes available and to support all functions of the Ecological Services Program of the Service, from Candidate Assessment to Listing to Consultations to Recovery. As such, the SSA Report will be a living document that may be used to inform Endangered Species Act decision making, such as listing, recovery, Section 7, Section 10, and reclassification decisions (the latter four decision types are only relevant should the species warrant listing under the ESA). Therefore, we have developed this SSA Report to summarize the most relevant information regarding life history, biology, and factors influencing viability for the southern hognose snake. In addition, we describe the current condition and forecast the possible response of the species to various future factors and environmental conditions to formulate a complete risk profile for the southern hognose snake.

The objective of this SSA is to thoroughly describe the viability of the southern hognose snake based on the best scientific and commercial information available. Through this description, we determined what the species needs to support viable populations, its current condition in terms of

those needs, and its forecasted future condition under plausible future scenarios. In conducting this analysis, we took into consideration the likely changes that are happening in the environment – past, current, and future – to help us understand what factors drive the viability of the species.

For the purpose of this assessment, we define **viability** as a description of the ability of a species to sustain populations in the wild over time. Viability is not a specific state, but rather a continuous measure of the likelihood that the species will sustain populations over time (USFWS, 2016, p. 9). Using the SSA framework (Figure 1-1), we consider what the species needs to maintain viability by characterizing the status of the species in terms of its **resiliency**, **representation**, and **redundancy** (Shaffer & Stein, 2000, pp. 308–311; USFWS, 2016, entire).

Resiliency describes the ability of a population to withstand stochastic disturbance. Stochastic events are those arising from random factors such as weather, flooding, or fire. Resiliency is positively related to population size and growth rate and may be influenced by connectivity among populations. Generally speaking, populations need enough individuals within habitat patches of adequate area and quality to maintain survival and reproduction in spite of disturbance. Resiliency is measured using metrics that describe population condition and habitat; in the case of southern hognose snake, we used current persistence probabilities, habitat conditions and connectivity to assess population resiliency.

Figure 1-1. Species Status Assessment Framework.

Representation describes the ability of the species to adapt to changing environmental conditions over time. Representation can be measured through the genetic diversity within and among populations and the ecological diversity (called environmental variation or diversity) of populations across the species' range. Theoretically, the more representation the species has, the higher its potential of adapting to changes (natural or human caused) in its environment. The number and distribution of resilient populations across a spatially explicit unit based on ecoregions was used to assess representation for the southern hognose snake.

Redundancy describes the ability of a species to withstand catastrophic events. A catastrophic event is defined here as a rare, destructive event or episode that may have impacts on a population or multiple populations. Redundancy is about spreading risk among populations, and thus, is assessed by characterizing the number of resilient populations across a species' range. The more resilient populations the species has distributed over a larger area, the better the chances that the species can withstand catastrophic events. For the southern hognose snake, we

used the number and distribution of resilient populations within the representative units and across the range of the species to measure redundancy.

To evaluate the viability of the southern hognose snake, we estimated and predicted the current and future condition of the species in terms of resiliency, representation, and redundancy.

This SSA Report includes the following chapters:

1. Introduction;
2. Species Ecology and Individual Needs. The life history of the species and resource needs of individuals;
3. Factors Influencing Viability. A description of likely causal mechanisms, and their relative degree of impact, on the status of the species;
4. Population and Species Needs and Current Condition. A description of what the species needs across its range for viability, and estimates of the species' current resiliency, representation, and redundancy; and,
5. Future Conditions and Viability. Descriptions of plausible future scenarios and predictions of their influence on southern hognose snake resiliency, representation, and redundancy.

Cited literature can be found after the final chapter. Additional supplemental information and analysis were used to complete this SSA Report. Details for the current and future condition analysis is presented in Appendix A.

This SSA Report provides a thorough assessment of what is known of the biology and natural history and assesses demographic risks, stressors, and limiting factors in the context of determining the viability and risks of extinction for the southern hognose snake. Importantly, this SSA Report does not result in, nor predetermine, any decisions by the Service under the ESA. In the case of the southern hognose snake, the SSA Report does not determine whether the southern hognose snake warrants protections of the ESA, or whether it should be proposed for listing as a threatened or endangered species under the ESA. That decision will be made by the Service after reviewing this document, along with the supporting analysis, any other relevant scientific information, and all applicable laws, regulations, and policies. The results of the decision will be announced in the *Federal Register*. The contents of this SSA Report provide an objective, scientific review of the available information related to the biological status of the southern hognose snake.

CHAPTER 2 – SPECIES ECOLOGY AND INDIVIDUAL NEEDS

In this chapter, we provide biological information about the southern hognose snake, including its taxonomic history, morphological description, historical and current distribution and range, and known life history. We then outline the resource needs of individuals.

2.1 Taxonomy

Figure 2-1. Southern hognose snake. Photo by J. Beane, North Carolina Museum of Natural Sciences.

The southern hognose snake was first described in 1766 by Carl Linneaus as *Coluber simus* from a specimen received from Charleston, South Carolina but it has been suggested that Linnaeus may have had an eastern hognose (*Heterodon platirhinos*) in hand (Edgren, 1953, p. 64; Meylan, 1985, p. 375.1). The species was then reassigned to the genus *Heterodon* by Holbrook, (1842, p. 57), who went on to describe the species in great detail. There are currently five species recognized within the genus *Heterodon,* all of which are endemic to North America: eastern hognose snake, western hognose snake (*H. nasicus*), Mexican hognose snake *(H. kennerlyi*), dusty hognose snake (*H. gloydi*), and southern hognose snake (Integrated Taxonomic Information System, 2017, unpaginated). The current recommended standard name is southern hog-nosed snake (Crother et al., 2017, p. 67) but the Service has decided to use the more commonly used name, southern hognose snake. Other names include hissing adder, blow viper, puff adder, spreading adder, and hissing sand snake (Conant and Collins, 1998, p. 327; Gibbons and Dorcas, 2005, p. 92).

The currently accepted classification of southern hognose snake is:

Kingdom: Animalia
Phylum: Chordata
Class: Reptilia
Order: Squamata
Suborder: Serpentes
Family: Colubridae
SubFamily: Dipsadinae
Genus/Species: *Heterodon simus*

2.2 Species Description

The southern hognose snake is the smallest of the hognose snakes, with adult specimens typically ranging from 33 to 51 centimeters (cm) (12.9-21.8 inches [in.]) with a maximum total length of 74.3 cm (29.25 in.) (Ashton and Ashton, 1981, p. 85; Conant and Collins, 1998, p. 328; Ernst and Ernst, 2003, p. 151; Beane and Thorp, 2007, p. 193). Adult females are significantly longer than adult males, and males have significantly longer tails than females (Palmer and Braswell, 1995, p. 151; Beane et al., 2014, p. 171). Males have 112–122 ventral scales (mean = 115) and tails with up to 44 subcaudal scales; females have 123–134 (mean = 127) ventral scales and 35 or fewer subcaudal scales (Ernst and Ernst, 2003, p. 151). In captivity, the current longevity record for the species is 12 years and 42 days (Beane and Thorp, 2007, p. 193).

Figure 2-2. Adult southern hognose snake (*Heterodon simus*). Photo by P. Hill, Florida Fish and Wildlife Commission.

The species' head is short with a sharply upturned keeled snout (Holbrook, 1842, p. 57; Conant and Collins, 1998, p. 328). The body scales are keeled and anal plate divided (Conant and Collins, 1998, p. 328). The head is dusky brown above the snout, with a dark transverse bar that often occurs on the snout in front of the eyes (Figure 2-2; Holbrook, 1842, p. 58; Ernst & Barbour, 1989, p. 39; Ernst & Ernst, 2003, p. 151). There is a dark brown or black stripe on either side of the neck and a short dark stripe may occur from the rear of the eye to the corner of the mouth (Ernst and Barbour, 1989, p. 39). The dorsum of the body is beige or tan with three longitudinal rows of dark brown blotches outlined anteriorly and posteriorly with black and a light orange to tan stripe along the center of the back (Ernst and Barbour, 1989, p. 39; Tuberville and Jensen, 2008, p. 356). The ventral side varies in color from white, cream, yellowish, or pinkish brown and has faint brownish pigment, usually near the tail (Ernst and Ernst, 2003, p. 151). The underside of the tail is the same color as the belly.

Hognose snakes are known for their defensive displays of hissing, flattening their necks, and death feigning. Like other hognose snake species, the southern hognose snake also will hiss and flare its neck when threatened and occasionally roll over and feign death, but it tends to be less theatrical (Figure 2-3; Tuberville & Jensen, 2008, p. 357).

Figure 2-3. Southern hognose snake displaying defensive behavior, flattening neck (left) and death feigning (right). Photos by P. Hill and K. Enge, Florida Fish and Wildlife Conservation Commission.

All snakes in the genus *Heterodon*, meaning different tooth, possess a pair of enlarged, ungrooved, posterior teeth, termed rear fangs. Venom, produced in the Duvernoy's glands, exits through ducts connecting to the fang sheath (Averill-Murray, 2006, p. 99). Though species within this genus are not considered dangerous, there are a few cases of human reactions to the venom, usually from a sustained bite (Weinstein and Keyler, 2009, p. 358). Specifically, the toxicity of the southern hognose snake has not been tested, and may only be toxic to anurans and lizards (Ernst and Ernst, 2003, p. 153).

2.3 Range and Distribution

The southern hognose snake is endemic to the Coastal Plain of the southeastern United States. States with known occurrence records include North Carolina, South Carolina, Georgia, Florida, Alabama, and Mississippi (Figure 2-4). The species was historically distributed through the southeastern United States from the vicinities of Morehead City and Raleigh, North Carolina, south to Tampa, Florida; west to the Pearl River separating Louisiana and Mississippi; and north to Calhoun County, Alabama (Meylan, 1985, p. 375). Historic records are known from two disjoined areas from the rest of the range, with multiple records in Autauga, Shelby, and Calhoun Counties, Alabama up to 1968, and a single historic record from Butts County, Georgia in 1952. Southeastern Louisiana was once included in the historical range for the species, but those records are considered erroneous (Meylan, 1985, p. 375; Tuberville et al., 2000, p. 23). There is also a museum record from Miami-Dade that we did not include because it is far outside of its accepted range; in some cases old museum records list the city from which specimens were shipped by the collector, not the site where specimens were actually collected (Enge et al., 2016, p. 20).
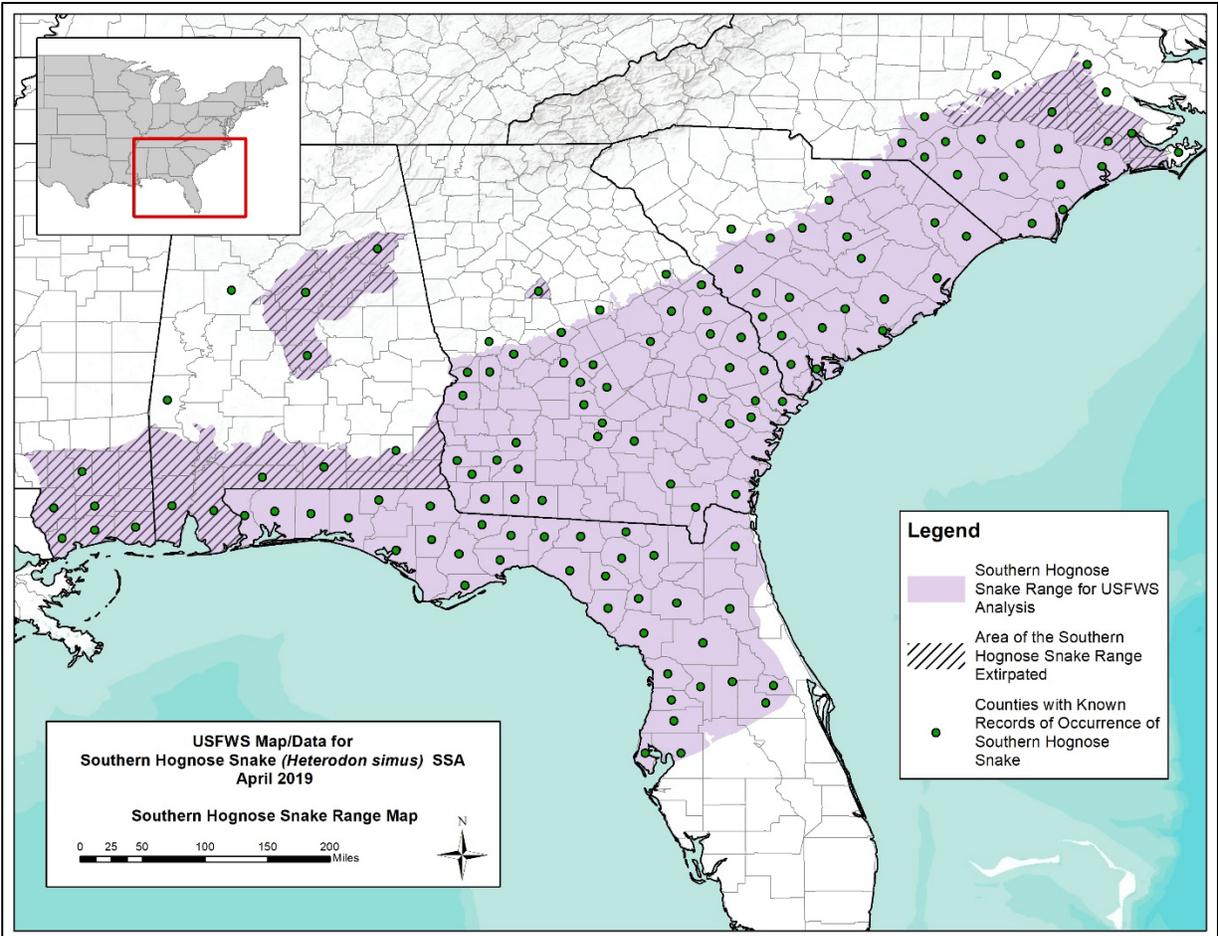
Figure 2-4. Southern hognose snake range map. The shaded range represents an estimate of the range based on locality information and known habitat needs for the species; areas presumed extirpated are in black hatching. County records indicated by dots in the center of the county, which in some cases means the center point may fall outside the shaded range.

2.4 Individual Ecology

2.4.1 Life History

Life history of a species includes events in a species' life and characteristics that affect the likelihood that an individual will survive and contribute to the population from one year to the next. We consider the southern hognose snake to have three life stages: egg, hatchling/juvenile, and adult.

The annual cycle of the southern hognose snake is characterized by seasonal peaks of activity (Tuberville et al., 2000, p. 21). Records for the species occur across all months, but there are generally two peak periods of detection (when this species is above ground): breeding season (May-June) and hatchling season (October-November) (Figure 2-5 and Figure 2-6). In Florida, 33.3% of records came from May–June during the breeding season, and 34.5% came from

October–November (Enge et al., 2016, p. 6). During a survey in Hernando County, Florida, most snakes were found in June and October–November, with 96% of snakes in October–December being hatchlings (Enge and Wood, 2003, p. 192, 2002, p. 369). Peak activity was May–June and October in South Carolina (Gibbons & Semlitsch, 1987, p. 400) and September–October in North Carolina (Beane et al., 2014, p. 173). The southern hognose snake is diurnal, with peak activity occurring in the late morning to early afternoon (Beane et al., 2014, p. 173).
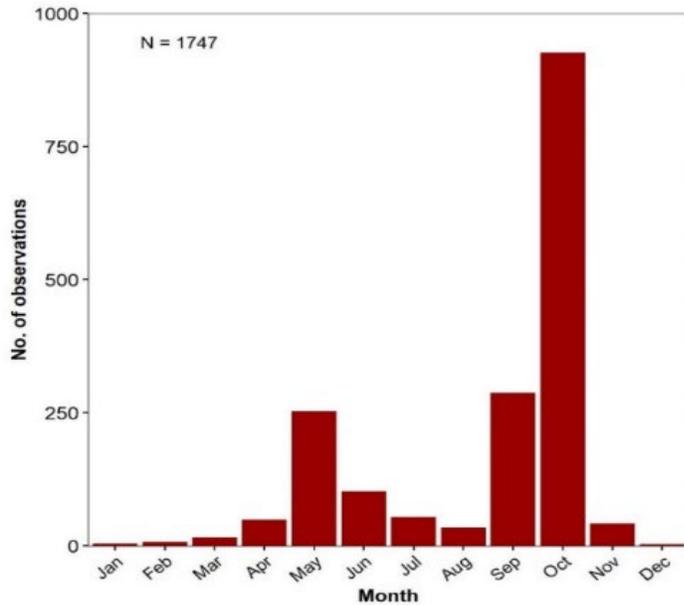
Figure 2-5. Number of southern hognose snake observations by month. There are two peaks of seasonal activity with relatively more observation records, a small one in May-June and a much larger one in September-October.

Figure 2-6. Diagram of the natural history of the southern hognose snake in Florida. Some of the information in this diagram may be based on observations of captive animals and may not fully represent what is occurring in the field (e.g., adults going dormant from August until very late September). (Source: Bartolotti, 2018, unpaginated).

2.4.2 Reproduction and Sex Ratios

Figure 2-7. Copulating pair of southern hognose snakes. Photo by J. Beane, North Carolina Museum of Natural Sciences.

During the first seasonal peak of activity (spring), southern hognose snakes emerge from underground refugia for breeding (Figure 2-7). It has been speculated that sexual maturity occurs when adults reach 36 cm (14.2 in.) in total length, but others defined an adult as greater than 25 cm (8 in.) snout-vent length (Beane et al., 2014, p. 171). Breeding occurs from mid-April through August (Ernst and Ernst, 2003, p. 152), although in North Carolina, the species has been observed breeding in the fall, with observations in late September and early November (Beane, 2019, pers. comm.). The southern hognose snake is oviparous, and in captivity eggs are usually laid in July and hatch in approximately 60 days (September–October), although oviposition in October has occurred (Price and Carr, 1943, p. 193; Palmer and Braswell, 1995, p. 179; Ernst and Ernst, 2003, p. 152). In captivity, clutch size has been reported as 6−19 eggs with an average of 9.6 (Palmer & Braswell, 1995, p. 179; Ernst & Ernst, 2003, pp. 152–153; Enge, 2004, p. 76). Eggs are oval and pale white in color and do not adhere to each other (Rossi and Rossi, 1991, p. 265). Hatchlings resemble adults, but their body color and patterning is more pronounced. Hatchling snout-vent length ranges from 13.9 to 14.7 cm (5.5 to 5.8 in.) and total body length from 13.4 to 18.0 cm (5.3 to 7.1 in.) (Jensen, 1996, p. 25; Ernst and Ernst, 2003, p. 153).

There is no information available on natural nests, as one has never been found. For the eastern hognose snake, nests were reported at 15 cm (5.9 in.) below the surface in a gravel deposit, under a rock, and at depths of 10 to 15 cm (3.9 to 5.9 in.) in sandy fields (Edgren, 1955, pp. 105–108). There are also little data on hatching success or hatchling survival, although data on the eastern hognose snake suggested high hatching rates (Edgren, 1955, p. 108).

The sex ratio has been reported biased toward males and becomes increasingly biased toward males within the largest size class – a pattern that suggests differential survivorship between the sexes or a sampling bias (Beane et al., 2014, p. 173). Studies of two populations of eastern hognose snakes have also shown a male-biased sex ratio (Platt, 1969, p. 389; Scott, 1986, p. 54), whereas adults of the western hognose snake exhibit even sex ratios (Platt, 1969, p. 388).

Hatchlings and juveniles potentially make up a large proportion of a population of southern hognose snakes, similar to eastern hognose snakes studied in Kansas, and in contrast to the adult-dominated population structure exhibited by western hognose snakes in Kansas (Beane et al., 2014, p. 173; Platt, 1969, p. 390). Due to detections being largely along roads during the fall when young have just hatched and are dispersing, care should be taken when interpreting these skewed age ratios as this could be an artifact of sampling bias and further research may be needed.

2.4.3 Foraging Ecology

Frogs and toads (anurans) have been reported to make up the largest portion of the southern hognose snake's diet, but they are also known to eat small lizards and in some cases invertebrates (Figure 2-8; Ashton and Ashton, 1981, p. 85; Beane et al., 1998, p. 45; Ernst and Ernst, 2003, p. 153; Beane et al., 2011, p. 292, 2014, p. 171). However, a more recent study suggests lizards and anurans may contribute equally to the diet, or a possible diet shift with age or size may happen, due to the fact that

Figure 2-8. Southern hognose snake eating an eastern spadefoot toad, Madison County, Florida. Photo by K. Enge, Florida Fish and Wildlife Conservation Commission.

lizards have only been found in the stomachs of smaller, juvenile individuals (Beane et al., 2014, p. 173). There have been accounts of southern hognose snakes eating newborn mice in captivity, but they are usually rubbed with an anuran scent to entice the eating of the mouse (Rossi & Rossi, 1991, p. 266; Palmer & Braswell, 1995, p. 329; Enge, 2004, p. 76).

The specialized upturned snout of the southern hognose snake is used to dig out buried prey (Goin, 1947, p. 275; Conant and Collins, 1998, p. 328; Ernst and Ernst, 2003, p. 153). Previous gut content analyses showed the presence of mostly eastern spadefoot toad (*Scaphiopus holbrookii*) and six-lined racerunner (*Aspidoscelis sexlineata*). It has been speculated that the southern hognose snake forages in the early morning, before prey, such as the six-lined racerunner, emerges from its nocturnal burrows or during other periods when this lizard is likely to be inactive, such as late evenings or on cool days (Beane et al., 2014, p. 173).

It has been hypothesized that the southern hognose snake's enlarged posterior maxillary teeth at the rear of its mouth are used to puncture inflated toads and spadefoots (Ashton and Ashton, 1981, p. 85), but the snake is more likely injecting mildly toxic venom into its prey. In a study of

the effects of eastern hognose snake's venom on mice and various anurans, it was noted there were no effects to the mice whereas most of the anurans died (McAlister, 1963, p. 134).

2.4.4 Hibernacula

Little is known about hibernacula use of the southern hognose snake range-wide, but in North Carolina, snakes excavate their own hibernacula and burrow more or less vertically into sandy soil in inconspicuous spots (Beane et al., 2007, p. 467). Southern hognose snakes were observed excavating and entering hibernacula, in North Carolina from late October to late November, and emerging from late March to mid-April (Beane et al., 2007, p. 467). Individual snakes do not depend on stump holes or other existing subterranean chambers for hibernacula and did not display hibernaculum site fidelity, though the sample size was small (n=4) (Beane et al., 2007, p. 467; Beane, 2019, pers. comm.).

2.4.5 Individual Species Needs (Habitat)

Southern hognose snakes are commonly associated with the longleaf pine ecosystem. They occupy xeric, upland habitat with well-drained, sandy soils, characterized by pine-dominated or pine-oak woodland. They favor habitat where the canopy is open with a grassy understory (Enge et al., 2016, p. 12).

The southern hognose snake can be found in multiple physiographic regions across its range. In North Carolina, they have been found in mixed oak-pine forests occurring on well-drained, sandy soils (Palmer and Braswell, 1995, p. 176; Tuberville et al., 2000, p. 21). Typical habitat in North Carolina has been reported as longleaf pine-wiregrass (*Aristrida stricta*)-turkey oak (*Quercus laevis*) forests (Beane et al., 2014, p. 169). Habitat associations for a subset of southern hognose snakes were recorded between 1985-2012; of those records, 51% were found crossing roads between open longleaf pine-wiregrass-turkey oak forests; 12% were found crossing between longleaf pine-wiregrass-turkey oak forests and disturbed forests, old fields, or agricultural areas; and 37% were found crossing roads between various disturbed forests and ruderal habitats (old fields, agricultural plots, clear cuts, and rural yards), or between ruderal habitats (Beane et al., 2014, p. 173).

In Florida, sandhills seem to be the core natural habitat, but snakes have also been found crossing roads near ruderal habitats, such as clearcuts, residential lawns, improved pastures, and old fields (Enge, 1997, pp. 28–49; Enge and Wood, 2003, p. 198; Enge et al., 2016, p. 12). Disturbed habitats are frequently used, but xeric hammock and scrub are seldom used (Enge, 1997, pp. 28–49; Enge et al., 2016, p. 12). In a study conducted from 1998-2001 in Hernando County, Florida, half of the southern hognose snakes observed crossing roads were found near longleaf pine-wiregrass (*A.beyrichiana*)-turkey oak forests and 48.7% of snakes were found near old fields, agricultural areas, or disturbed forest types (Enge and Wood, 2003, p. 189, 2002, p. 371). Near Eglin Air Force Base along the Florida Panhandle, road-killed hatchlings were observed adjacent

to longleaf pine-turkey oak sandhill, invaded by off-site sand pine (Jensen, 1996, p. 25; Tuberville et al., 2000, p. 21).

Little is known about any specific habitat requirements that may be needed for nesting and hibernation. The southern hognose snake is strictly diurnal and notably highly fossorial and thus may make little use of aboveground cover (Carr, 1940, p. 80; Palmer and Braswell, 1995, p. 178). The most rigorous report of the use of burrows discussed finding animals under 20 to 30 cm (7.9 to 11.8 in.) of sand, in open areas (Palmer and Braswell, 1995, p. 178), with burrows than can be very obvious (Beane, 2019, pers. comm.). More recently, southern hognose snakes have been reported using southeastern pocket gopher (*Geomys pinetis*) mounds and gopher tortoise (*Gopherus polyphemus*) burrows (Stevenson et al., 2018, p. 547). It is suspected that they occasionally use the southeastern pocket gopher mounds for sub-surface thermoregulation, particularly on cool, sunny days and may be using the gopher tortoise burrows for both refugia and for foraging for anurans (Stevenson et al., 2018, p. 548).

We used existing life history literature and expert judgment to identify specific ecological needs for individuals to survive and reproduce (Figure 2-9; as well as factors influencing viability that are discussed in Chapter 3). Three main habitat elements, however, appear to be essential to the survival and reproductive success of individuals: well-drained soils, suitable vegetation structure and composition, and presence of prey.
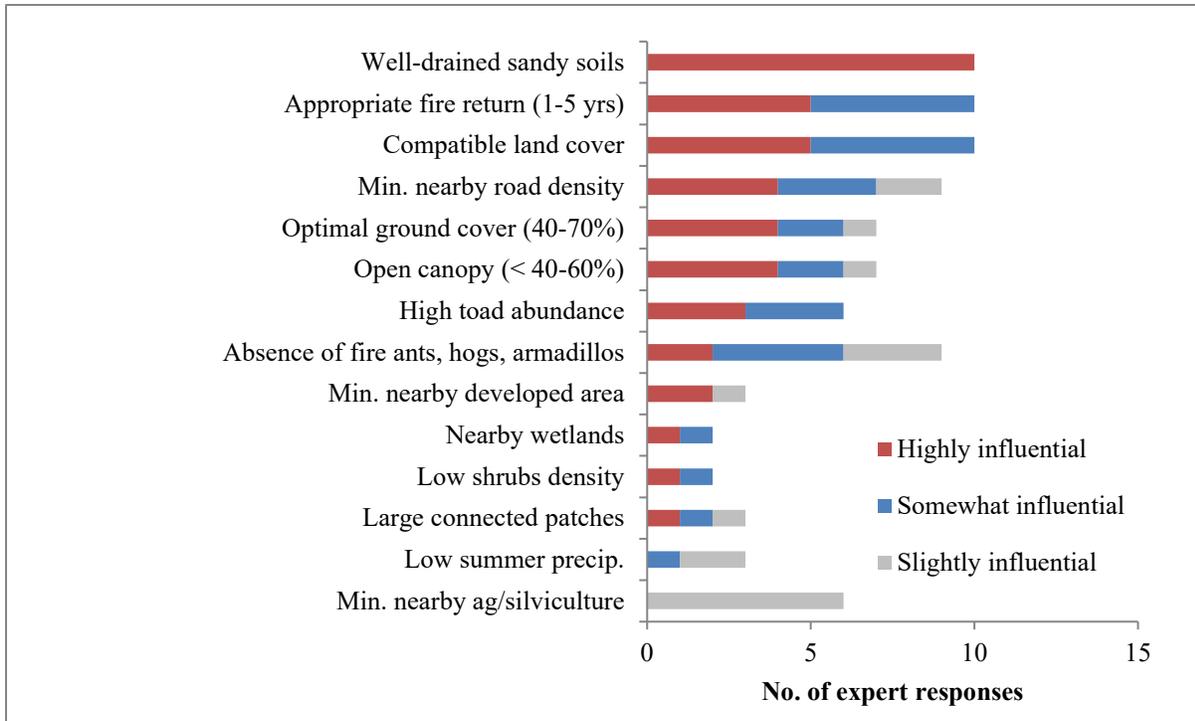
Figure 2-9. Influential habitat, landscape, and biophysical attributes for southern hognose snake presence at a site, as identified by 12 species experts. Some attributes reflect species needs while others reflect factors influencing viability (discussed in Chapter 3). Experts were asked to list attributes they associate with ideal habitat for the species. Definitions for habitat rankings: Highly – attributes must occur at a site for the species to be present; Somewhat – attributes occurring on the landscape greatly increase the likelihood of species being present, but species may occasionally use landscapes without these attributes; Slightly – attributes occurring on the landscape slightly or variably increase the likelihood of species being present, but species may use landscapes without these attributes.

CHAPTER 3 – FACTORS INFLUENCING VIABILITY

The following discussion provides a summary of the factors that are affecting or could be affecting the current and future condition of the southern hognose snake throughout some or all its range. Risks that are not known or not suspected to have effects on southern hognose snake populations, such as environmental pollution are not discussed in this SSA.

3.1 Habitat Loss, Conversion, and Fragmentation

Loss of Longleaf Pine Ecosystem

The southern hognose snake is associated with longleaf pine savanna, particularly xeric uplands that were historically maintained by fire. The longleaf pine ecosystem is a fire-dependent ecosystem that once dominated the Coastal Plain of the Atlantic and Gulf coast regions, from Virginia to Texas (Ware et al., 1993, p. 447). The longleaf pine uplands once covered an estimated 92 million acres (Frost, 1993, p. 20). By the 21st century, the longleaf pine community had declined to less than three million acres due to forest clearing and conversion for agriculture, silviculture (tree farming), and development (Landers et al., 1995, p. 39; Jensen et al., 2008, p. 16). Little old-growth longleaf remains, and of the uplands that remain, only about 3% are in relatively natural condition due to the exclusion/suppression of naturally-occurring wildfires (Frost, 1993, p. 17; Simberloff, 1993, p. 3).

Original longleaf pine communities were old-growth, open-canopied, and contained a structure of two layers: canopy and diverse herbaceous groundcover. Frequently burned, the natural condition was a canopy cover that rarely exceeded 60 percent and permitted a grassy groundcover to flourish (Noss, 2013, p. 9). In contrast, much of today's forest is young, dense, and dominated by slash pine (*Pinus elliottii*) or loblolly pine (*Pinus taeda*), with a substantial hardwood component and little or no herbaceous groundcover (Noel et al., 1998, pp. 534–535).

The longleaf ecosystem was first heavily altered by exploitation for naval stores and then virtually eliminated by widespread logging (Frost, 1993, pp. 24–37). Naval stores industries harvested pine resin for the production of tar, pitch, and turpentine—commodities in high demand during colonial times. Pine woodlands were logged for lumber and converted to agricultural fields. Impacts to easily accessible areas began with the arrival of Europeans, but technological developments of the 1800s, such as the copper still, steam power, and especially railroads, dramatically increased the rate and area of loss (Frost, 1993, pp. 23–24). In the late 1800s, logging operations moved to the previously inaccessible interior forests of longleaf, shortleaf (*Pinus echinata*), and loblolly pines. This especially intense period of logging from 1870 to 1930 resulted in the loss of nearly all of the remaining old-growth forest in the Southeast.

Historically, natural disturbances created and maintained open pine conditions throughout the southeast and fire was the predominant disturbance in the longleaf ecosystem. Although there is still uncertainty in burn regimes between various habitat types and along environmental gradients, fire frequencies in longleaf pine savanna have been estimated at one to three years (Frost, 1998, p. 76). Frequent burning has been shown to maintain species richness of the ground cover layer (Glitzenstein et al., 2003, p. 23). Season of fire is also widely presumed to have important effects on vegetation composition. Growing season burns, generally defined as the period of time when most plants are actively growing, coincides with the bulk of wildfires caused by lightning strikes, and has been shown to better meet management objectives for longleaf pine forests (Knapp et al., 2009, p. 3).

Historically, lightning was the primary ignition source shaping the evolution of these fire-maintained ecosystems, but Native Americans may have played a role in maintaining them (Frost, 1993, p. 34; Van Lear et al., 2005, p. 151). After European settlement and prior to the mid-1800s, farmers burned the woodlands regularly to improve forage for free-ranging livestock, but by the mid to late 1800s fencing of livestock caused a decrease in burning (Frost, 1993, p. 34). Although many people continued to use fire in agricultural fields well into the 1900s, the rise of mechanical and chemical agriculture replaced fire-based agricultural methods.

Active fire exclusion/suppression began to be institutionalized in the southeastern United States between 1910 and 1930 (Frost, 1993, p. 35). Some foresters denounced fire as detrimental to southern pines rather than an integral or useful component of the natural system. Fire suppression increased with the rise of pine plantations, a land use that began in the 1930s and continues today (Frost, 1993, p. 36). Due to the suppression of lightning-ignited fire and the natural disturbance fires provide, longleaf pine communities have converted to fire-intolerant trees and shrubs that eventually shade out the ground cover and render the forest unsuitable for much of the fire adapted biota (Jensen et al., 2008, pp. 16–17; Van Lear et al., 2005, p. 155). In addition to directly affecting reptiles, habitat loss can indirectly affect them by limiting their ability to meet ecological needs for survival and reproduction (Todd et al., 2010, p. 50). This habitat conversion has likely negatively impacted southern hognose snake populations (Enge et al., 2016, p. 21). Planting of densely stocked sand pines and succession of sandhill habitat to xeric hammock in the absence of fire are probably responsible for the apparent southern hognose snake population declines in the central Florida Panhandle (Enge et al., 2016, p. 21).

In addition to fire suppression, longleaf pine communities continue to be altered for agriculture, short-rotation pine plantations, residential, and commercial purposes, most of which are incompatible with the habitat needs of southern hognose snakes. Like other reptiles and amphibians associated with the longleaf pine ecosystem, the southern hognose snake has declined in parallel with the decline of the longleaf pine ecosystem (Beane et al., 2014, p. 168).

Although the southern hognose snake is more common in sandy, open longleaf pine forests and flatwoods, it can persist in fragmented and altered habitats. The effects of habitat conversion to agriculture on long-term viability of the species is unknown but believed to be contributing to declines (Enge and Wood, 2002, p. 365; Enge et al., 2016, p. 21). Many southern hognose snakes have been found on roads near disturbed habitats such as clearcuts, residential lawns, improved pastures, and old fields and agricultural areas (Enge and Wood, 2002, p. 371; Beane et al., 2014, p. 173), but we still do not know the extent to which southern hognose snakes are using disturbed areas. Agricultural areas where snakes are being detected have an open canopy; thus, they may be selecting these areas due to the presence of sandy soils and open canopy, whereas the surrounding areas may be fire-suppressed with a closed canopy and dominated by hardwood species. In addition, agricultural practices, such as plowing and other soil disturbing activities, may cause direct mortality to southern hognose snakes due to their fossorial nature and may alter the soil profile or characteristics, rendering soils less suitable for snakes. Southern hognose snakes are more commonly found in fire-maintained upland habitat than agriculture areas, and when found in agricultural areas those areas are typically adjacent to natural upland habitats. It is likely that natural upland habitats are optimal for individuals' survival and reproduction while agriculture and other low-impact areas of human use (e.g., pastures, pine plantations, rural and urban open areas) support survival and movement through these areas but may not support long-term viability of populations.

Timber harvesting is one of the more prominent forms of habitat alteration that shapes plant and animal communities, and the southeastern United States is the leading timber-producing region in the country (Prestemon and Abt, 2002, p. 299). Many open pine forests in the Southeast have been replaced by pine plantations or mixed pine hardwood stands, often harvested on short rotation intervals (15-30 year). Short-rotation planted pine forests differ from the natural ecosystem in a variety of ways, including higher stand densities, closed canopies, deep litter beds, and sparse understories, additionally, harvesting of the short-rotation planted pine is done primarily through clear cutting (Means, 2005, pp. 142–143; Todd and Andrews, 2008, p. 754). Timber stands with high stand density and a dense mid-story with little to no groundcover do not provide adequate habitat for the southern hognose snake, but it should be mentioned that thinning dense stands of forest, as opposed to clear cutting, can benefit species that occupy longleaf forests. Thinning of dense stands can help mimic the historic condition of longleaf stands, mainly through the opening of the under- and mid-story. In fact, many forests are so densely stocked that thinning is required before a prescribed burning regime can be established.

Many reptile species have been shown to decline in abundance over time following the clearing of primary forest or conversion to plantation forest (Glor et al., 2001, p. 719; Kanowski et al., 2006, pp. 13–14). At a finer scale, a study from the southeastern United States found lower abundances of small snakes in planted pine forests with recent clear-cuts compared with open-canopied, partially harvested forests (Todd and Andrews, 2008, p. 757). Direct mortality has

been attributed to timbering operations (Reinert et al., 2011, p. 23), and intensive forestry practices such as shearing, raking, disking, harrowing, roller-chopping, bedding, replanting, and the use of herbicides negatively affect snake populations (Enge and Marion, 1986, p. 187; Todd and Andrews, 2008, p. 760). Not only can mechanical site preparation techniques directly kill or injure fossorial herpetofauna; they also damage the subterranean and soil structures in which those species occur, making the habitat less suitable in the future (Bailey et al., 2006, p. 45).

Urban Development

Urbanization plays both direct and indirect roles in the decline of many species (McKinney, 2002, p. 883). Urbanization fragments and replaces natural habitats with artificial structures, impervious concrete and asphalt surfaces, manicured lawns, and gardens full of exotic plant species, and increases levels of air, water, noise, and light pollution, putting the survival of many wildlife species in jeopardy (Sutherland, 2009, p. 35). Snakes seem to be particularly sensitive to effects of urbanization, and this intolerance has played a key role in the general declines reported for reptile species around the world (Gibbons et al., 2000, entire; Andrews and Gibbons, 2005, entire; Row et al., 2007, entire; Sutherland, 2009, p. 52).

Urbanization impacts many wildlife species from direct loss of habitat, fragmentation of habitat, increased road mortality, increased human persecution, and the increase in domestic predators, such as cats (*Felis catus*) and/or dogs (*Canis lupus familiaris*). Also, a combination of urban sprawl and migration of humans to rural areas has created an extensive wildland-urban interface (WUI), the area where houses and wildland vegetation meet or intermingle. Wildland-urban interfaces limit the ability to conduct prescribed fires due to issues associated with smoke management and fear of fires escaping and having catastrophic effects. Active fire exclusion/suppression and a lack of a controlled burning program in WUIs results in increased fuel loads and a subsequent increase in the likelihood of future destructive fires (Winter et al., 2002, p. 15). Furthermore, because of constraints on implementing prescribed fire in WUIs, there is an increased risk of habitat degrading to the point that it is unsuitable for southern hognose snakes due to woody species encroachment.

In the southeastern United States, projections predict the urban footprint will greatly increase over the next 50 years, with median projections showing that the amount of land in urban areas will increase by 139% by 2060 (Terando et al., 2014, p. 4). Urbanization is not predicted to be uniform across the region. The largest urban expansions are projected in the Blue Ridge, Ridge and Valley, Southern Coastal Plain, and Piedmont ecoregions, and new urban centers are projected in the Appalachian Mountains and central Florida regions (Terando et al., 2014, p. 6).

Many "hotspots" of projected urban development are predicted to occur within, or near known occurrence records for southern hognose snakes, or predicted suitable habitat. Although we do not know the exact response of the southern hognose snake to various levels of urbanization, we

do know that urbanization will likely result in the loss, degradation, and fragmentation of habitat, increased amount of WUI, increased persecution by humans, increased road mortality, and increases in domestic predators. In the case of domestic predators, killing by domestic dogs has been noted (Enge et al., 2016, p. 22). Additionally, urbanization increases the number of mesopredators, such as raccoons (*Procyon lotor*), potentially impacting southern hognose snakes through direct predation or through indirect means by potentially affecting their prey base. Thus, we consider urbanization to be a significant threat to the southern hognose snake.

Fragmentation

Human-induced disturbances, particularly from land use changes discussed in the previous sections, not only have the potential to result in loss or degradation of habitat, but also fragmentation of habitat. Habitat fragmentation is the breaking apart of contiguous habitat into multiple patches (Fahrig, 2003, p. 509). Development increases the prevalence of roads and associated infrastructure, which increase the fragmentation of the habitat and additionally result in the potential for increased mortality from vehicular traffic. Fragmentation can have a variety of negative impacts on wildlife, including greater mortality rates associated with landscape modifications (e.g., roads), more frequent encounters with humans, reduced resources in smaller patches, reduced reproduction, restricted gene flow, and increases in predation and competition (Wiens, 1994, p. S97; Kjoss and Litvaitis, 2001, p. 285). Reduction of larger habitat patches into smaller patches can lead to population declines due to limited resource availability and can also negatively affect day-to-day movement (Barbour and Litvaitis, 1993, p. 326). Fragmentation may also negatively affect larger-scale movements such as dispersal and seasonal migration.

Many snake species are likely to be sensitive to habitat fragmentation because they occur at low densities, have limited dispersal abilities, have thermal constraints, and are subject to direct and indirect mortality caused by humans (Webb and Shine, 1997, p. 213; Kjoss and Litvaitis, 2001, p. 286). Of particular concern is the role that roadways play in fragmenting habitat. Depending on the size and traffic volume, newly-constructed roads can effectively become barriers that divide and isolate populations (Roe et al., 2006, p. 162). The increasing encroachment of roads into natural areas may isolate populations, prevent movement between nest sites and hibernacula, restrict gene flow, and limit access to mates (Vanek and Wasko, 2017, p. 115). Additionally, roads not only impinge on life history requirements of species but also facilitate other threats, such as conversion of more habitat, creation of roads for access, and the spread of invasive species (Forman and Alexander, 1998, pp. 221–222), and lead to increases in direct mortality, discussed in the next section.

How individuals move between patches and how they respond to different habitats will ultimately determine how populations are impacted by fragmentation; thus, few generalizations can be made about the effects of habitat fragmentation on individual species. One might expect relatively sedentary species, such as the southern hognose snake, with specialized habitat

requirements to be vulnerable to habitat fragmentation (Wiens, 1994, p. S101). Direct data is unavailable on the impact of habitat fragmentation on the southern hognose snake, but it has been hypothesized that habitat fragmentation is the cause for regional eastern hognose snake declines due to isolating sub-populations, restricting gene flow, limiting access to mates, and preventing movement (Vanek and Wasko, 2017, p. 115).

3.2 Road Mortality

As discussed above, roads create habitat fragmentation and pose a barrier to movement that can isolate populations and increase direct mortality for many snake species (Andrews and Gibbons, 2005, p. 772). Snakes are more severely affected by road mortality than other animal groups because they are thought to use roads for thermoregulation, are relatively slow-moving, some will remain immobile on roads in response to oncoming vehicles, and are often intentionally hit by drivers (Rosen and Lowe, 1994, p. 143; Bonnet et al., 1999, p. 40; Andrews and Gibbons, 2005, p. 778). It has been observed that reptiles are struck by vehicles at a greater rate than would be expected by chance, suggesting that drivers intentionally target reptiles on roads (Ashley et al., 2007, p. 137). It has been estimated that vehicular traffic has killed tens or hundreds of millions of snakes in the United States since the start of motorized transportation (Rosen and Lowe, 1994, p. 147).

An increase in the number of mortalities from vehicles may result in reduced gene flow among populations, decreased potential for dispersal into fragmented habitats, and alter demographics in the form of lower survival and immigration rates – all of which can lead to declines or extirpation of populations of snakes. One study of black ratsnakes (*Pantherophis obsoletus*) found that, when including an estimate of road mortality to a population viability analysis, the extinction probability increased from 7.3% to 99% over 500 years (Row et al., 2007, p. 117). An increased mortality rate for different reproductive classes can have profound consequences for a population; for example, increased mortality of females can reduce a population's growth rate more than mortality of males (Row et al., 2007, p. 118).

A snakes' vulnerability to vehicle encounters is highest when they travel outside of their normal home range, with the highest mortality occurring in adult males during the mating season, neonates or hatchlings immediately after birth or hatching, and adult females on egg laying migrations (Bonnet et al., 1999, p. 47). Roads that bisect high quality habitat have higher levels of mortality than those that bisect lower quality habitat (Shepard et al., 2008, p. 357). Snake populations could experience especially high levels of road mortality during periods where high traffic volumes and species' seasonal movements coincide (Ashley et al., 2007, p. 141).

Due to the secretive nature of the southern hognose snake and the difficulty in surveying for them, many records of this species are from encounters on roads; additionally, many of those records are documented as Dead on Road (DOR; Figure 3-1). In North Carolina, during road

surveys conducted between 1985–2012, 764 southern hognose snakes were detected; of those detections, 643 (84%) were observed DOR, 110 (14.4%) were observed Alive on Road (AOR), and 11 (1.4%) were encountered incidentally, not on a road (Beane et al., 2014, p. 170). Observations in Florida between 1998-2001 detected 39 southern hognose snakes, all of which were DOR, and 62% of those observations were juveniles (Enge and Wood, 2003, p. 192, 2002, p. 369). The majority of southern hognose snakes encountered on North Carolina roads tend to be juveniles (Beane et al., 2014, pp. 170–171).

Figure 3-1. Southern hognose snake crossing dirt road in North Carolina (upper left) and a DOR southern hognose snake on paved road in North Carolina (lower right). Photos by J. Beane, North Carolina Museum of Natural Sciences.

Their cryptic coloration; small size; and aspects of their behavior such as slow movement, remaining motionless, and death feigning, lend this species to be particularly susceptible to road mortality compared to other snake species. Behavioral observations for a subset of southern hognose snakes found AOR in North Carolina support this idea. Many individuals encountered on roads would ''freeze'' and remain motionless when approached, whereas others would continue crawling very slowly, often in a characteristic hesitant, jerky fashion, and only a few individuals, mostly juveniles, would attempt to crawl away rather rapidly (Beane et al., 2014, p.

173). It was also estimated that it takes the southern hognose snake 7.69 minutes to cross the typical two-lane road (Willson et al., 2018, p. 451). We do not know the full impact that road mortality may play on this species, but the high number of observed DOR provides evidence that road mortality is occurring at a rate that is likely having population level effects and contributing to population declines in parts of the species' range.

3.3 Invasive Species

3.3.1 Red Imported Fire Ants

Negative impacts on wildlife associated with documented introductions of non-native species are increasing, but the long-term consequences of many introductions are still poorly known (Langkilde, 2009, p. 208). The red imported fire ant (RIFA; *Solenopsis invicta*), originating from South America, was first introduced as early as 1918 to the United States at the port of Mobile, Alabama, and subsequently spread from there (Wilson, 1951, p. 68). The current range of the red imported fire ant across the United States is shown in Figure 3-2 (U.S. Department of Agriculture, 2017, p. unpaginated).

Red imported fire ants can multiply rapidly, and infiltrate disturbed and early-successional habitats (Todd et al., 2008, p. 540). Reptiles are particularly susceptible to red imported fire ants. Many species of reptiles are oviparous (egg-laying), and it has been shown that their eggs can be depredated by red imported fire ants, both pre- and post-hatching (Swartwout and Willson, 2022, p. 139). In addition, many reptile species inhabit disturbed areas, which red import fire ants prefer, and excavate nests, creating disturbance and providing scent that attracts red imported fire ants (Darracq et al., 2017, p. 2). Species that nest under or on the ground, such as the southern

Figure 3-2. Current range and predicted range expansion of the red imported fire ant (RIFA; *Solenopsis invicta*) across the contiguous United States. Survival of RIFA is certain in the red area, possible in the green, undetermined in the dark blue, and improbable in the light blue area. Source: United States Department of Agriculture, 2017, unpaginated.

hognose snake, and in or near open habitat may be more negatively affected by red imported fire ants (Todd et al., 2008, p. 544). Red imported fire ants are aggressive and their stings can result in direct mortality, as well as reduced survival by preventing weight gain, altering behavior,

changing foraging patterns, reductions in food availability, and altered habitat (Wilcox and Giuliano, 2014, pp. 3–4).

Red imported fire ants have been linked to population declines of several native species, including the Houston toad, (*Bufo houstonensis*; Brown et al., 2012, entire), bobwhite quail (*Colinus virginianus*; Allen et al., 2000, entire), Texas horned lizard (*Phrynosoma cornutum*; Price, 1990, p. 469.4), and have been proposed as contributing to the decline of the southern hognose snake (Tuberville et al., 2000, pp. 33–34).

The apparent declines and extirpations of the southern hognose snake are concurrent with the range expansion of red imported fire ants in the Southeast. Portions of the snake's range within the Coastal Plains of Mississippi, Alabama, and the Florida Panhandle had become infested with red imported fire ants by 1958 and would be the first to experience the full impact of red imported fire ant predation (Callcott and Collins, 1996, p. 245; Mount, 1981, p. 75). The last detections for southern hognose snakes were 1975 in Alabama and 1981 in Mississippi. There is some speculation that a time lag occurs from when an area becomes heavily infested with red imported fire ants and the impacts become obvious (Mount, 1981, p. 77). It should be noted that red imported fire ants have difficulty establishing colonies in excessively sandy soils; in such habitat, the impact would be less severe than in those capable of supporting dense populations of red imported fire ants (Mount, 1981, p. 75). This may help explain why southern hognose snakes were extirpated from Mississippi and Alabama. Besides always being rare in that portion of their range, the soils are generally wetter west of the Mobile basin and are not as deep as the sandy soils in other portions of the range. Wetter soils are more readily colonized by red imported fire ants (LeBrun et al., 2012, p. 888). Thus, in that portion of the range red imported fire ants were possibly one of the main factors leading to their extirpation. This also might help explain why southern hognose snakes continue to occupy areas like the Florida Ridge that have the deep sandy soils.

The southern hognose snake may be particularly susceptible to red imported fire ants because of its small size, slow speed, use of open, disturbed habitats, and the fact that it is a burrowing species. Southern hognose snakes also rely heavily on crypsis and immobility as an antipredatory defense, which in the case of red imported fire ants does not work to fend off the attack (Beane et al., 2014, p. 174). There are examples of other reptiles exhibiting immobility when exposed to fire ants, as was the case in fence lizards (*Sceloporus undulatus*) where those lizards that had longer history with red imported fire ants were more likely to exhibit defensive behavior and quickly flee from them (Langkilde, 2009, p. 213). It is possible that the slow, cryptic behavior of the southern hognose snake has become maladaptive in the presence of red imported fire ants, creating an evolutionary trap that has contributed to its decline (Beane et al., 2014, p. 174).

3.3.2 Feral Hogs

Feral hogs (*Sus scrofa*) negatively affect almost all aspects of ecosystem structure and function (Jolley et al., 2010, p. 519) and are known to have significant impacts to native animal and plant communities through direct consumption and indirectly through rooting and soil disturbance (Barrios-Garcia and Ballari, 2012, pp. 2284–2293). Reptile species are particularly susceptible to impacts from feral hogs (Taylor and Hellgren, 1997, p. 38). In addition to causing direct mortality to reptiles and amphibians, feral hogs also have indirect effects on populations through rooting and habitat alteration (Jolley et al., 2010, p. 520). Their rooting disturbs soil layers and natural decomposition cycles, which can lead to changes in nutrient cycling (Bratton, 1975, pp. 1358–1359).
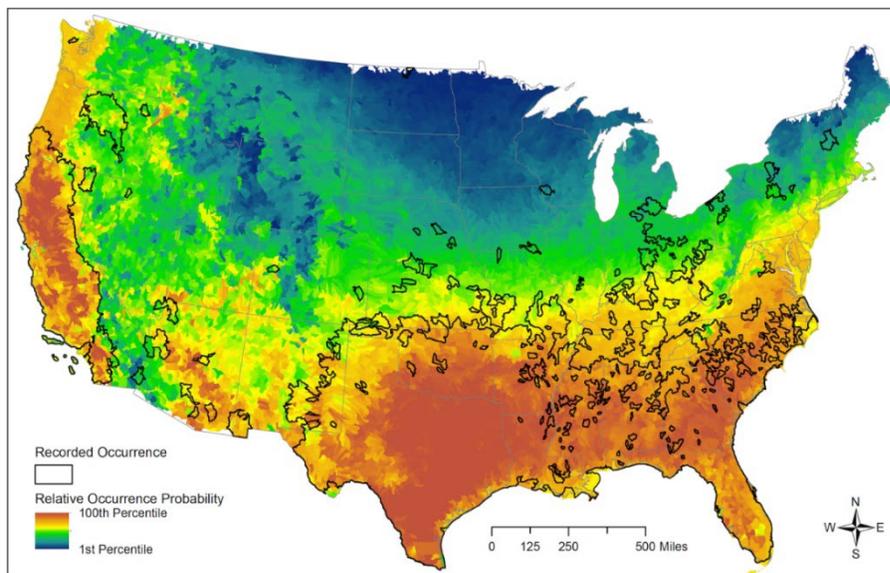
Figure 3-3. Current and predicted range expansion of feral hogs across the contiguous United States. Current range (recorded occurrence) of feral hogs from 1982 to 2012 is outlined in black. Predicted feral hog occurrence is displayed in color based on probability. Source: McClure, et al., 2015, p. 11.

A study at Fort Moore (formerly Fort Benning), Georgia found that an entire population of feral hogs (i.e., estimated to be 3,196 individuals) could consume 3.16 million reptiles and amphibians per year (Jolley et al., 2010, p. 521). For southern hognose snakes, feral hogs could be a predator, particularly while foraging around wetland edges where snakes are searching for anuran prey (Enge et al., 2016, p. 22). Feral hogs could also be impacting frogs and toads, a critical prey base of the southern hognose snake. For example, the eastern spadefoot toad remains underground for most of the year, but emerges on warm, rainy nights to breed during the spring and summer months in the southeastern United States (Hansen, 1958, p. 57). During these periods of breeding, eastern spadefoot toads are found at extremely high densities, and it is possible that feral hogs respond to this concentrated food source and focus their hunting on these spadefoot toads (Jolley et al., 2010, p. 522). There are concerns that this selective foraging by feral hogs could threaten not only spadefoot toad populations but also other species that have a similar life history (Jolley et al., 2010, p. 522) and impact other species further up the food chain, such as southern hognose snakes. The range and abundance of feral hogs in the contiguous

United States is shown in Figure 3-3 (McClure et al., 2015, pp. 11, 17); there is substantial overlap between feral hog occurrence and the range of the southern hognose snake.

3.3.3 Cogongrass
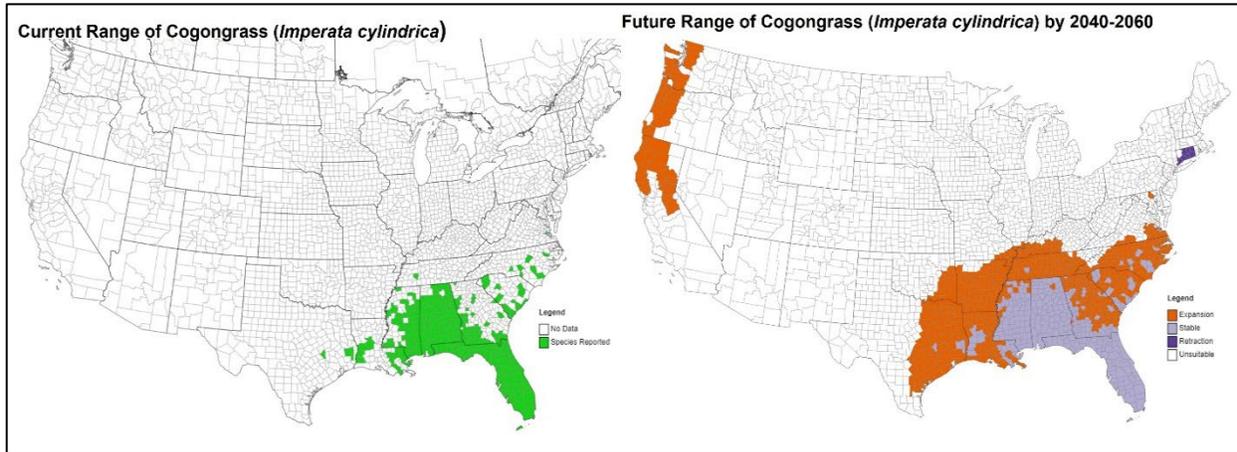
Figure 3-4. Current and future range of cogongrass (*Imperata cylindrica*) within the United States. Current range is in green in the left map and future range is on the right map with purple indicating stable and orange showing expansion. Source: (EDDMapS, 2021, unpaginated)

Cogongrass (*Imperata cylindrica*) was introduced into the U.S. as a forage crop and soil stabilizer in the early part of the 20th Century, is well adapted to frequent burning and full sunlight, and now considered one of the worst invasive weeds in the world (Holzmueller and Jose, 2011, p. 436). Cogongrass is known to impact longleaf pine ecosystems in the southeast, already occurs throughout much of the southern hognose snake's range and is predicted to continue to expand (Figure 3-4). Cogongrass can rapidly spread in disturbed areas and those undergoing habitat management and restoration. Unlike other undesirable species in xeric upland communities, cogongrass is well adapted to fire, and may rapidly spread following a disturbance in an ecosystem, such as a prescribed fire (Holzmueller and Jose, 2011, pp. 436–437). Once established it is very difficult to eradicate and requires aggressive control with herbicides (Yager et al., 2010, pp. 229–230). Cogongrass displaces native grasses and forms thick dense stands that decrease native species biodiversity (Holzmueller and Jose, 2011, p. 436).

When cogongrass invades an area, it can quickly result in habitat loss for many of the longleaf pine ecosystem associated species, such as gopher tortoises, which will not use invaded areas or consume cogongrass (Basiotis, 2007, p. 21). Because it is fire adapted, cogongrass has additional impacts on the use of prescribed fire by altering fire regimes via increased fuel loads. This effect of cogongrass on fire behavior has the potential to increase direct southern hognose snake mortality, reduce plant diversity and forage for keystone species and some ecosystem engineers (e.g., gopher tortoise), and facilitate other invasive plant species (Basiotis, 2007, p. 24; Lippincott, 1997, pp. 48–65). While the effects of cogongrass on southern hognose snakes or

other snake communities have not been assessed, cogongrass is currently the most likely invasive plant that could negatively affect southern hognose snake habitat suitability and populations.

3.4 Climate Change

In the southeastern United States, climate change is expected to result in more frequent drought, more extreme heat (resulting in increases in air and water temperatures), increased heavy precipitation events (e.g., flooding), more intense storms (e.g., frequency of major hurricanes increases), and rising sea level and accompanying storm surge (Intergovernmental Panel Climate Change (IPCC), 2013, entire). Warming in the Southeast is expected to be greatest in the summer, which is predicted to increase drought frequency, while annual mean precipitation is expected to increase slightly, leading to increased flooding events (Alder and Hostetler, 2013, unpaginated; IPCC, 2013, entire). Changes in climate may affect ecosystem processes and communities by altering the abiotic conditions experienced by biotic assemblages resulting in potential effects on community composition and individual species interactions (DeWan et al., 2010, p. 7). These changes have the potential to impact southern hognose snakes and/or their prey and habitat. There is uncertainty about how the ecosystems and species in this region will respond to the shifting climate, and effects on species of conservation concern may result from yet undetermined synergistic effects. Climate change may act as a risk multiplier by increasing the risk and severity of more imminent threats such as urbanization or altered fire regimes.

Terrestrial ectotherms, such as the southern hognose snake, may be at particularly high risk from climate change because they are less effective at buffering body temperature against ambient temperature. Instead, southern hognose snakes rely on ambient thermal heterogeneity to regulate their temperature behaviorally. The ability to optimally regulate body temperatures by moving among diverse microhabitats affects their growth, locomotion, and reproduction (Aubret & Shine, 2010, p. 246; Deutsch et al., 2008, p. 6668; Kearney et al., 2009, entire). Southern hognose snake reproduction is tied to seasons with suitable temperature and moisture regimes, and altered weather conditions during these seasons may result in frequently recurring "bust" years of reproductive failure, and ultimately population declines. Among other reptiles, it has been shown that high temperatures that restrict foraging activity can lead to energy shortfalls, and ultimately reduced population growth (Gibbons et al., 2000, p. 660; Huey et al., 2010, p. 833; Sinervo et al., 2010, entire). Reptile species with specialized diets, such as the southern hognose snake, could be particularly vulnerable to changes in climate that affect their prey base. Populations of southern hognose snakes could decline in response to drought-induced population declines of frogs and toads, their primary prey.

The most substantial impacts from climate change on the southern hognose snake are likely habitat based. Current and continued projected warming will increase the risk of wildfire, insect, wind, and disease damage to southeastern forests, and limit the number of suitable days to implement prescribed fire. For example, predicted longer growing seasons will likely increase

the risk of insect outbreaks and very likely will expand the northern range of some species, such as the southern pine beetle (*Dendroctonus frontalis*) (McNulty et al., 2013, p. 175).

The Southeast leads the nation in number of wildfires per year, and climate change will likely increase the frequency and intensity of wildfires (Blate, 2009, p. 58; McNulty et al., 2013, p. 173). The projected temperature increase across the Southeast will likely contribute to increased fire frequency and intensity, total burned area, change in fuel conditions, and longer fire seasons (McNulty et al., 2013, p. 174).

Alternatively, constraints to managing southern hognose snake habitat with prescribed fire is likely the most substantial risk factor associated with climate change for this species. Predicted changes in temperature and precipitation due to climate change will limit the number of days with suitable conditions for controlled burns, and combined with issues associated with WUIs discussed earlier, will further constrain the ability to manage habitat with prescribed burning. As the ability to implement prescribed fire becomes further constrained, the ability to reduce woody vegetation and maintain an open under- and mid-story will be severely limited, and southern hognose snake habitat will likely degrade.

Additionally, there is risk to coastal populations of the southern hognose snake due to sea level rise (SLR) under climate change. Global mean sea level has risen about 7-8 inches (16-21 cm) since 1900, with about half of that rise occurring since 1993 (Hayhoe et al., 2018, p. 85). In areas of the Southeast, tide gauge analysis reveals as much as 1 to 3 feet (0.30 to 0.91 meters) of local relative SLR in the past 100 years (Carter et al., 2018, p. 757). The future estimated amount that sea level will rise depends on the response of the climate system to warming, as well as on the future scenarios of human-caused emissions (Hayhoe et al., 2018, p. 85).

Coastal populations of southern hognose snakes are predicted to be directly impacted by inundation of upland habitat directly along the coast by rising sea levels, resulting in loss of habitat. Although the amount of habitat predicted to be lost within a given population due to SLR varies considerably depending on the location of the population, 50 southern hognose snake populations are considered to be vulnerable to SLR (i.e., population is anticipated to lose some amount of suitable habitat under all SLR scenarios). Loss of suitable habitat within a population will result in a decreased probability that a given population will persist.

3.5 Persecution, Harassment, and the Pet Trade

Humans have a long history of persecuting snakes; whether a snake is venomous or not, they tend to be viewed as vile and loathsome creatures (Burghardt et al., 2009, p. 262). Fear of snakes, called ophiophobia, has made snake conservation more difficult than other vertebrate groups (Burghardt et al., 2009, p. 262). The negative perception of snakes ranges from low interest, to harassment, to persecution resulting in deliberate killing. Many human-snake encounters result in the death of the snake (Whitaker and Shine, 2000, p. 121). Due to the

hognose snake's defensive behavior of flattening their head like a cobra, opening their mouth, and hissing loudly, they tend to be viewed as a threat to humans and thus when encountered in the wild they may be killed by people who do not know they are harmless (Kelley, 2011, p. 19).

There has also been an increase in recreational herpetology by enthusiasts actively looking for the southern hognose snake because it is considered an uncommon species, and they want to add this species to their life list. With the rise of social media there has been an increase of public knowledge of roads where it is easy to spot these animals. September and October, the most common months the species can be found, has become known as "Hogtober". These hobbyists may not be collecting individuals, rather just photographing and releasing, but this increased harassment may cause individuals increased stress that could be detrimental to them. Additionally, the increase in traffic on the roads from hobbyists leads to increased road mortality for the species (Martin, 2018, pers. comm.).

Hognose snakes have been in the North American pet trade dating back to the late 1980s and into the 1990s, but within the last several decades their numbers in the pet trade have expanded (Kelley, 2011, p. 18). Many view hognose snakes as desirable pets due to their upturned snout and coloration making them aesthetically attractive, as well as their tendency to seldom bite, unless a hand or finger is mistaken for food (Kelley, 2011, p. 18). Endearing nicknames such as "hoggies" and the fact that they are rear fanged, carry mild venom, and will play dead, add to their mystique as pets (Kelley, 2011, pp. 18–19). Western hognose snakes comprise most of the pet trade, with eastern and southern hognose snakes having a smaller commercial role (Kelley, 2011, p. 21). This may be because both the eastern and southern hognose snakes eat predominantly frogs and toads, and breeding in captivity can be more problematic for the southern hognose snake (Kelley, 2011, p. 19).

However, there is evidence that collection for the pet trade is a threat to this species. From 1990−1994, 135 wild-caught southern hognose snakes were reportedly sold in Florida, collected on primarily four areas of Florida roads where they were relatively abundant (Enge, 2005, pp. 208–209). Although there is some potential that some of these snakes were misidentified and were actually eastern hognose snakes, this shows that there is a demand for the southern hognose snake in the pet trade (Enge et al., 2016, p. 22). Since the 1990s, the demand for this species continues to remain in the pet trade and hatchlings often sell for more than $200 at reptile shows (Enge et al., 2016, p. 22; Kelley, 2011, p. 19). In Florida, two areas of Madison and Suwannee counties are well known to snake hunters for sometimes producing red-colored individuals that are worth up to $500 (Enge et al., 2016, p. 22). Though the population impact of collecting southern hognose snakes from roads is unknown, social media has allowed rapid dissemination of locations of prime or new collecting areas, and commercial or recreational snake hunters may come from hundreds of miles away to look for this species (Enge et al., 2016, pp. 22–23).

3.6 Disease

In wild populations of reptiles, debilitating diseases are most likely secondary expressions in individuals with impaired resistance caused by one or more primary environmental stressors, such as habitat degradation, invasive species, or pollution (Gibbons et al., 2000, p. 658). These primary environmental stressors can lead to immune suppression, which can further lead to an increase in morbidity and mortality from infectious disease (Allender et al., 2006, p. 107). Over the past several decades, the number of emerging fungal diseases and the number of species extinctions and extirpations caused by those diseases has increased (Lorch et al., 2015, p. 1).

3.6.1 Ophidiomycosis – Snake Fungal Disease

Ophidiomycosis (also known as snake fungal disease) caused by the fungus *Ophidiomyces ophiodiicola*, is a pathogen of North American snakes that poses a potentially serious threat to the health and stability of snake populations (Allender et al., 2020, p. 1). Infected wild snakes have several distinct lesions on various parts of the body, head, or tail, and often the animal will die from complications from the infection rather than from direct fungal damage (Lorch et al., 2016, pp. 4–5). First noted in 2006 as a severe skin infection associated with a precipitous decline in timber rattlesnakes (*Crotalus horridus*) in the northeastern United States, Ophidiomycosis has since been implicated in widespread morbidity and mortality across the eastern United States (Allender et al., 2015, p. 188; Lorch et al., 2016, p. 1). The fungus *O. ophiodiicola* has been detected in at least 23 states and one Canadian province, though there is some speculation that it may be more widely distributed than the documented cases suggest because the efforts to monitor the health of many snake populations are limited (Thompson et al., 2018, p. 1). The prevalence of disease within a snake population can cause differences in the health and body condition of snakes in the population. For example, the inadequate condition of female snakes in a population due to disease can affect reproductive rates and viability of that population (Allender et al., 2006, p. 31). Additionally, behavioral changes from ophidiomycosis may manifest as prolonged periods spent basking, resulting in higher metabolic rate and faster consumption of resources and may increase exposure to predators (Allender et al., 2020, p. 11).

To date, there have been no documented cases of snake fungal disease in southern hognose snakes; however, the disease has been detected in every State within the species' current range. The impact of snake fungal disease on snake populations is currently unknown, but the effects of infectious diseases on wildlife populations are an increasing concern, especially for species persisting at small population sizes (Allender et al., 2015, p. 194).

3.6.2 Raillietiella orientalis – Parasitic Snake Lungworm

Another emerging threat that could eventually impact wild snake populations, including the southern hognose snake, within the southeast United States is *Raillietiella orientalis,* an invasive pentastomid parasite introduced by nonnative Burmese pythons (*Python bivittatus*; (Farrell et al.,

2019, p. 73). The snake lungworm has been found to have infected at least 14 native snake species in peninsula Florida and has been documented outside the established range of the Burmese python, indicating that native snakes are competent hosts and that the parasite is rapidly moving north (Miller et al., 2020, p. 1,8). There is evidence of increased mortality in native snakes, such as the pygmy rattlesnake (*Sistrurus miliarius*; Farrell et al., 2019, p. 75).   It is unknown if there are any sublethal effects on native snakes and how the parasite impacts snake fitness and populations (Farrell et al., 2019, p. 75).

Research indicates that lizards and anurans serve as important intermediate hosts for *R. orientalis* (Palmisano et al., 2022, entire). Native snakes that forage on anurans are at a higher risk of infection and can be highly competent hosts which heightens the likelihood of transmission (Miller et al., 2020, pp. 7–8). Though this parasite has not yet been documented in southern hognose snakes, their diet is primarily anurans and lizards, making them potentially highly suspectable to infection.

3.7 Conservation Measures

3.7.1 Conservation Lands

Suitable habitat for southern hognose snakes can be found within National Wildlife Refuges, National Forests, State Lands, and other conservation areas across the species' range (Table 3-1). Habitat improvements, including ecosystem restoration, enhancement, protection, prescribed burning, and mechanical upland habitat restoration conducted across the species' range have likely provided some benefits to the southern hognose snake. Most conservation lands owned by Federal and State agencies are expected to remain protected and managed for conservation purposes in the near future, which would eliminate the risk of direct loss of habitat to urbanization in these areas.

It should be noted that while most conservation lands, whether federal, state, county, city, or private in nature, have regulations, rules, and policies that protect most wildlife occurring on such lands, enforcement and prosecution is often ineffective. Therefore, caution is advised regarding populations as "protected" simply because they occur on conservation land.

Many of these conservation lands in which southern hognose snakes occur manage habitat for other longleaf-associated species, such as red-cockaded woodpeckers (*Leuconotopicus* (=*Dryobates*) (=*Picoides*) *borealis*) and gopher tortoises. This habitat management likely has some benefits to the southern hognose snake when the managed habitat results in an open canopy system with more diverse groundcover.

Table 3-1. Conservation lands within the current southern hognose snake range that continue to provide suitable habitat and have occurrence records. This is not a comprehensive list of all conservation lands for the species and does not include private lands held in conservation easement.

STATE	MANAGER	PROPERTY
NORTH CAROLINA	Dept. of Defense	Fort Liberty (formally Fort Bragg)
		Camp Lejeune
	State	Sandhills Game Land
SOUTH CAROLINA	U.S. Fish and Wildlife	Carolina Sandhills National Wildlife Refuge
	U.S. Forest Service	Francis Marion National Forest
	Dept. of Defense	Shaw Air Force Base/Poinsett Electronic Combat Range
		Fort Jackson/McCrady Training Center
	Dept. of Energy	Savannah River Site
	State	Sandhills State Forest
		Santee Coastal Reserve
		Tillman Sand Ridge Wildlife Management Area
		Webb Wildlife Center
GEORGIA	U.S. Fish and Wildlife	Eufaula National Wildlife Refuge
	Dept. of Defense	Fort Moore (formally Fort Benning)
		Fort Eisenhower (formally Fort Gordon)
		Fort Stewart
	State	Big Hammock Wildlife Management Area
		Chattahoochee Fall Line Wildlife Management Area
		Sandhills Wildlife Management Area
		Yuchi Wildlife Management Area
FLORIDA	U.S. Fish and Wildlife	Lower Suwannee National Wildlife Refuge
	U.S. Forest Service	Apalachicola National Forest
	Dept. of Defense	Eglin Air Force Base
		Navy Air Station Pensacola
	State	Ashton Biological Preserve
		Choctawhatchee River Water Management Area
		Dade Battlefield State Historic Site
		Goethe State Forest
		Little River Conservation Area
		Marjorie Harris Carr Cross Florida Greenway State Recreation Area
		Palatlakaha Environmental and Agricultural Reserve Park
		Perry Oldenburg Wildlife and Environmental Area
		Rainbow Springs State Park
		River Rise Preserve State Park
		Roy L. Hyatt Environnemental Center
		Subtropical Agricultural Research Station
		Suwannee Ridge Wildlife and Environmental Area
		Torreya State Park
		Troy Spring Conservation Area
		Twin Rivers State Forest
		Watermelon Pond Wildlife and Environmental Area
		Withlacoochee State Forest
		Withlacoochee State Trail
		Wood Ferry Conservation Area
		Yellow Jacket Conservation Area
		Yellow River Water Management Area
		Yulee Sugar Mill Ruins Historic State Park

(Source: North Carolina Wildlife Resources Commission, 2015, p. 128; South Carolina Department Natural Resources, 2015, p. 8; Georgia Department Natural Resources, 2015, pp. D15–D16; Enge et al., 2016, pp. 64–65; Petersen et al., 2017, pp. 3–20)

3.7.2 Department of Defense

Throughout the Southeast, 12 military installations have records of southern hognose snakes, and an additional 26 installations could potentially have them (Petersen et al., 2017, pp. 3–20). Active prescribed burning programs are implemented on most military installations to manage for longleaf pine ecosystems, which can benefit conservation of the southern hognose snake. As part of implementation of the Sikes Improvement Act (1997), the Secretaries of the military departments are required to prepare and implement Integrated Natural Resource Management Plans (INRMP) for each military installation in the United States. No installations specifically include southern hognose snake habitat and population management prescriptions and goals within their INRMPs; however, most of the INRMPs do include specific management for other longleaf pine ecosystem species, such as the red-cockaded woodpecker and gopher tortoise, which would provide some benefit to southern hognose snakes. The Department of Defense's Readiness and Environmental Protection Integration (DoD REPI) program also offers opportunities to expand land conservation beyond installation boundaries to improve military training flexibility by defending against incompatible development and reducing regulatory restrictions that inhibit military activities. Working through landscape partnerships, the DoD REPI program has helped protect, restore, and maintain longleaf pine habitat across the Southeast.

3.7.3 Longleaf Ecosystem Conservation and Restoration
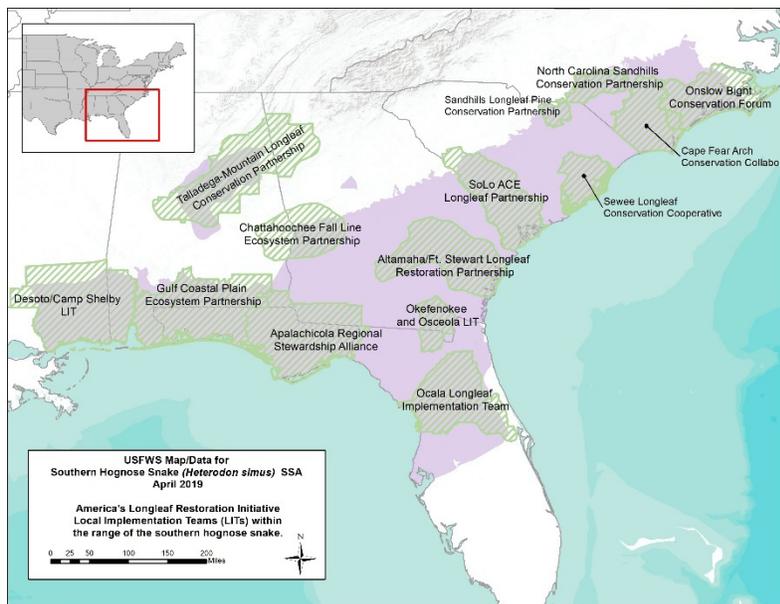
Figure 3-5. Locations of American's Longleaf Pine Restoration Initiative Local Implementation Teams (LITs) within the range of the southern hognose snake.

There are several initiatives and programs in the Southeast whose objectives include the establishment, restoration, and management of the native upland longleaf pine ecosystem. These include the Working Lands for Wildlife programs of the Natural Resources Conservation Service, the Service Partners for Fish and Wildlife programs, and America's Longleaf Restoration Initiative. Public land partners, including Federal and State Agencies, private landowners, non-governmental organizations are all active partners in

America's Longleaf Restoration Initiative. This is a collaborative effort of multiple public and private sector partners that actively supports range-wide efforts to restore and conserve longleaf pine ecosystems with a 15-year goal to increase longleaf from 3.4 to 8.0 million acres. These efforts are focused within 16 "significant landscapes" (Figure 3-5). Within these significant landscapes, Local Implementation Teams (LITs) are leading conservation efforts by coordinating partners, developing priorities, and fundraising to implement on-the-ground conservation. The majority of LITs are working within the range of the southern hognose snake, and each of these LITs has components of their conservation plans that support restoration of longleaf habitat and play an important role in southern hognose snake habitat restoration and management. Over the past decade, more than 1.3 million acres of longleaf has been planted and now 4.7 million acres of longleaf forests occur across the historic range (America's Longleaf Restoration Initiative, 2019, p. 2).

Conservation Benefit Agreements (CBA), previously Candidate Conservation Agreements with Assurances (CCAA) and Safe Harbor Agreements, are voluntary commitments made by non-Federal partners to undertake actions that will remove or reduce threats to the agreement's covered species. The goal of any CBA is to provide a net conservation benefit to the covered species and to preclude the need to list species under the ESA. As an incentive to the non-Federal property owner who engages in voluntary conservation actions for a particular species or group of species, landowners are given regulatory assurances if the species is listed under the ESA. Two such agreements could provide benefits to the southern hognose snake.

In 2017, a CCAA was established with the Camp Blanding Joint Training Center in Florida, providing protections for approximately 17,000 acres (6,879 hectares [ha]) of sandhill to be managed for the benefit of multiple at-risk species (USFWS et al. 2017, entire). There are no records of southern hognose snakes at Camp Blanding; however, there is suitable habitat on the installation and surrounding area.

In September 2023, the Quail County Programmatic CCAA for North Florida and Southwest Georgia, an agreement between the Service, Florida Fish and Wildlife Conservation Commission, and Georgia Department of Natural Resources, in cooperation with Tall Timbers Research Station, was finalized. This programmatic CCAA aims to enroll landowners to manage lands to the benefit of the covered species, including the southern hognose snake (USFWS et al., 2023, entire).

3.7.4 State Protections

The southern hognose snake is listed as State threatened in North Carolina, South Carolina and Georgia, State endangered in Alabama and Mississippi, and not listed in Florida (Table 3-2). In Florida, the species is ranked as a species of greatest conservation need (Florida Fish and Wildlife Conservation Commission, 2019, p. 156).

Table 3-2. Southern hognose snake listing status and rank by state (north to south) within the species' range.

State	State Listing	State Rank/Priority
North Carolina	Threatened	S2-Imperiled
South Carolina	Threatened	Highest Priority
Georgia	Threatened	S1/S2 - High Priority
Florida	Not Listed	Species of Greatest Conservation Need
Alabama	Endangered	Highest Conservation Concern
Mississippi	Endangered	SX- Believed to be Extirpated from the State

3.8 Summary of Factors Influencing Viability

We reviewed the potential factors that could be affecting the viability of the southern hognose snake (Figure 3-6). Concerns about the species' status revolved around the following factors: (1) habitat loss, conversion, and fragmentation resulting in the loss of longleaf pine savanna habitat across the range of the southern hognose snake; (2) road mortality based on the number and age classes of DOR individuals that could result in altered population structures; (3) invasive species, such as the red imported fire ant and feral hogs; (4) effects of climate change resulting in increased temperatures, decreased precipitation, increased severe weather such as drought, flooding, or storms, changes in wildfire frequency and intensity, decreased ability to conduct prescribed burns, and SLR; (5) the collection of individual snakes for the pet trade and persecution by humans; and (6) infectious diseases such as snake fungal disease may have on existing populations.

The primary concerns for the southern hognose snake's status are related to the loss and degradation of habitat. Habitat loss is due to a number of factors including fire suppression, silvicultural practices, SLR, conversion of land to agriculture, and urbanization. The current constraints on the ability to manage longleaf pine habitat through prescribed fire may be exacerbated by urbanization and climate change. It is likely that several of these factors are acting synergistically to impact the southern hognose snake, and the combination of multiple stressors may be more harmful than a single factor alone. Although there is some inherent uncertainty surrounding the stressors we evaluated and their synergistic effects, this does not prevent us from making a credible assessment of the likely direction and magnitude of those impacts, even though it may not be possible to make such predictions of impacts with precision.

Projections of habitat loss due to urban development and climate change are carried forward in our assessment of southern hognose snake populations and the overall viability of the species. We were not able to assess impacts from invasive species, such as red imported fire ants and feral hogs, persecution, over-collection for the pet trade and increased harassment, and disease

because datasets and or other information sources do not exist that capture the extent and degree of impact of these stressors to southern hognose snake populations across the species' range.
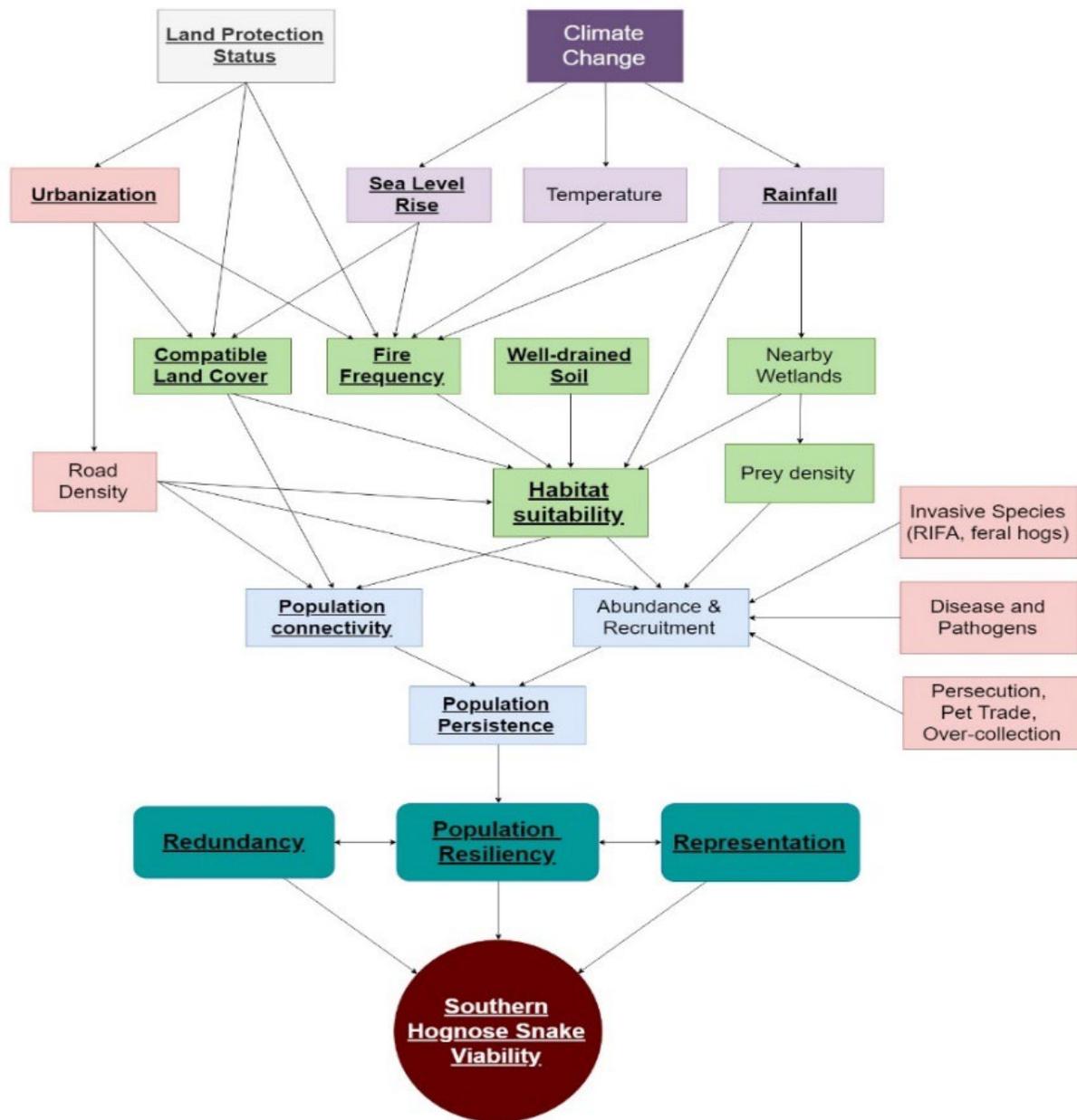
Figure 3-6. Influence diagram for the southern hognose snake, showing relationships between factors and species' viability. Color meanings: Grey – land ownership and protection status; Light red – stressors; Purple – climate-based factors; Green – habitat-based factors; Light blue – population metrics; Teal – components of viability (3Rs); Dark red – species viability. The factors that we were able to move forward in our analysis are bold/highlighted.

CHAPTER 4 – POPULATION AND SPECIES NEEDS AND CURRENT CONDITION

In this chapter, we consider the southern hognose snake's historical distribution, its current distribution, and what the species needs for viability. We first define populations of the species. Next, we characterize the needs of the species in terms of population resiliency and species' representation and redundancy (the 3Rs). Finally, we estimate the current condition of the southern hognose snake using population and habitat metrics used to characterize the 3Rs.

4.1 Methods for Estimating Current Condition

For the purpose of this assessment, we defined *viability* as the ability of the southern hognose snake to sustain populations in the wild over time. Using the SSA framework, we describe viability of the southern hognose snake by first defining our populations, estimating current condition, and then in Chapter 5 predicting the future condition using the metrics of the 3Rs.

To characterize the 3Rs for the southern hognose snake, we estimated habitat suitability and population persistence across a portion of the species' range, which we refer to as the analysis area (Figure 4-1). We then used the patterns found in these analyses to perform a qualitative assessment of conditions for areas outside of the analysis area. The analysis area
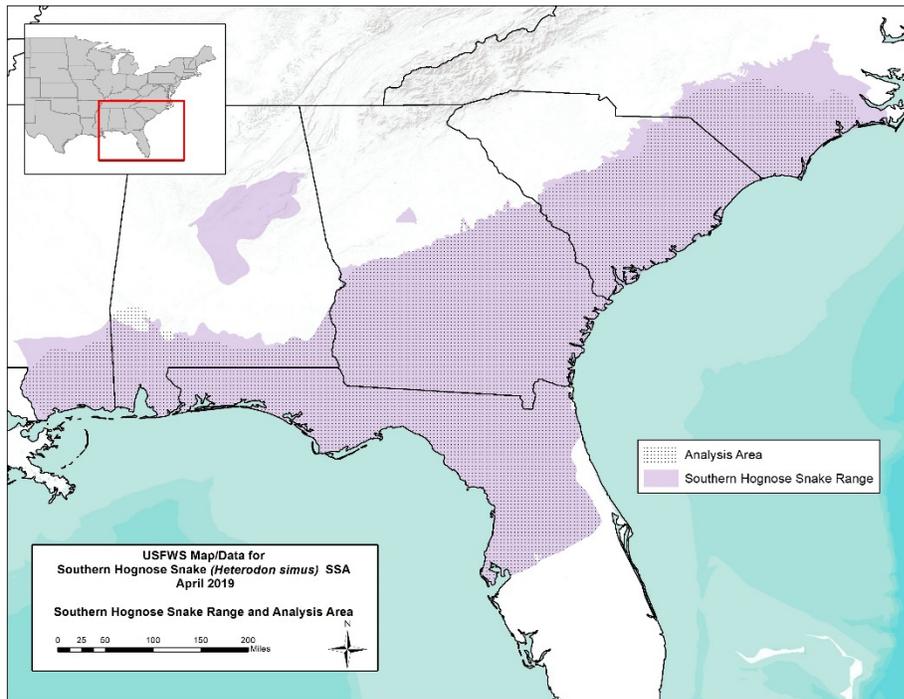
Figure 4-1. Comparison of the southern hognose snake range (purple) and analysis area used in the habitat and persistence modeling in the SSA (dotted area).

boundary was created during a habitat modeling study that began prior to developing the SSA and has since been published (Crawford et al., 2020a, entire) (see below). This boundary does not extend to disjunct portions of the species' range in central Alabama and the Georgia Piedmont as well as contiguous areas in Alabama, Mississippi, and eastern North Carolina. Most records obtained from outside of the analysis area are from 1990 or earlier, except for two records were reported in 2019 and 2021. All records are included in the full species' range.

Because habitat suitability metrics were also used to estimate population persistence, we used the same analysis area boundary for all quantitative analyses.

4.1.1 Habitat Analysis

Prior to developing this SSA, a habitat suitability model was developed for the southern hognose snake and subsequently published after version 1.0 of this SSA (Crawford et al., 2020a, Supplemental Text, entire). We compiled a geospatial database of occurrence records in a Geographic Information System (GIS). The compiled dataset included records maintained by Natural Heritage Programs, the Service, U.S. Forest Service, DoD, State agencies, academic researchers, and HerpMapper (HerpMapper, 2023, unpaginated), which include opportunistic sightings and observations during research and monitoring studies. Southern hognose snake records and available habitat/landscape data layers were used to identify habitat features that best predict species presence and the amount and distribution of potential suitable habitat across the species' range. Since the analysis focused on modeling current habitat suitability and not historical conditions, we used only species records since 1980 and habitat/landscape data layers showing conditions between 2000 and 2016. These decisions were made prior to the SSA with the support of species experts for capturing current habitat suitability. Model results showed habitat suitability, as measured by habitat suitability index (HSI) ranging from 0 (unsuitable) to 1 (most suitable), was strongly influenced by soil characteristics, land cover, and fire interval (Crawford et al., 2020a, Supplemental Text S1, entire). These relationships agree with previous studies and expert opinion that the species generally favors fire-dependent, xeric habitat that is locally elevated (e.g., longleaf pine sandhills).

To aid map users in interpreting patterns of suitable habitat, HSI was converted to classes of Unsuitable (HSI = 0 – 0.24), Low (HSI = 0.25 – 0.39), Moderate (HSI = 0.4 – 0.59), and High Suitability (HSI = 0.6 – 1). Range-wide, there is an estimated 2.5 and 1.3 million ha of moderately and highly suitable habitat, respectively (Figure 4-2). Habitat was further summarized by its current protection status to inform partners of the degree of conservation assurances and potential opportunities. We classified habitat as "protected" if it occurred on publicly owned land or on privately owned land designated for conservation uses in protected area databases. We note that these methods classified habitat on DoD and other multi-use lands as protected. Although these lands are often actively managed for habitats and wildlife species, there is the potential that land use changes have/could result in the loss or degradation of suitable habitat. Predicted areas of higher habitat suitability tended to accurately highlight known species strongholds, such as National Forests, DoD lands, and other conservation lands; 28% and 36% of moderately and highly suitable habitat, respectively, currently exists in patches larger than 100 ha on public and protected lands.
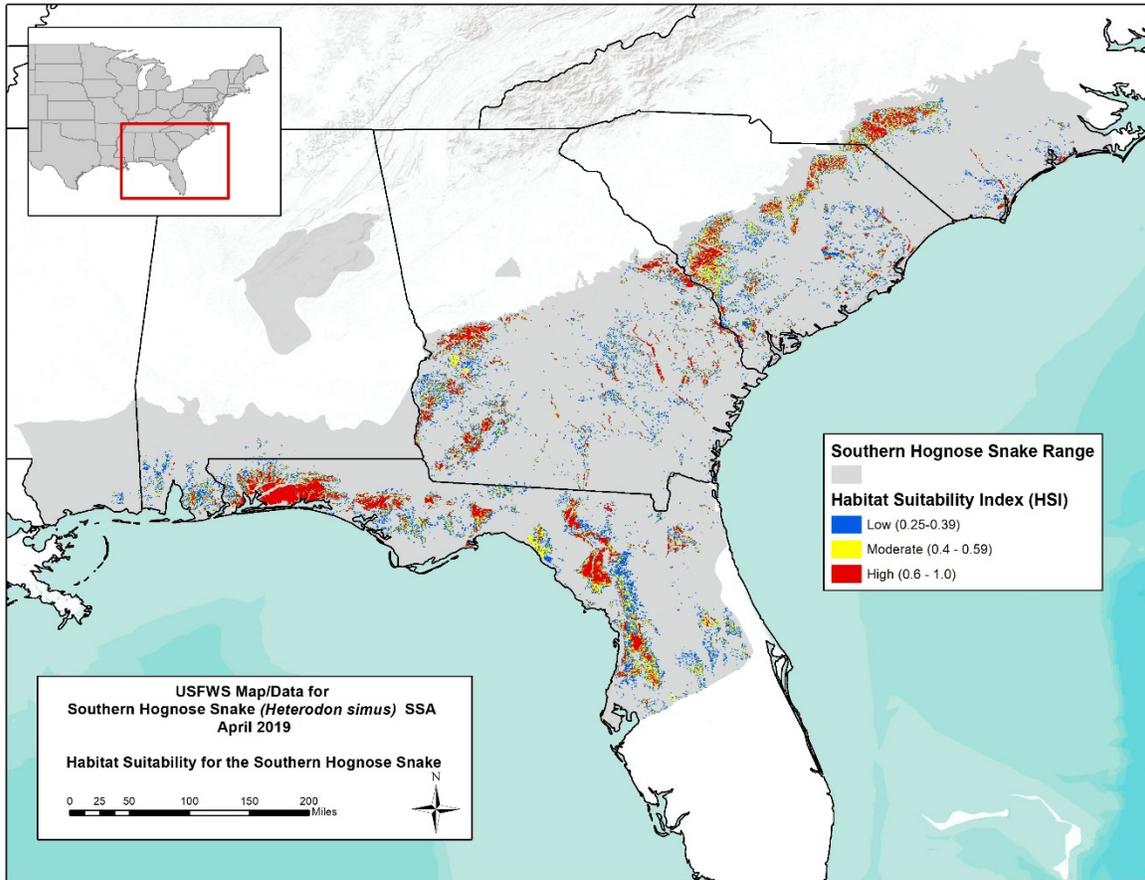
Figure 4-2. Spatial distribution of suitable habitat for the southern hognose snake across its range in the Southeast. The southern hognose snake range is shown in grey in the background.

4.1.2 Defining Populations

For this assessment, we defined populations for the species as contiguous areas surrounding known southern hognose snake occurrences with habitat conducive to survival, movement, and inter-breeding among individuals within the area. We compiled all species records in GIS and included every record regardless of year of observation. The compiled dataset included records maintained by Natural Heritage Programs, the Service, U.S. Forest Service, DoD, State agencies, academic researchers, and HerpMapper, which include opportunistic sightings and observations during research and monitoring studies. To delineate populations, we used records with available latitude and longitude information. County records (n=27) that were lacking coordinates were placed at the county's centroid and included as populations, assuming that at some point in time southern hognose snakes occurred within that county somewhere on the landscape. Then we buffered the species occurrence records by 5 kilometers (km) (3.1 miles) and divided contiguous areas by large rivers and interstate roads that likely prevent movement and interbreeding among individuals on opposite sides of the barrier (Figure 4-3).
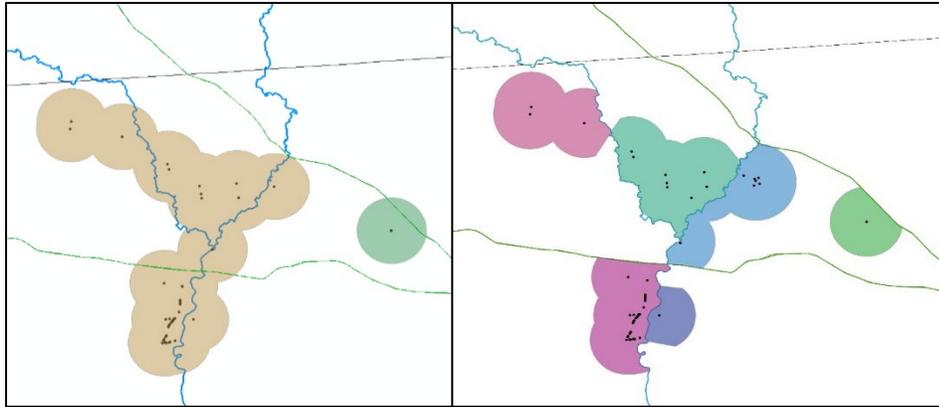
Figure 4-3. Example of delineating populations. Left panel: southern hognose snake location records buffer by 5 km then group together by population, with different colors depicting different populations. Right panel: populations were then divided by ecologically-relevant barriers, such as major rivers and major highways, to derive our final populations, with different colors again depicting different populations.

The choice of buffer distance was informed by expert input and protocols used by NatureServe (NatureServe, 2018, unpaginated). Ideally, we would have selected a buffer distance using a reported maximum annual movement or dispersal distance metric. For the southern hognose snake, these values have not been reported, nor could we find these values reported for a surrogate species. NatureServe suggests a separation distance for colubrid snakes of 10 km (6.2 miles) for suitable habitat and 1 km (0.62 miles) for unsuitable habitat. This recommendation was based on a limited number of studies of movement and range in colubrid snakes and was selected by NatureServe for the colubrid group because it seems generally unlikely that two locations separated by less than 10 km of suitable habitat would represent distinct occurrences (NatureServe, 2018, unpaginated).

Data reported for a limited sample of southern hognose snakes seems to indicate a 10 km buffer may be too large for purposes of delineating populations. Southern hognose snakes have relatively small home range sizes, between 8-30 ha (19.7-74.1 acres), and these home ranges are smaller than those reported for eastern hognose snakes (Beane, 2018; Tuberville, 2018, pers. comm.). One female southern hognose snake was reported to have moved 1.44 km (0.9 mi) in one day (Beane, 2018, pers. comm.). Taking the NatureServe recommendation into account, using expert opinion, species size and cryptic nature, and other species biology, 5 km was determined to be an acceptable buffer distance. This distance represents the potential maximum extent an individual could occupy. By using a maximum extent, our intent is to capture the majority of the area potentially used by an individual; this is likely an overestimate of the area actually used by an individual.

Once the 5 km buffers were created, any buffers that overlapped each other were merged, which created contiguous areas (populations) where any points within 5 km of each other were part of the same population. We then divided populations by two ecologically relevant barriers: (1) large rivers of the 6th order or higher, accessed from the National Hydrography Dataset (U.S. Geological Survey, 2022, unpaginated), and (2) primary roads designated as "interstate" route

type from the TIGER/Line 2023 Primary Roads dataset (U.S. Census Bureau, 2023, unpaginated). Based on expert opinion, movement of individual snakes across these barriers is extremely unlikely, thus areas on either side of the barrier are considered separate populations in our analysis.

4.1.3 Population Resiliency

To begin to characterize resiliency, we used a modified version of the model developed in version 1.0 of this SSA and subsequently published in the peer-reviewed literature that estimates the likelihood that a site is currently (in 2023) occupied by southern hognose snakes for each defined population in the species' range (Crawford et al., 2020b, entire). We define this metric estimated from the model as the "current persistence probability." In other words, current persistence represents the probability that there is at least one southern hognose snake that has survived through a time period and is still remaining within the population boundary. The complement (1 – current persistence) can be interpreted as the probability a population has become extirpated. Current persistence is not a direct measure of population size or growth rates, which are population-level metrics we could not estimate with available data. Estimating population sizes or growth rates

How does the persistence model work? The population persistence model took information about southern hognose snake detections, search effort, and site conditions to estimate the probability each population has persisted from one year to the next, as well as the probability the population currently persists in 2023. More specifically, the model used three types of information to estimate persistence for each population. First, it used a history of when southern hognose snakes were or were not seen in a population area. We would expect populations where southern hognose snakes have been detected often and recently to have a higher probability of currently persisting. Second, it used a history of search effort in the area, captured by records of southern hognose snakes and 14 other snake species that share similar habitats. Search effort helped the model estimate when southern hognose snakes may be persisting in an area but have gone undetected. Third, it used three attributes of a population's conditions that may influence persistence probability: (1) mean habitat suitability inside a population boundary, (2) the proportion of the population boundary on protected land, and (3) the number of nearby populations within 10 km.

We ran the model 400,000 times. In each run, the model estimated each population's probability of persisting one year to the next, based on data inputs, and used that probability to randomly draw an outcome for each population in the next year. We can think of this as a coin flip determining whether a population persisted or has become extirpated. Because of this randomness (stochasticity), estimates varied between model runs.

We calculated each population's current persistence probability as the proportion of model runs where the population was still persisting in 2023. Additionally, we summed the number of populations still persisting in 2023 within each representative unit and range-wide in each model run, and we used these to calculate the mean number of populations persisting at these scales.

usually relies on first estimating demographic rates, such as individual survival, with mark-recapture and other data. We were not able to use mark-recapture for this species, as existing datasets contain low numbers of recaptures that prevent any traditional analyses (Smith, 2018, pers. comm.). However, we can make reasonable inferences about resiliency based on persistence. We can assume large populations with sufficiently high survival and recruitment rates will have a higher probability of persisting over time. We can also assume that more resilient populations are those that have continued to persist on the landscape over time, tend to occupy higher quality habitat, are more likely on protected lands, and have some level of connectivity to other populations. We also further examined resiliency based on current persistence, HSI, and connectivity to other populations to evaluate whether conditions on the landscape are sufficient to support populations and their needs.

We structured our persistence model similar to the Cormack-Jolly-Seber model (Lebreton et al., 1992, entire; Brooks et al., 2000, entire), which was designed to estimate survival of individual animals based on mark-recapture data, to analogously estimate persistence ("survival") of populations based on observation histories. We used the delineated populations created from the comprehensive dataset of southern hognose snake occurrence records to create a time series of when snakes were or were not observed within each population boundary. Inference in this model is thus at the site occupancy level, similar to an occupancy model; however, like the Cormack-Jolly-Seber model, site persistence is conditioned on the initial observation of a southern hognose snake at the site. This type of model does not account for the potential colonization of sites or addition of populations, only the probability that populations persist once established (and initially observed).

Models using a similar approach rely on absence information (i.e., when searches for the target species occurred, but the species was not observed) to estimate survival, occupancy, and persistence (MacKenzie et al., 2002, p. entire; Kéry et al., 2009, p. entire). However, robust search effort and absence data do not exist for the southern hognose snake. Therefore, we developed a search effort dataset from occurrence records of other snake species (non-target species) commonly observed in southern hognose snake habitats. We obtained these non-target species records from the same sources as the southern hognose snake records (i.e., Natural Heritage Programs, the Service, U.S. Forest Service, DoD, State agencies, academic researchers, and HerpMapper). We used the search effort dataset to account for imperfect detection of the southern hognose snake and improve the precision of persistence estimates. We assumed that records of other, non-target snake species that fall within a given population boundary indicate that the area was searched by a person in a given year and provide information about the chance a population is persisting. For example, consider two populations (A and B), in which southern hognose snakes have not been observed in either population since 1990. Population A has been frequently searched since then, and other species of common snakes continue to be reported in the area. Population B, however, has only been searched once since then. Assuming everything

else is equal, there is more evidence that the southern hognose snake has become extirpated in Population A, while Population B is more uncertain. In using non-target species data, we made the following assumptions: (1) non-target records indicate an event when an area known to have been occupied by southern hognose snakes at some time was searched, and the search was performed in a way that southern hognose snakes could be observed (e.g., road surveys), and (2) that southern hognose snake records would have been reported if found when a person submitted non-target records to Herpmapper. For more information on which non-target species we used and how we queried the data, see Appendix A.

Next, we summarized population-specific metrics for several spatial variables that likely influence persistence and incorporated them into the model. For each population, we calculated three metrics to be used as predictors of persistence: (1) the average HSI estimated in the habitat analysis within each population boundary, (2) the proportion of the population that is currently on protected land, and (3) the number of populations within a 10 km radius of the population (Table 4-1). For protected lands, we used areas that are currently publicly owned and managed, as well as private lands that are registered in State or Federal programs where natural resource conservation is the goal.

Table 4-1. List of predictors used to model southern hognose snake population persistence, the hypothesized relationships to population resilience, and the average and range of predictors across 213 populations within the analysis area.

Site condition predictor	Biological justification	Mean (range)
Habitat Suitability Index (HSI)	Higher habitat suitability represents areas of higher quality (well-drained, sandy soils, compatible forest/grassland landcover, frequent fires) that should increase southern hognose snake survival, recruitment, and persistence. The average HSI within a population boundary is highly correlated to the amount of suitable habitat.	21.3% (0 – 80.3%)
Proportion on protected land	Higher proportions of a population that occur on protected land should increase habitat quality through regular management practices and may limit direct threats such as road mortality and collection.	24.3% (0 – 100%)
No. of populations within 10 km	Populations close to other populations may have a higher chance of long-term persistence. Nearby populations may provide opportunities for "rescue" where recolonization can occur after a catastrophe and provide for some genetic exchange; alternatively, nearby populations could provide a signal that there are localized conditions (e.g., geological, climatic) that promote population persistence that have not been otherwise captured in our analyses.	2.1 (0 – 9)

Once we had time series of southern hognose snake observations, search effort indices, and spatial predictor metrics for each population, we fit the persistence model using a state-space formulation in a Bayesian framework (Kéry and Schaub, 2011, pp. 171–239). State-space models explicitly model how the state of a system (what is truly happening in a system) changes over time (e.g., population persistence and extirpation) as well as the process of observing an individual (what we actually see), given the population has not become extirpated (Figure 4-4). Thus, they are helpful in separating real biological signals from error in observation data. For persistence probability, in addition to the three metrics described above related to HSI, protected lands, and number of nearby populations, we included a fixed effect for the population's representative unit. This allowed for a different baseline persistence probability for each unit. For detection, we included a trend effect that allowed mean detection to change over time, given that the amount of search effort in our dataset substantially increased between 1880 and 2023 and the quality of search effort may be higher in recent years due to more easily accessible information on where and how to search for this species. We also included a fixed effect for population- and year-specific effort, using the search effort index data. Lastly, because a high percentage of southern hognose snake records were encounters on roads, we assumed a bias for roads increasing the likelihood of detection and we included a measure of area near roads when we modeled detection. Specifically, we quantified the total area within each population boundary that was within 2 km (1.24 mi) of a major road.
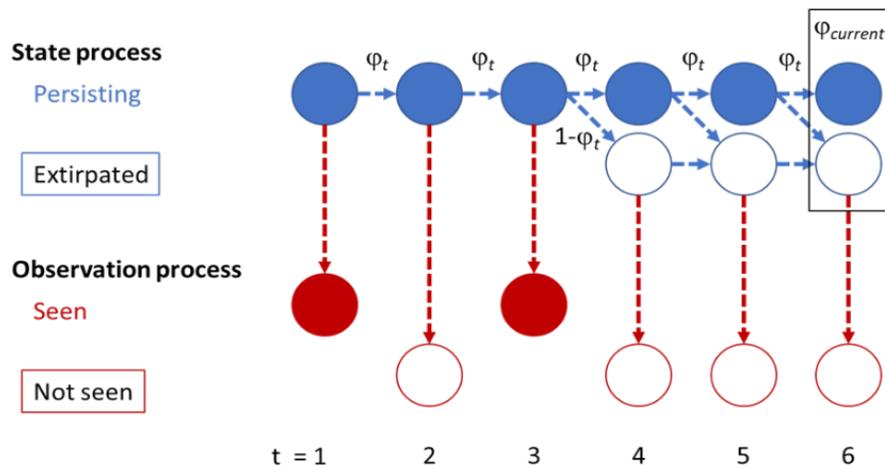
Figure 4-4. Example of the state process (true state of the system) and observation process (what we observe) of a population over time for the persistence model. The population persists or becomes extirpated each year based on the annual persistence probability (φ_t), which is estimated in the model. This probability is used to derive the current persistence probability ($\varphi_{current}$) – i.e., the probability a site has survived over the entire time period modeled and is currently occupied in 2023. Its complement ($1 - \varphi_{current}$) is interpreted as the probability a population has become extirpated. In this figure, imperfect detection is represented in time period 2 when individuals were not observed but the population was still known to be persisting (because individuals were seen in time 3). Since time 3 was the last year individuals were observed, the model estimates the probability the population persists or becomes extirpated each year after that. If the population became extirpated in time period 4, then the sequence of the true state process would be z = [1, 1, 1, 0, 0, 0]. The observed capture history (when individuals were seen in this population) would be y = [1, 0, 1, 0, 0, 0]. Source: Kéry & Schaub, 2011, p. 176.

We modeled the probability of populations persisting from one year to the next through 2023 (i.e., "annual persistence probability"). We ran the model with Markov chain Monte Carlo (MCMC) methods in Jags called from R via the R2jags package (Su & Yajima, 2012, unpaginated). We calculated each population's current persistence probability and the associated uncertainty from the proportion of model iterations where the population was still persisting in 2023. Additionally, we summed the number of populations estimated to persist in 2023 within each representative unit and range-wide in each model iteration, and we used these to calculate the mean estimated number of populations persisting at these spatial extents. We assigned diffuse prior distributions for all parameters, and we generated three MCMC chains using 500,000 iterations where we retained every third iteration from the last 400,000 iterations. We assessed convergence based on the Brooks-Gelman-Rubin statistic (< 1.1 for all parameters) and by visually inspecting chain mixing in MCMC trace plots and posterior distribution plots for evidence of unimodality. To assess goodness-of-fit, we conducted posterior predictive checks (Gelman et al. 2000, entire) where we simulated datasets using parameters estimated in the model, calculated the mean number of populations with simulated detections of southern hognose snakes in four time periods (1920-1929, 1950-1959, 1980-1989, and 2014-2023), and compared mean observations in these periods from the real dataset with values from simulated datasets. We based parameter inferences on posterior means and 95% Bayesian credible intervals (BCIs; 2.5^{th} – 97.5^{th} percentile of the distribution).

Estimates of southern hognose snake persistence probabilities range between 0 (0%) and 1 (100%). Based on expert input, we developed the following categories: unlikely or extirpated on the landscape (< 50%), more likely than not on landscape (50 – 79%), very likely on landscape (80 – 94.9%), and extremely likely on landscape or extant (95 – 100%). For a population to be classified in the more than likely, very likely, or extremely likely categories, the lower 95% credible interval of the estimated current persistence probability had to be equal to or greater than 50%, 80%, or 95% respectively. This criterion allowed us to say that we were 97.5% certain that a population was in that persistence category. A population was classified as unlikely or low likelihood of persisting if the lower limit of the 95% credible interval for current persistence probability was below a probability of 0.5 even if the mean estimate for that population exceeded 0.5. This means that our classification of persistence was conservative and unlikely to over-represent the current resilience of a population or range-wide status of the species.

Although a number of populations are likely to currently be extant (>50% population persistence), the habitat conditions and a populations connectivity to other populations may be impaired. To consider what resiliency means for the extant populations, we further examined the HSI to evaluate whether conditions on the landscape are sufficient to support populations and their needs into the near future. The HSI used the most accepted method for determining model

performance and fit. This approach identified an HSI value of 0.4 as the most appropriate threshold for locations where southern hognose snakes occur versus where they do not occur. This value is estimated by the best available data and the model is a formalization of the relationships between conditions that experts have determined are important for southern hognose snake population persistence. We then examined connectivity in terms of the spatial distance (kilometer (km) and mile (mi)) between each population and its closest population. We considered that a population must have other extant populations within 10 km (6.21 mi) to provide demographic connectivity that contribute to genetic diversity within the species, whereas a population that is further away than 10 km (6.21 mi) from its closest population indicates an isolated population.

For a population to have high resiliency, it must have a relatively high current persistence probability (>80%), currently occupy higher quality habitat (well-drained, sandy soils, compatible forest/grassland landcover, frequent fires), and be within 10 km of at least one other extant population. To have moderate resiliency a population must be more likely than not on the landscape with a persistence probability between 50-79.9%, currently be located on suitable habitat, and be within 10 km of at least one extant population. Low resiliency populations are those that we determined their persistence probability is ≥50% so they are considered to be extant, however they are not currently on suitable habitat and are not within 10 km of one other extant population.

Table 4-2. Resiliency evaluated for extant populations based on combination of probability of persistence, habitat suitability, and connectivity metrics.

Resiliency	Probability of Persistence	Habitat Suitability	Connectivity
High	>80%	Average HSI value >.4	≥ 1 extant population within 10 km
Moderate	50-79.9%	Average HSI value >.4	≥ 1 extant population within 10 km
Low	≥50%	Average HSI value >.4	0 populations within 10 km
Low	≥50%	Average HSI <.4	≥ 1 extant population within 10 km
Low	≥50%	Average HSI <.4	0 populations within 10 km

4.1.4 Species Representation and Redundancy

Representation reflects the ability of a species to adapt to changing environmental conditions and can be measured by the breadth of genetic or environmental diversity within and among populations. For the southern hognose snake, we do not have information related to genetic diversity. In the absence of species-specific genetic and ecological diversity information, representation can be assessed based on the extent and variability of habitat characteristics across the geographical range (Wolf et al., 2015, p. 204). Ecoregions are a system of classification based on physiography, where areas with similar characteristics of land formation, dominant soil

and vegetation types, climate, air and sea currents, and distribution of flora and fauna are grouped into a single ecoregion (Bailey 1983, entire; Bailey et al. 1994, entire). Ecoregions have been used to reflect broad areas within which local adaptations and genetic coadaptation have likely occurred. Therefore, we used ecoregions to act as an appropriate proxy for factors likely to influence the adaptive capacity of southern hognose snakes across the landscape. We broke the southern hognose snake range into nine representative units based on grouping Environmental Protection Agency (EPA) Level IV ecoregions by similar ecological characteristics (e.g., soil, geology) and dividing them by the Savannah, Chattahoochee-Apalachicola, and Mobile-Tombigbee Rivers where appropriate (Figure 4-5). We considered how the distributional and habitat variation between the representative units is indicative of the species' ability to adapt to changing environmental condition (adaptive capacity). We also considered the species' behavior to understand its' ability to adapt in a changing environment.
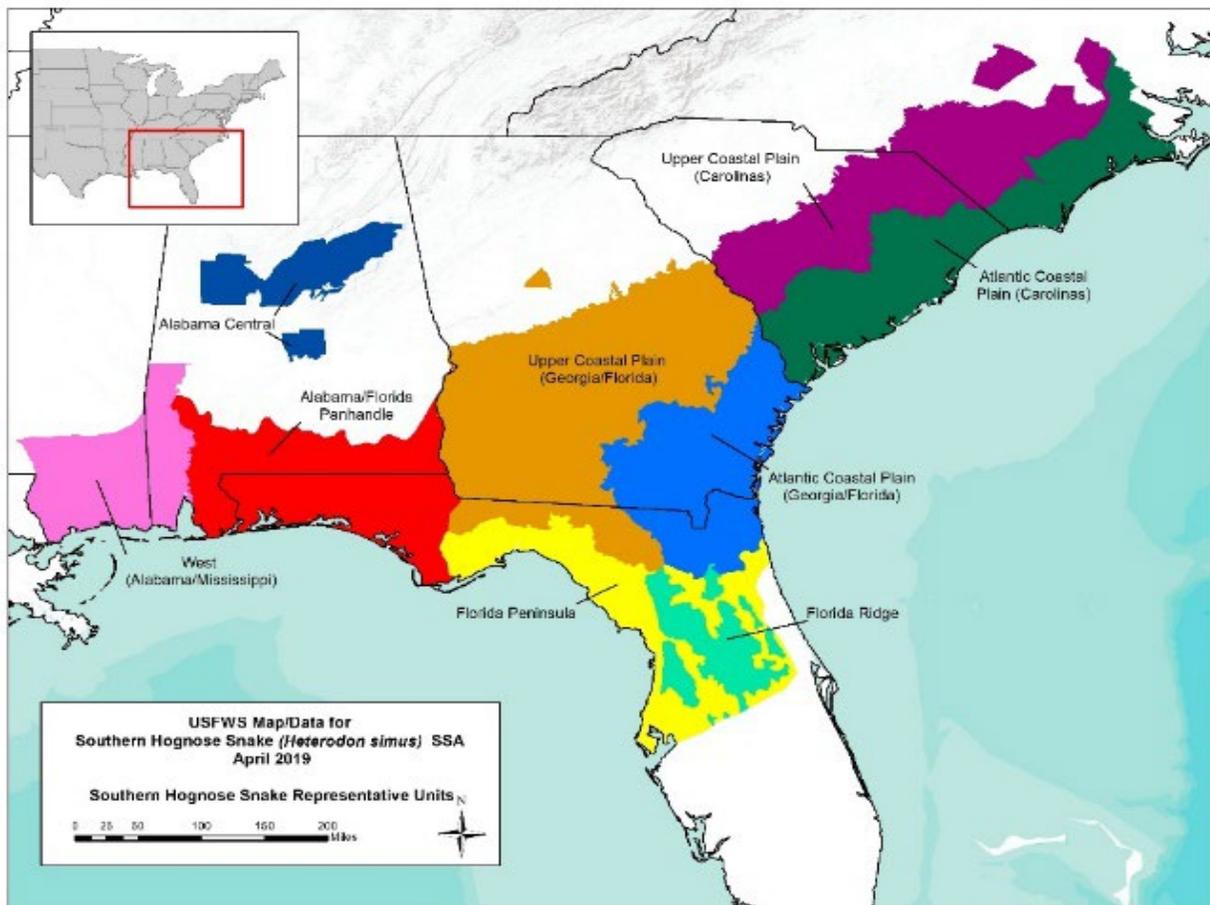
Figure 4-5. Representative units for the southern hognose snake. Nine units were selected based on ecoregion groups.

The southern hognose snake needs to exhibit some degree of spatial redundancy to maintain viability. Species-level redundancy reflects the ability of a species to withstand catastrophic events and remain extant, and is best achieved by having multiple, widely distributed populations

relative to the spatial occurrence of catastrophic events. Species that are well-distributed across their historical range are considered less susceptible to extinction and more likely to be viable than species confined to a small portion of their range (Carroll et al. 2010, entire; Redford et al. 2011, entire). In addition to guarding against a single or series of catastrophic events, redundancy is important to protect against losing irreplaceable sources of adaptive diversity.

When investigating redundancy for southern hognose snakes, we consider a catastrophe to be any destructive event or episode that involves population-level impacts with the potential to negatively influence population resiliency outside of normal environmental and demographic stochasticity. Natural catastrophes that have the potential to occur in the southern hognose snakes' range include large-scale drought, wildfires, hurricanes, and disease outbreaks. Although we do not have data on the direct effects that these catastrophic events have on populations of southern hognose snakes, these catastrophes have the potential to negatively impact populations outside of the normal environmental and demographic stochasticity they experience. Additionally, drought, wildfires, and hurricanes occurring across the range of the species are predicted to increase under climate change.

To characterize representation and redundancy, we captured predictions of the number of resilient populations within a representative unit and range-wide in two ways. First, we summed the number of populations within a unit and range-wide with current persistence probabilities at or above each category (threshold), as described for characterizing population resiliency (Section 4.1.3). Second, we recorded the number of populations predicted to persist in 2023 within each unit and range-wide, using direct outputs from the model. Each model iteration recorded the number of populations persisting in 2023 in each representative unit and range-wide, and we used all model iterations to calculate the mean (the most likely prediction) and 95% confidence intervals for the predicted number of persisting populations in 2023.

One can think of the difference between a specific population's probability of persistence and the mean number of populations persisting within a representative unit by considering a set of four fair coins. Each has a 50% probability of getting a heads – this is a population's persistence probability. If we flip all four coins many times, the most likely outcome, on average, is getting two heads and two tails – this is the mean number of persisting populations predicted in a model iteration. The specific coins that yield a heads may change each trial, but we still expect two out of four heads most commonly. Therefore, when assessing representation and redundancy at the scale of a representative unit and range-wide, it may be helpful to consider the two types of results alongside each other. One can interpret the mean number of persisting populations as the most likely outcome then further assess the current resiliency of populations within a representative unit and range-wide, using the number of populations above a certain persistence threshold (e.g., 80%). When comparing these two metrics, it is important to remember that for a population to be classified above a certain persistence threshold, the lower 95% credible interval

of the estimated current persistence probability had to be equal to or greater than the respective threshold (as described in section 4.1.3). For more information on our methods, see Appendix A.

We measured representation using the number and distribution of resilient populations across representative units in the species' range, as well as assessing the spatial distribution (latitudinal and longitudinal variability) of resilient populations. To have high representation, southern hognose snakes must have multiple moderate to high resiliency populations located in each of the representative units, and these populations should span the latitudinal and longitudinal extent of historical populations. We measured redundancy using the current number and distribution of resilient populations within representative units and across the range of the species. To have high redundancy, the southern hognose snake would need to have multiple moderate to high resiliency populations within a representative unit and throughout its range.

4.2 Current Condition Results

4.2.1 Populations

For our population analysis, we obtained 2,662 southern hognose snake records, from years 1880-2023. Many of the early occurrence records were for the county only without available coordinates. The occurrence records were spread throughout the species' range, but a majority of the records came from the Upper Coastal Plain (Carolinas) representative unit (Table 4-2). From these records, we identified a total of 233 populations of southern hognose snakes with a mean area of 13,360 ha (range = 1,248 – 236,477 ha; Figure 4-6). If a population spanned more than one representative unit, the population was placed in the unit where most of the population boundary occurred for that population.

Table 4-3. Summary of number of occurrence records for the southern hognose snake, with number of populations for representative units and range-wide.

Representative unit	No. of records	No. of populations
Upper Coastal Plain (Carolinas)	1651	33
Upper Coastal Plain (GA/FL)	384	61
Atl. Coastal Plain (Carolinas)	194	39
Atl. Coastal Plain (GA/FL)	36	14
FL Peninsula	117	33
FL Ridge	187	16
AL/FL Panhandle	62	26
West (AL/MS)	18	7
AL Central	13	4
Range-wide	**2662**	**233**
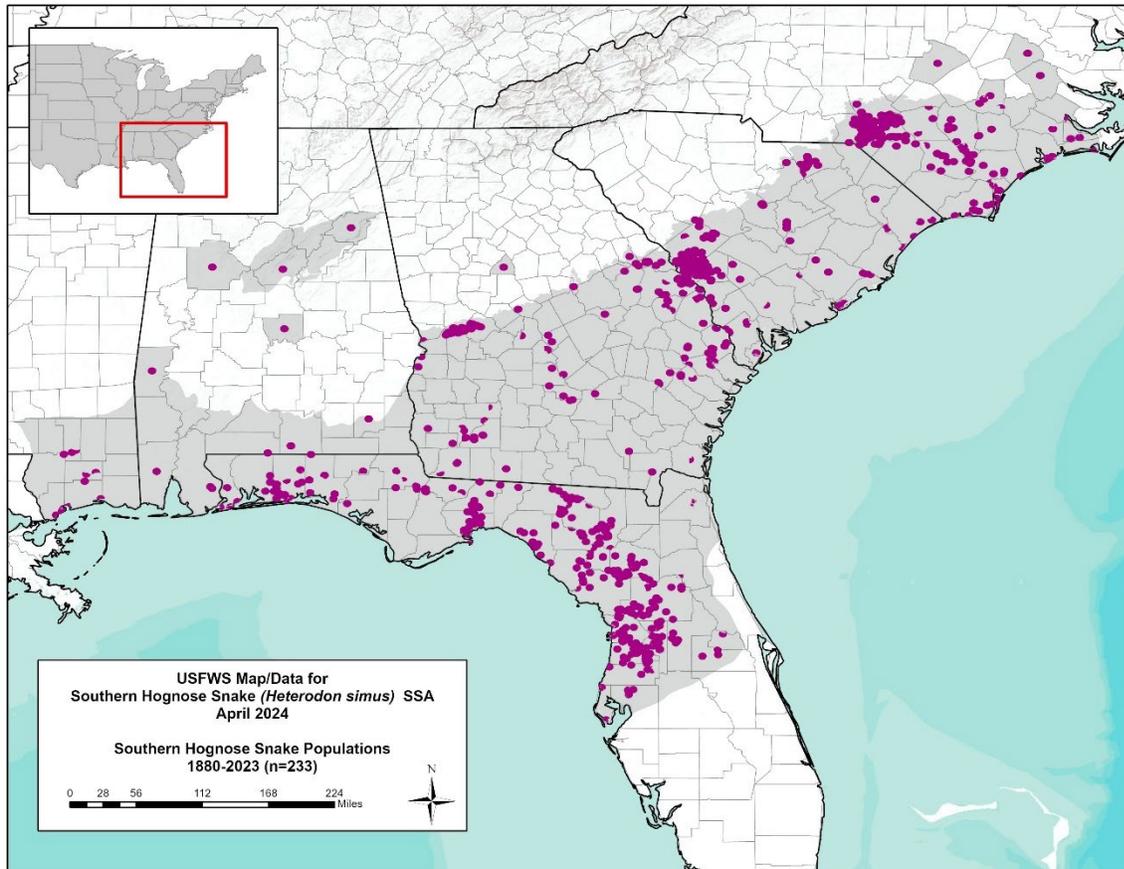
Figure 4-6. Distribution of 233 southern hognose snake populations across the species' range (shaded background).

4.2.2 Current Population Resiliency

To assess the current condition of the southern hognose snake, we modeled persistence using 2,632 occurrence records grouped into 213 populations that occurred within the analysis area. The remaining 30 occurrence records that fell outside of the analysis area were grouped into 20 populations. All but two of these records were found prior to or during 1990 and likely represent extirpated populations, and thus are included in our resiliency analysis as extirpated. The remaining two records located outside of the analysis area, representing two populations, were found within the last five years (2019 and 2021). Since we were unable to estimate current persistence probability for these two populations, we consider their status to be unknown. Out of the 144 years we modeled (1880-2023), the mean number of years southern hognose snakes were found in a population was 3.08 (range = 1 to 48). From the search effort dataset, the number of records per year per population ranged from 0 to 548 (mean = 0.622), and records of non-target species came from 174 of 213 (81.7%) populations. The persistence model showed adequate convergence and the posterior predictive check indicated that the model fit the data adequately in

the first and last time periods assessed but had poorer fit in the two intermediate time periods assessed (see Appendix A for details).

We present the number of populations (out of 233) in each persistence category, as well as the cumulative number of populations at or above each persistence category, in Table 4-4; Figure 4-7. Range-wide, there likely has been a 61.8% (144/233) extirpation of southern hognose snake populations (i.e., populations with a less than 50% probability of current persistence). These likely extirpated populations have no resiliency likely due to not persisting on the landscape, having lower quality habitat, not within protected lands, or not having connectivity to other populations. It is possible that individuals within these populations may still be on the landscape, however, these populations can be considered functional extirpated, since they likely do not have all their resource needs met. Conversely, 27.9% of populations had a greater than 80% probability of current persistence and 14.2% had a greater than 95% probability of current persistence. We estimate that 87 populations (>50% persistent probability) to likely be extant in 2023. We report mean persistence estimates and 95% confidence intervals for each population in Appendix A.

Table 4-4. Number and percentage of southern hognose snake populations in each persistence category and cumulative number of populations at or above each threshold for all populations (n=233).

Population persistence	Number of populations in each category	% of total	Cumulative number of populations at or above each threshold	% of Total
Extremely Likely on Landscape (Extant) 95-100%	33	14.2%	33	14.2%
Very Likely on Landscape 80-94.9%	22	9.4%	55	27.9%
More Likely than Not 50-79.9%	32	13.7%	87	37.3%
Unlikely < 50% (Extirpated)	144	61.8%	-	-
Unknown	2	0.9%	-	-
Total	**233**	**100%**		

Figure 4-7. Populations of southern hognose snakes by category of current persistence probability in 2023.

Current persistence was equal to 1 for populations where southern hognose snakes were observed in 2023 and generally decreased with years since the last observation (Figure 4-8). Not surprisingly current persistence probability, increased with habitat suitability and number of populations within 10 km. However, the model results did not support a relationship between current persistence probability and proportion of protected land. Conducting additional, follow-up surveys at sites where southern hognose snakes have not been observed in recent years might have yielded additional observations that would affect current persistence estimates.

The relationship between persistence and HSI agreed with expert judgment about the habitat conditions that should favor southern hognose snake persistence. The relationship between number of populations within 10 km and persistence supported the importance of connectivity among populations. This may indicate the demographic importance of "rescue effects", where recolonization can occur after a catastrophe, or be an artifact of large core areas of high-quality habitat that support multiple populations or subpopulations over large geographic areas. The model did not support the idea that populations on protected lands should have a greater likelihood of

persistence). Representative unit did not appear to have a large effect on persistence probability (see Appendix A for additional details).
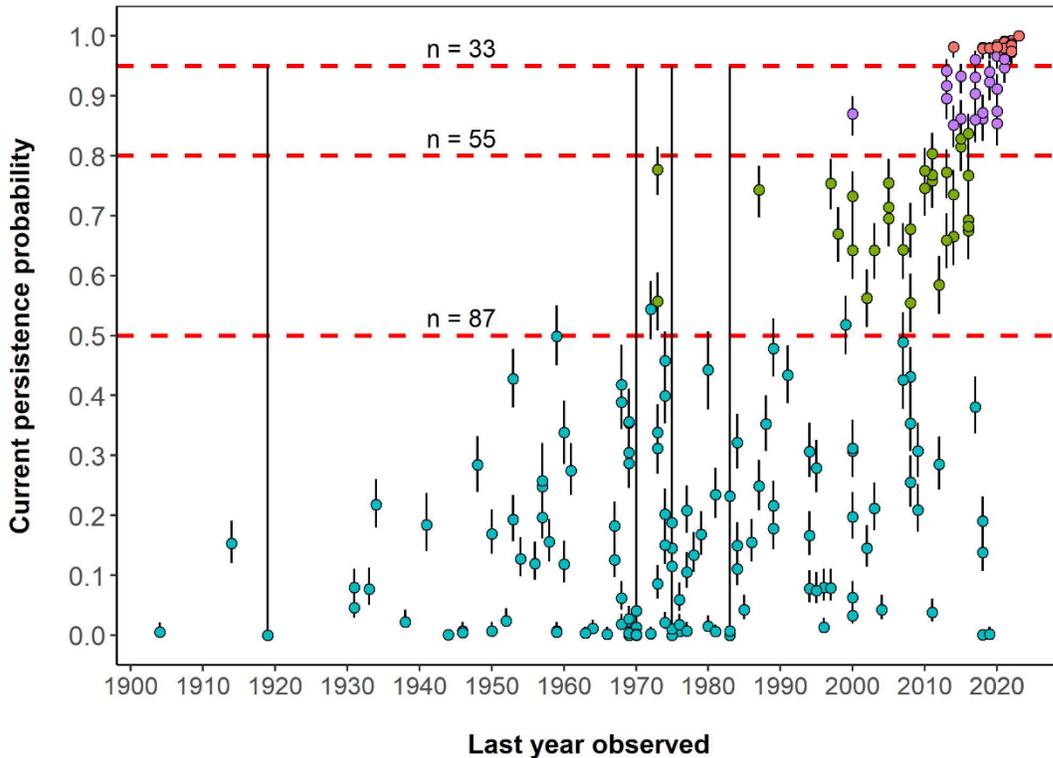
Figure 4-8. Probability of persistence in the current year (2023) for southern hognose snake populations (n = 213) related to the last year an individual was observed in a population. Blue points represent populations unlikely to be persisting on the landscape (i.e., do not have a 95% or greater probability of exceeding the 50% persistence probability threshold), and green, purple, and red points represent populations that have at least a 95% probability of exceeding the 50, 80, or 95% persistence probability thresholds, respectively. The 50, 80, and 95% thresholds are indicated with horizontal red dashed lines and n values indicate the total number of populations with lower 95% credible interval above each threshold.

To further define resiliency, we evaluated the suitable habitat and connectivity within each of the 87 extant populations. We identified suitable habitat within a population as average HSI scores >0.4, and unsuitable of average HSI scores <0.4. Twenty-seven (27) of the extant populations were located within suitable habitat. Of these 27 populations, 26 of them have at least 1 population within the 10 km threshold, and 24 of them have at least 2 populations.

Of the 87 currently extant populations only 26 of them are having their resources needs met in terms of suitable habitat and connectiveness to other populations at some level (Table 4-5). When we break this down further by current persistence probability, we can reasonably say that 17 populations or 7.3% are at the highest level of resiliency because they are resilient (adequate suitable habitat and connectivity) and have a high probability of persistence (≥80%), 9 have moderate resiliency due to being placed in the more likely category (50-79.9%) (Table 4-6; Figure 4-9). Sixty-one (61) of the extant populations or 26.2% are considered to have low resiliency due to either or both suitable habitat or connectivity not meeting the population needs.

Table 4-5. Number and percentage of southern hognose snake populations in each persistence category and the number of resilient populations has been added for each persistence probability.

Population persistence	Number of populations in each category	% of total	Cumulative number of populations at or above each threshold	% of total	Number of high and moderate Resilient Populations	% of total (% of extant)	Number of Low Resilient Populations	% of total (% of total extant)
Extremely Likely on Landscape 95-100%	33	14.2%	33	14.2%	13	5.6% (14.9%)	20	8.6% (22.9%)
Very Likely on Landscape 80-94.9%	22	9.4%	55	27.9%	4	1.7% (4.6%)	18	7.7% (20.7%)
More Likely than Not 50-79.9%	32	13.7%	87	37.3%	9	3.9% (10.3%)	23	9.9% (26.4%)
Unlikely < 50% (Extirpated)	144	61.8%	-	-	-	-	-	-
Unknown	2	0.9%	-	-	-	-		
Total	**233**	**100%**			**26**	**11.2%**	**61**	**26.2% (70.1%)**

Table 4-6. Southern hognose snake populations current resiliency category. Resiliency includes only extant populations. Percent of total historical populations includes all extirpated and extant populations. The percent of extant total includes only the currently extant populations.

Population status/resiliency	Number of populations in each category	% of total	% of extant total
High Resiliency	17	7.3%	19.5%
Moderate Resiliency	9	3.8%	10.3%
Low Resiliency	61	26.2%	70.1%
Extirpated	144	61.8%	0.0%
Unknown	2	0.9%	0.0%

Figure 4-9. Southern hognose snake current population resiliency for all populations. Populations in green (n=13) indicate those with the highest resiliency, moderate (n=4) in blue, and those that we that we consider to be extant but have low resiliency are in dark grey. Extirpated populations are hatched.

4.2.3 Current Species Representation and Redundancy

We summarized estimated current [as of 2023] representation and redundancy in the southern hognose snake by summarizing the number and spatial distribution of populations by reporting persistence probability thresholds and the number of resilient populations in each of the nine representative units across its range as well as the mean number of populations predicted to persist with 95% confidence intervals (Table 4-7; Figure 4-10). Additionally, we describe changes in representation and redundancy that have occurred over time by reporting the percentage of populations currently persisting (at or above a threshold) relative to the total number of populations ever documented in each unit (Table 4-7). We also further summarized the number of extant and extirpated populations and the number of resilient populations (high, moderate and low) in their representative unit (Table 4-8; Figure 4-11).

All southern hognose snake populations have likely become extirpated from the Alabama Central representative unit (Table 4-7). Additionally, each of the 7 historical populations in the West (AL/MS) unit were within the likely extirpated category but the mean number of populations predicted to persist was 1 [95%CI = 0 – 3], due to differences between separately classifying each population using the lower 95% credible interval verses collectively classifying all populations within each representative unit using a mean estimate. The Atlantic Coastal Plain (GA/FL) unit was predicted to have only 2 extant populations, with one of the populations having moderate resiliency and the other is considered low resiliency. Therefore, this unit is also at a higher risk of unit-wide extirpation and indicates the potential for further loss of representation. The southern hognose snake has likely experienced a decrease in latitudinal and longitudinal variability (i.e., a range contraction), relative to its historic range extent. Specifically, all populations in the western portion of its range – the West (AL/MS) unit, the Alabama portion of the Alabama/Florida Panhandle unit, and the Alabama Central unit – and in the northeastern edge of the range are more likely than not to be extirpated. Because the Alabama Central unit represents a distinct ecoregion (Ridge and Valley) and associated habitats not existing in any other unit, extirpation of the southern hognose snake from this unit has decreased the species' representation in terms of ecological variability.

There has been a reduction in redundancy for the southern hognose snake within each representative unit, highlighted by the loss of the western units and that only two representative units (Florida Ridge and Upper Coastal Plain (GA/FL)) had at least 50% of their total populations currently existing at a level of 50% probability of persistence. In other words, 7 of the 9 representative units have likely lost > 50% of their populations. Furthermore, all representative units have seen a reduction in the number of highly resilient populations, and many of those remaining populations exhibit a degree of spatial clustering within the unit (they tend to be clumped near each other), which has left portions of the unit no longer occupied. Range-wide redundancy for the southern hognose snake has been reduced from historical levels. The southern hognose snake has extant populations in 7 of the 9 representative units (Table 4-7).

Currently, 7 representative units have at least one population with moderate to high resiliency and 4 representative units have more than two populations with high resiliency (Upper Coastal Plan (GA/FL), FL Peninsula, FL Ridge, and AL/FL Panhandle). The Atl. Coastal Plain (Carolinas and GA/FL) are the two units that only have one (1) moderate resiliency population each. Within the occupied portion of the range, populations with moderate to high resiliency are spread throughout the range but exhibit a degree of clustering, which has left large areas lacking resilient populations (e.g., southern Alabama, middle Georgia, eastern Florida Peninsula, and northeastern end of the Coastal Plain). Below, we report results for each of the representative units relevant to representation and redundancy.

Table 4-7. Southern hognose snake summary statistics of number of occurrence records, number of populations (pops), mean persistence probability, number of populations at each current persistence probability threshold for all populations (n=233), and the number of resilient populations within representative units. Number in parentheses represents the number of resilient populations for the extant populations (>50% probability of persistence).

Representative unit	No. of records	No. of pops total	Mean (±95% CIs) no. of pops predicted to persist	Unk.	Unlikely <50% (Extirpated)	More Likely than Not ≥ 50%	Very Likely on Landscape ≥ 80%	Extremely Likely on Landscape (Extant) ≥ 95%	Number of Resilient Populations
						No. of pops at each persistence threshold			
Upper Coastal Plain (Carolinas)	1651	33	12 (7, 18)	1	23	4	1	4 (1)	1
Upper Coastal Plain (GA/FL)	384	61	37 (26, 50)	1	23	16 (2)	12 (3)	9 (4)	9
Atl. Coastal Plain (Carolinas)	194	39	12 (8, 17)	0	30	2 (1)	1	6	1
Atl. Coastal Plain (GA/FL)	36	14	2 (0, 6)	0	12	1 (1)	1	0	1
FL Peninsula	117	33	13 (10, 17)	0	20	5 (2)	4 (1)	4 (3)	6
FL Ridge	187	16	10 (8, 12)	0	7	0	2	7 (2)	2
AL/FL Panhandle	62	26	9 (5, 13)	0	18	4 (3)	1	3 (3)	6
West (AL/MS)	18	7	1 (0, 3)	0	7	0	0	0	0
AL Central	13	4	0 (0, 0)	0	4	0	0	0	0
Range-wide	2262	233	89 (74, 107)	2	144	32 (9)	22 (4)	33 (13)	26

Table 4-8. Number of southern hognose snake populations considered extant (>50% probability of persistence) and extirpated (<50% probability of persistence) for all populations (n=233) with the representative units. The number of resilient populations (high, moderate, and low) has been added for each persistence probability.

Representative unit	Extirpated Population	Extant Populations	Low Resiliency Populations	Moderate Resiliency Populations	High Resiliency Populations
Upper Coastal Plain (Carolinas)	23	9	8	0	1
Upper Coastal Plain (GA/FL)	23	37	28	2	7
Atl. Coastal Plain (Carolinas)	30	9	8	1	0
Atl. Coastal Plain (GA/FL)	12	2	1	1	0
FL Peninsula	20	13	7	2	4
FL Ridge	7	9	7	0	2
AL/FL Panhandle	18	8	2	3	3
West (AL/MS)	7	0	0	0	0
AL Central	4	0	0	0	0
Range-wide	144	87	61	9	17
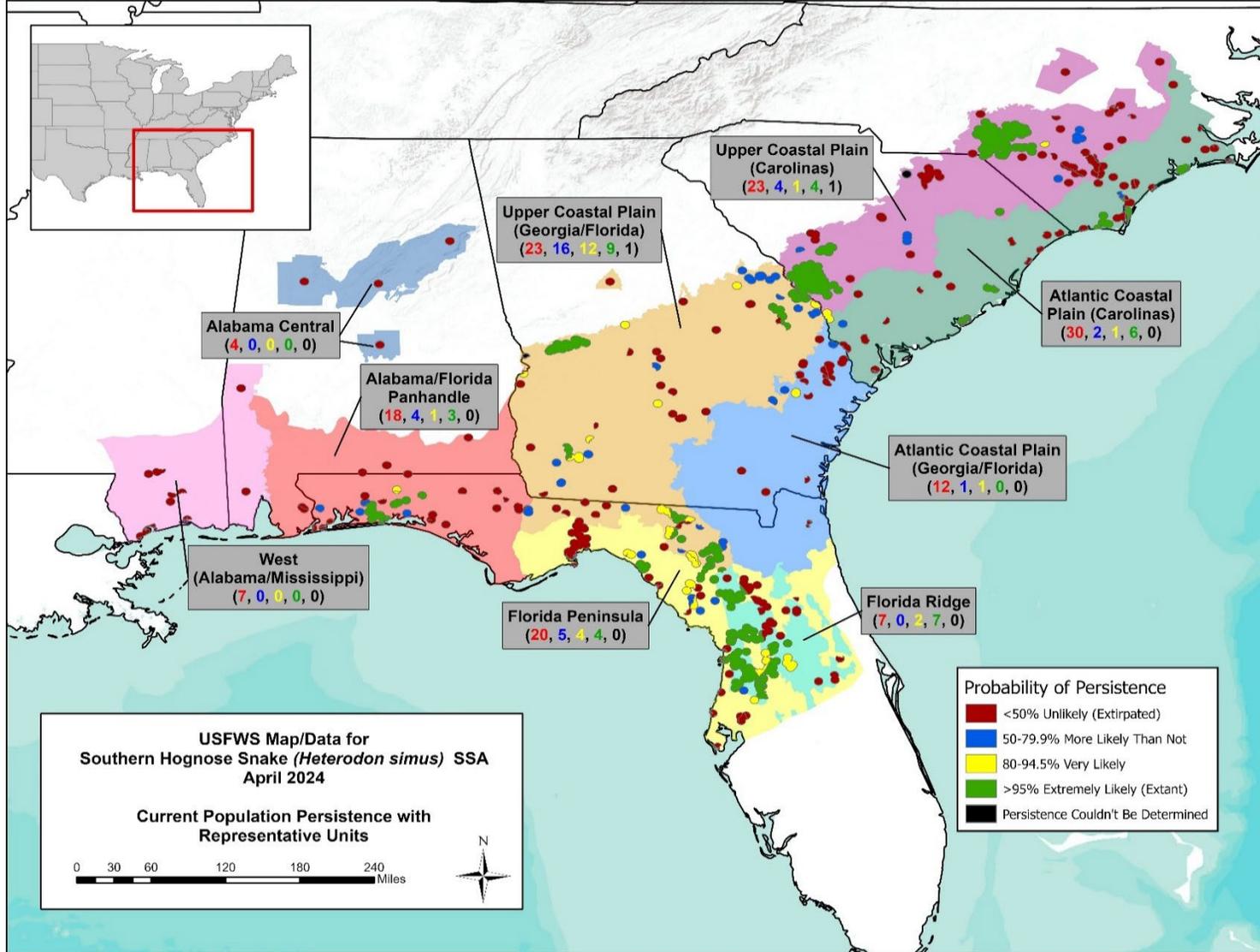
Figure 4-10. Southern hognose snake populations across representative units based on current persistence probability. Green populations are extremely likely to currently occur on the landscape or be extant; yellow populations are very likely; blue more likely than not; red populations are unlikely to currently exist (i.e., considered extirpated), and black are populations where persistence could not be estimated.
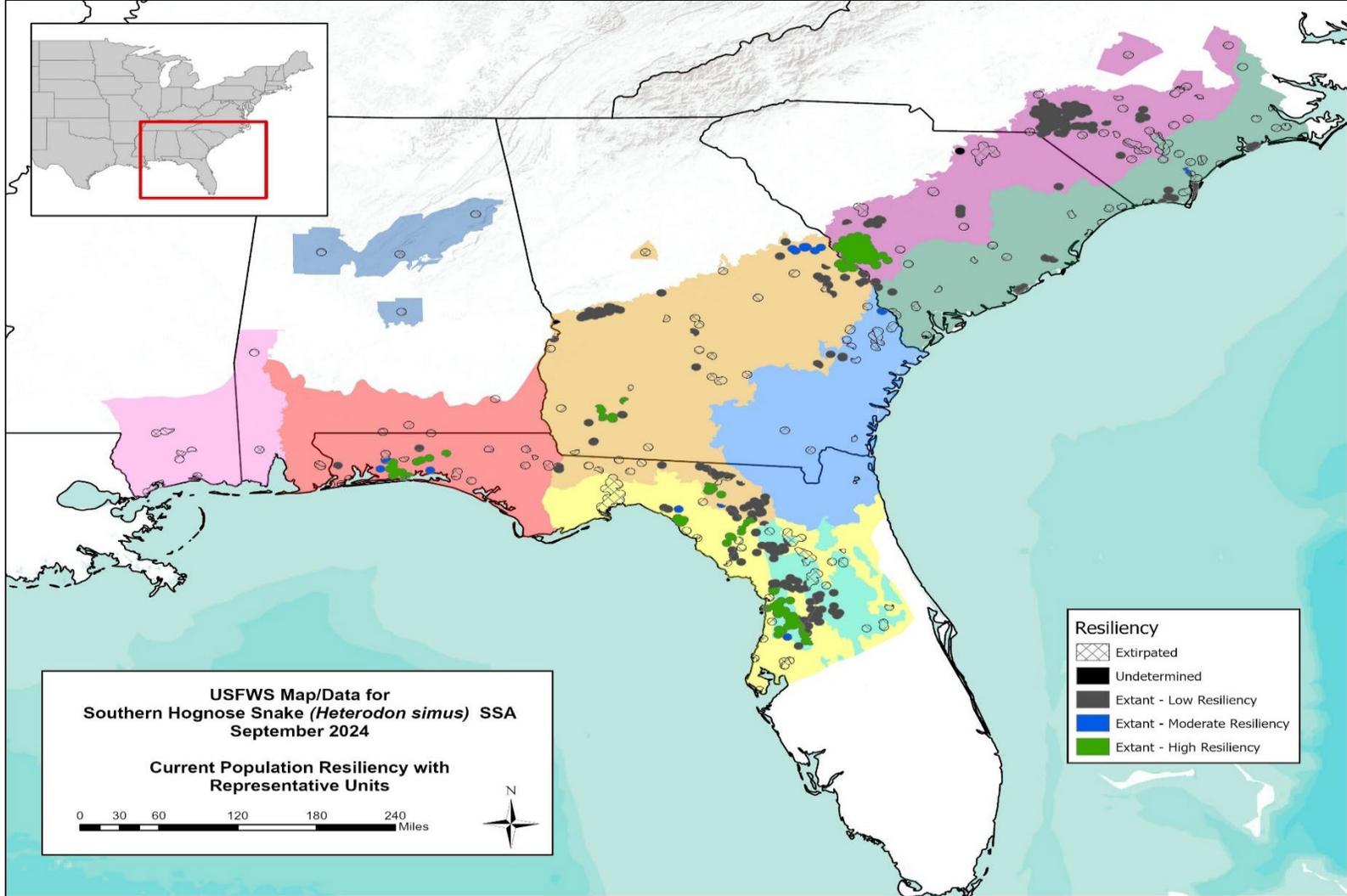
Figure 4-11. Current population resiliency for all the populations and their representative unit. Populations in green (n=13) indicate those with the highest resiliency, moderate (n=4) in blue, and those that we that we consider to be extant but have low resiliency are in dark grey. Extirpated populations are hatched.
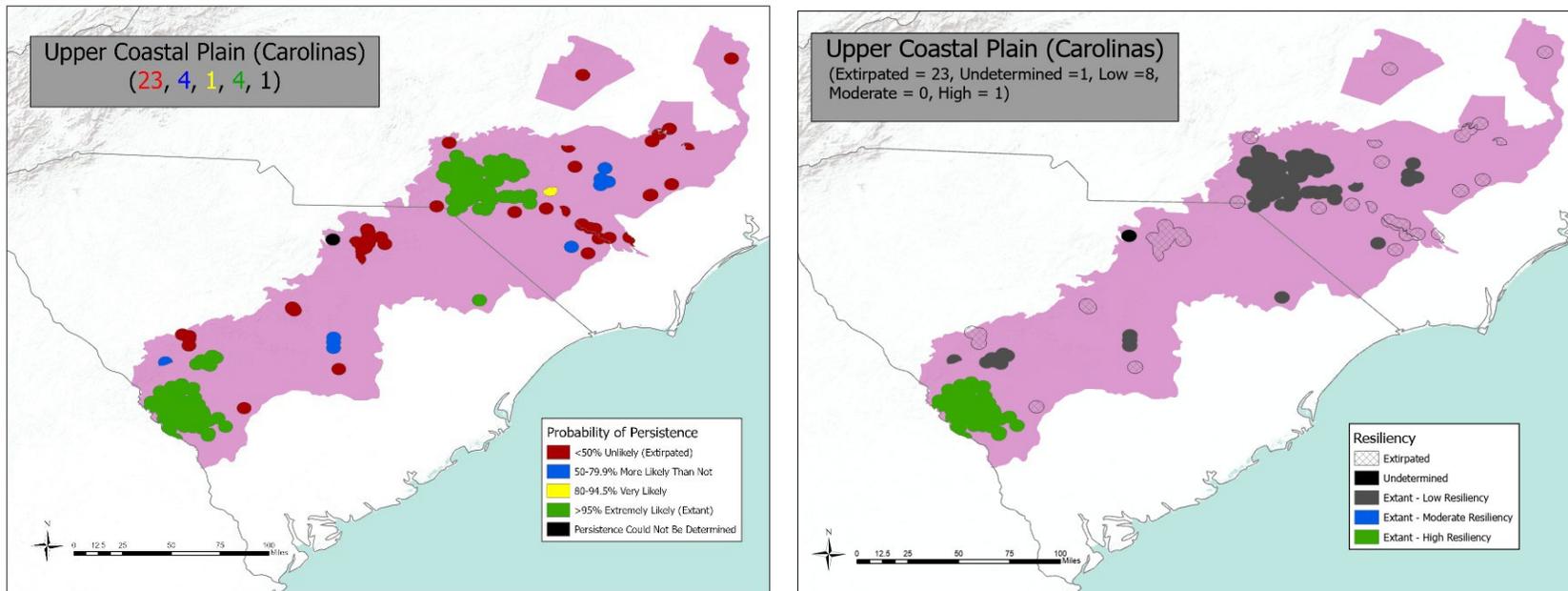
Figure 4-12. Populations of southern hognose snakes by category of current persistence probability (left) and by resiliency (right) in the Upper Coastal Plain (Carolinas) representative unit.

Upper Coastal Plain (Carolinas)

This unit only has 4 populations that are extremely likely on the landscape (≥95%) and of these four, two of these populations cover the largest area and consist of the highest number of records relative to other populations across the range of the southern hognose snake. However, only one of these two large populations appears to have high resiliency. Snakes continue to be commonly observed in low resiliency populations however, our analysis indicates that needs of the species are no longer being met. There appears to be a range contraction in the northeastern portion of this unit, as most populations in that area are likely extirpated (<50% probability of persistence). This representative unit has likely lost 23 of its 33 populations.
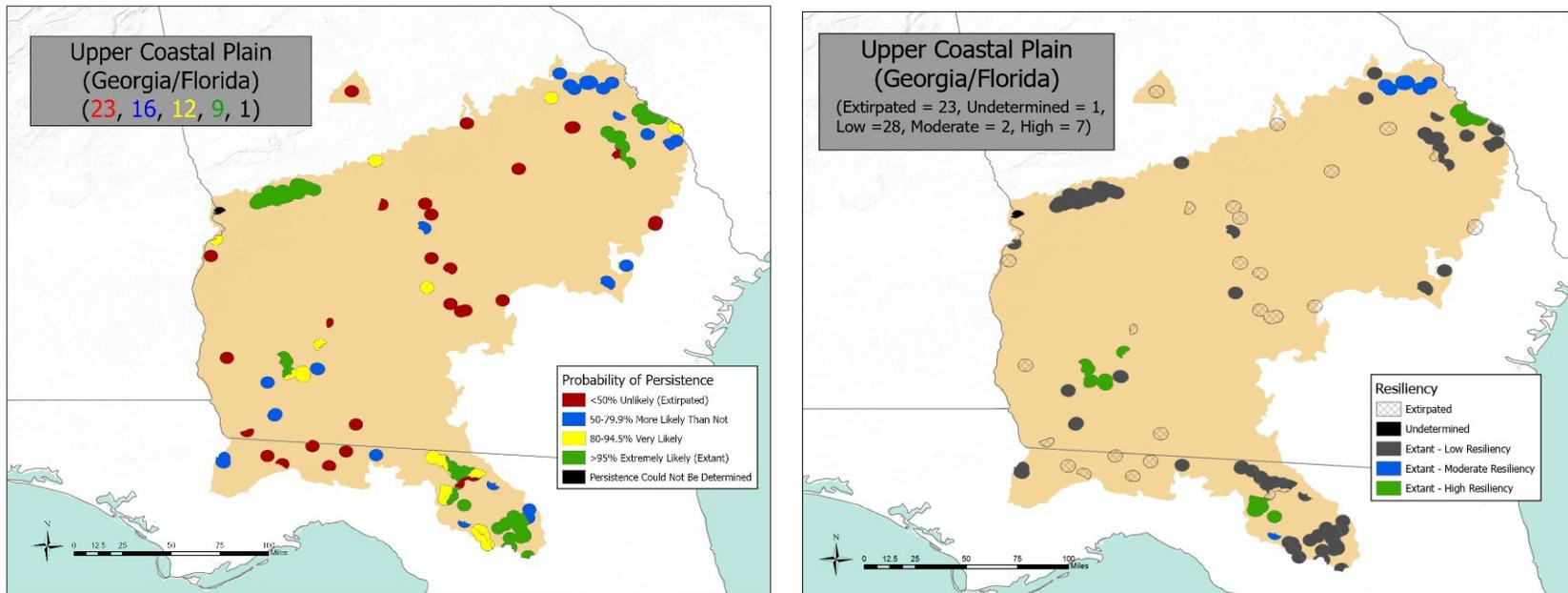
Figure 4-13. Populations of southern hognose snakes by category of current persistence probability(left) and by resiliency (right) in the Upper Coastal Plain (GA/FL) representative unit.

Upper Coastal Plain (GA/FL)

The Upper Coastal Plain (GA/FL) unit has the most populations (61) delineated, although the total number of records is relatively low (384) compared to the Upper Coastal Plain (Carolinas) unit. There are currently 37 extant populations. Out of all units, this unit has the highest number of populations (9) that are extremely likely to be persisting (≥95%). This unit has 7 populations that are highly resilient and 2 that are moderate resilient, while the remaining (28) extant populations are considered to have low resiliency. Resilient populations are mainly clustered at the periphery of the unit, leaving the central portion devoid of highly resilient populations. This representative unit has likely lost 23 of its 61 populations.
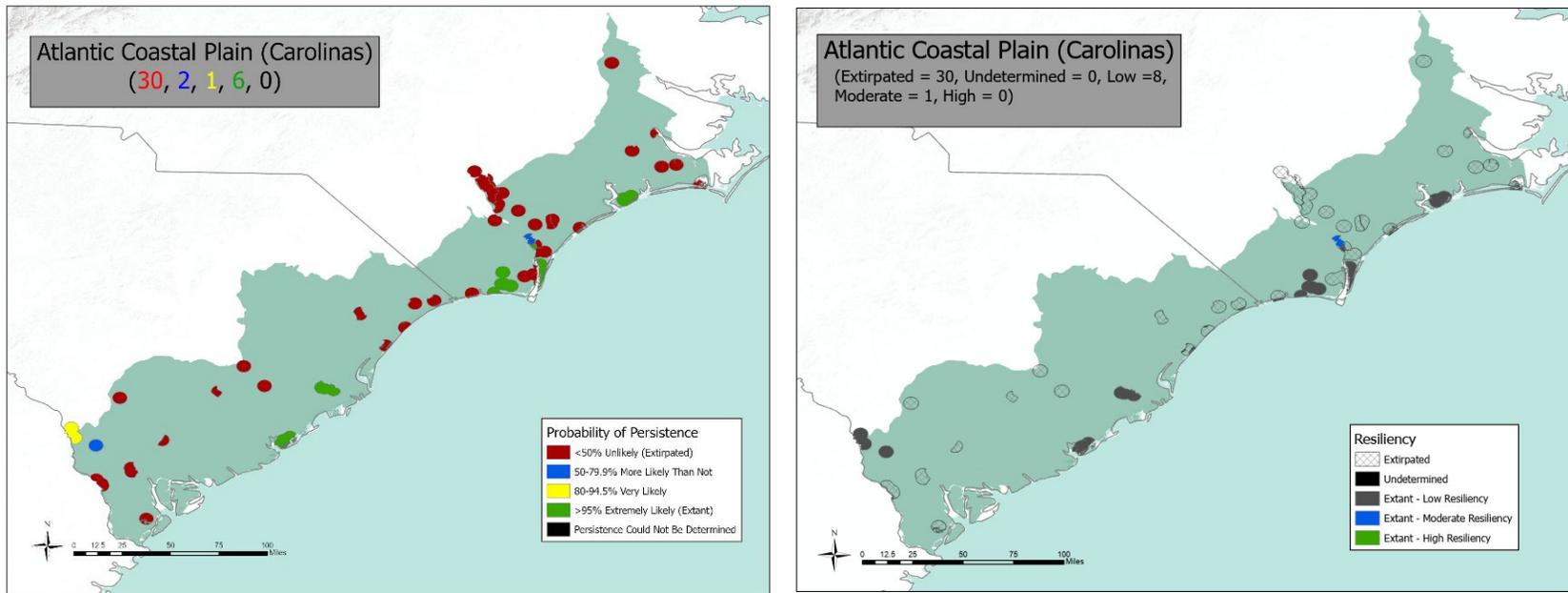
Figure 4-14. Populations of southern hognose snakes by category of current persistence probability (left) and by resiliency (right) the Atlantic Coastal Plain (Carolinas) representative unit.

Atlantic Coastal Plain (Carolinas)

This unit has 9 extant populations and of these 6 populations that are extremely likely to be persisting (>95%), however, all of these populations in the highest population persistence category have low resiliency. This unit only has 1 population with moderate resiliency and no populations with high resiliency. Extant populations are mainly located along the coast, making them more susceptible to habitat loss from future SLR. There appears to be a range contraction in the northeastern portion of this unit, as most populations in that area are likely extirpated (<50%). Out of all units, this unit has likely lost the highest number of populations, 30 of its 39 populations.
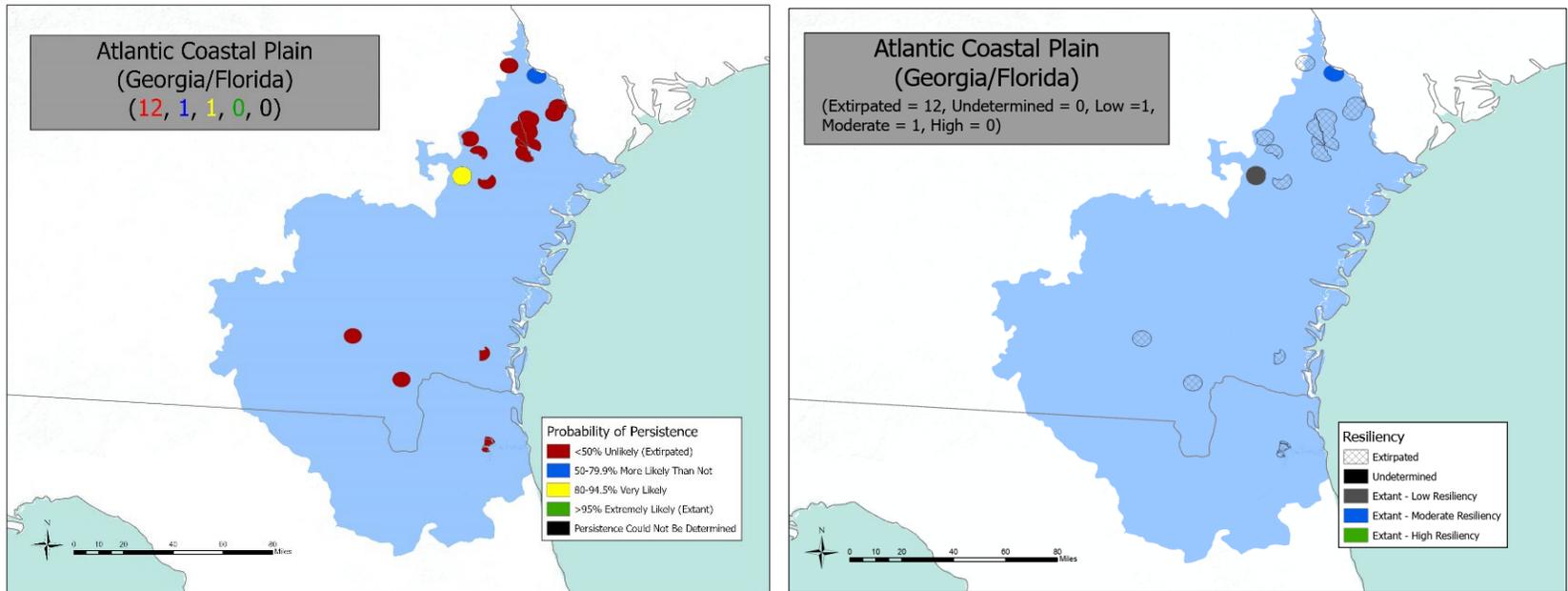
Figure 4-15. Populations of southern hognose snakes by category of current persistence probability (left) and by resiliency (right) in the Atlantic Coastal Plain (GA/FL) representative unit.

Atlantic Coastal Plain (GA/FL)

Other than the West and Alabama Central units, the Atlantic Coastal Plain (GA/FL) unit has the lowest number of resilient populations. This unit has seen an extreme reduction in redundancy, as there are no populations that are extremely likely to be persisting (>95%) and thus have no populations with high resiliency, only one population that is very likely to be persisting (>80%), which also has moderate resiliency, and only one additional population that is more likely than not to be persisting (>50%), which is considered to have low resiliency. Both of the extant populations are clustered in the northern portion of the unit, leaving a significant gap within the unit, and when combined with the loss of distribution in the Upper Coastal units, a significant range-wide gap. This representative unit has likely lost 12 of its 14 populations.
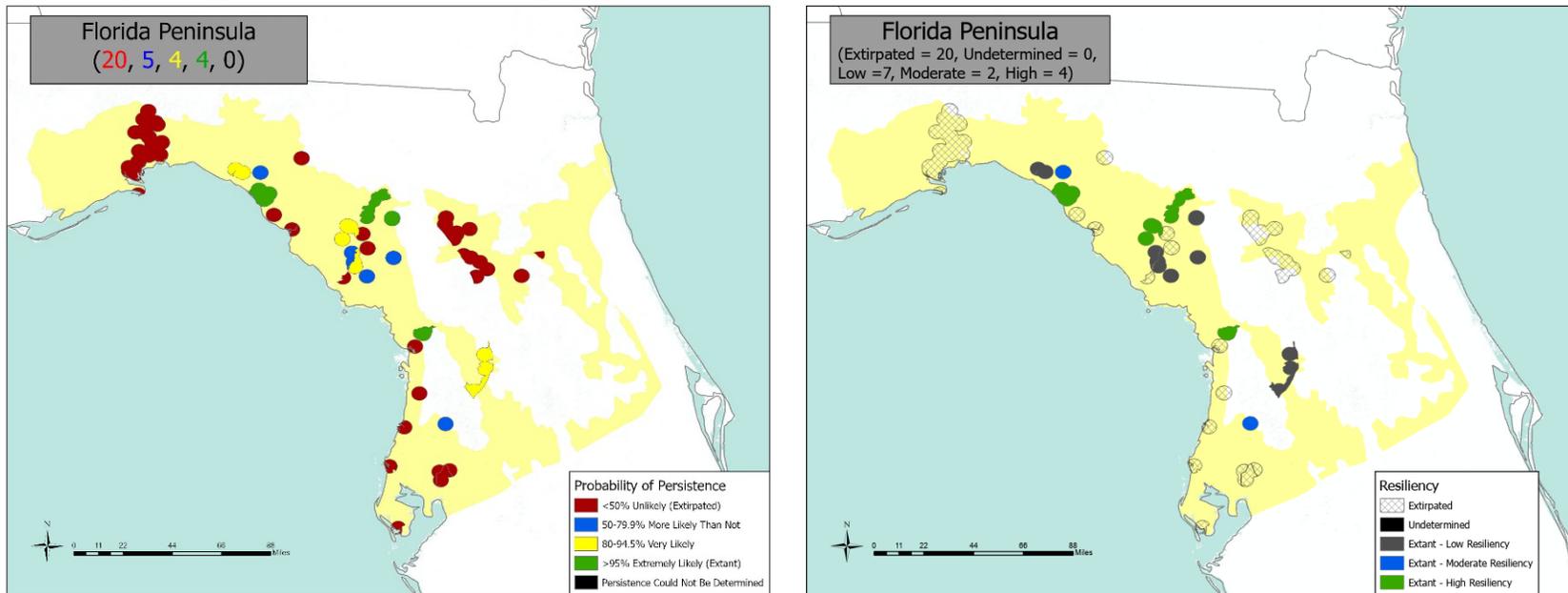
Figure 4-16. Populations of southern hognose snakes by category of current persistence probability (left) and by resiliency (right) in the Florida Peninsula representative unit.

Florida Peninsula

This unit has 4 populations that are extremely likely to be persisting (>95%) and all these populations have high resiliency. There are 2 populations with moderate resiliency, while the remaining populations are considered to have low resiliency. All extant populations are distributed throughout the western portion of the unit, with no populations likely remaining in the eastern portion of the unit. This representative unit has likely lost 20 of its 33 populations.
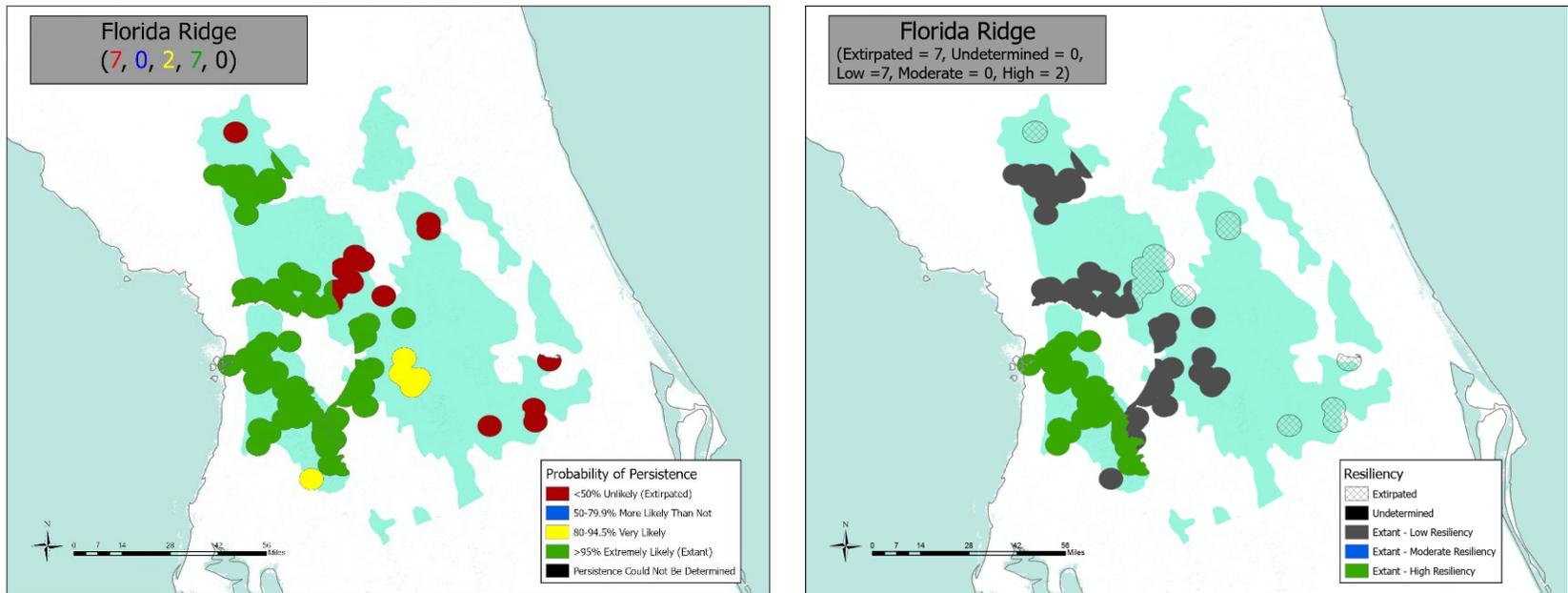
Figure 4-17. Populations of southern hognose snakes by category of current persistence probability (left) and by resiliency (right) in the Florida Ridge representative unit.

Florida Ridge

This unit has 9 extant populations, with 7 populations that are extremely likely to be persisting (>95%), however, only 2 of these populations with high persistence have high resiliency as well. Similar to the Florida Peninsula unit, the resilient populations in this unit are distributed throughout the western portion, with no populations likely remaining in the eastern portion. This representative unit has likely lost 7 of its 15 populations.
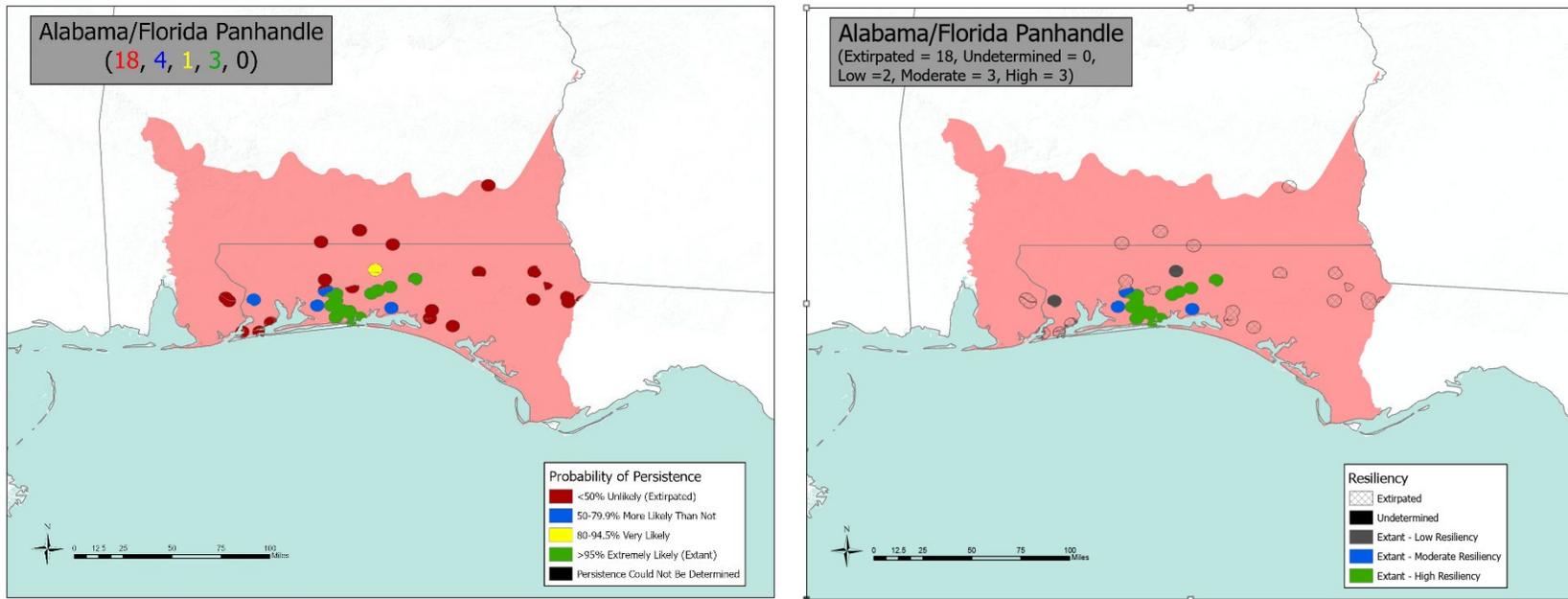
Figure 4-18. Populations of southern hognose snakes by category of current persistence probability (left) and by resiliency (right) in the AL/FL Panhandle representative unit.

Alabama/Florida Panhandle

This unit has 3 populations that are extremely likely to be persisting (>95%), all of which are also considered to have high resiliency, and all clustered along the coast. Two of these resilient coastal populations are found on Eglin Air Force Base, an area that has the highest predicted habitat suitability found within the range of the southern hognose snake. There has been a significant range contraction within this unit, exemplified by the fact that there are no populations in Alabama that are likely to be persisting. This representative unit has likely lost 18 of its 26 populations.
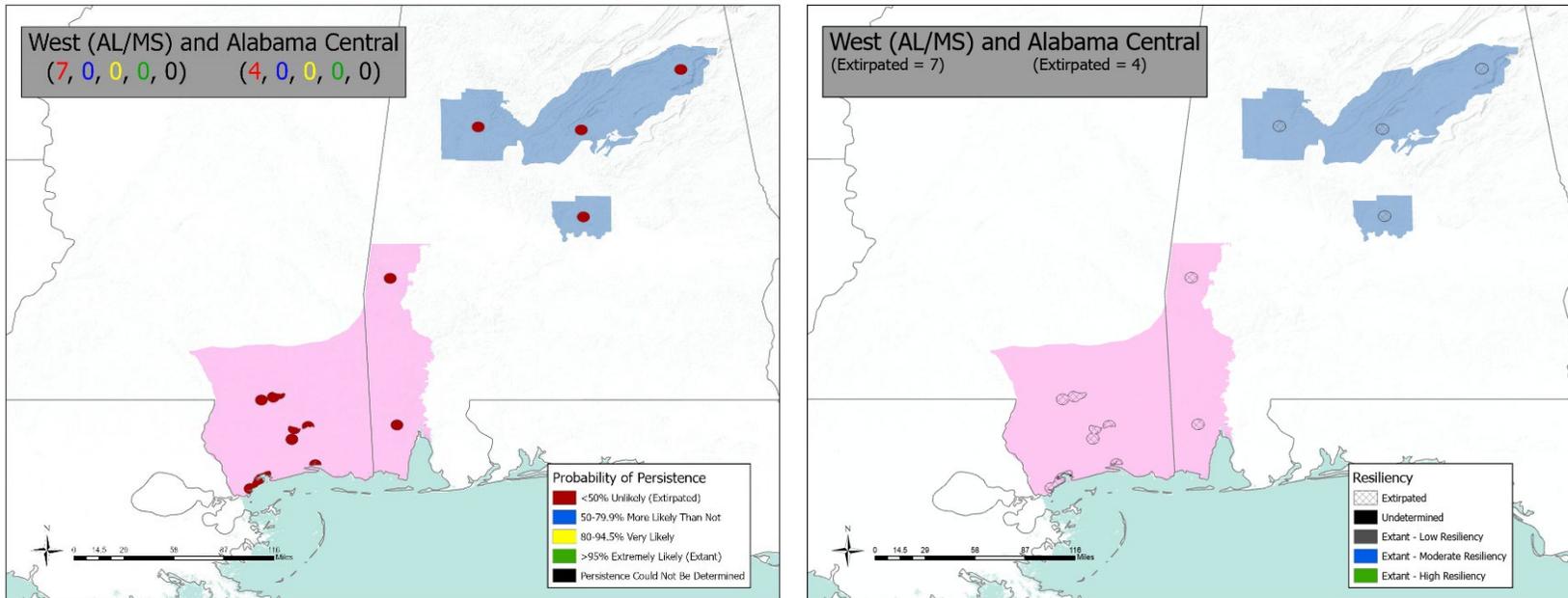
Figure 4-19. Populations of southern hognose snakes by category of current persistence probability (left) and resiliency (right) in the West (AL/MS) and Alabama Central representative units.

West (AL/MS) and Alabama Central Units

These units currently have zero populations with a probability of current persistence greater than 50%. In fact, the last detection of the southern hognose snake was in 1981 in the West unit, and 1968 in the Alabama Central unit. It is very likely that neither of these representative units are occupied, and thus represent a significant reduction in the western extent of the species' range.

4.3 Summary of Current Conditions

Current resiliency, for the southern hognose snake has decreased from historical conditions. We considered a population to have high resiliency if it had a relatively high current persistence probability, occurs on suitable habitat, and has connectivity to another extant population. The southern hognose snake has 87 currently extant populations. Of these extant populations, 17 populations (19.5%) exhibit high resiliency, while 9 population (10.3%) have moderate resiliency, and 61 (70.1%) have low resiliency. The species has likely experienced a loss of 144 (61.8%) of its total populations.

Current representation, as measured by the number and distribution of resilient populations across representative units in the species' range has also decreased from historical conditions. To have high representation the species must have moderate to high resiliency populations located in each of the representative units, and those occupied units should span the latitudinal and longitudinal extent of historical populations. The southern hognose snake has experienced a complete loss of two representative units, one additional representative unit is at risk of becoming extirpated, and all the remaining units are showing declines in the number of resilient populations. There has been a loss of latitudinal and longitudinal variability within the range as all of the populations at the northeastern and western extent of its range have been extirpated. Coupled with the range contraction and loss of populations, the species has lost some adaptive capacity compared to historical conditions, and therefore has low to moderate representation.

Current redundancy, as measured by using the current number and distribution of resilient populations within representative units and across the range of the species has been reduced from historical conditions. To have high redundancy the species needs to have multiple moderate to high resiliency populations within representative units and throughout its range. Each of the 9 representative units has likely lost at least 37.7% –100% of its populations. Range-wide, the number of populations has decreased by 61.8%, relative to the historical number of populations. The southern hognose snake has experienced a decline in the number of resilient populations within each of the representative units and across its entire range. However, the species has extant populations in 7 of the 9 representative units and all 7 of these units have at least one population with moderate to high resiliency and 4 representative units have more than two populations with high resiliency. The distribution of resilient populations within each representative unit has become clustered, leaving portions of each representative unit with a reduced distribution of populations and a loss of connectivity. Therefore, the species currently has a lower redundancy than historical conditions, and the species may be more vulnerable to the effects of catastrophic events, such as drought, wildfire, disease outbreak.

CHAPTER 5 – FUTURE CONDITIONS AND VIABILITY

In the previous chapters, we have considered the southern hognose snake's ecological needs, factors influencing viability, and the current condition of the species. We now consider what the species' future condition is likely to be. We apply our future scenarios to the concepts of resiliency, representation, and redundancy to describe the future viability of the southern hognose snake by considering plausible scenarios and the species' response to those conditions.

5.1 Methods for Estimating Future Condition

In evaluating future conditions for the southern hognose snake, we considered several stressors that may influence future viability of the species and developed six plausible scenarios representing the potential effects of these stressors. We performed spatial analyses to predict changes in land cover and fire frequency under various levels of urbanization, SLR, and climate change induced changes to the burn windows that dictate opportunities for prescribed fire. Then, using the model framework developed for the current condition analysis described in Chapter 4, we created a stochastic simulation model that allowed us to project population persistence into the future as influenced by changes in habitat suitability (Figure 5-1), and summarized predicted patterns of population persistence to the years 2040, 2060, and 2080.
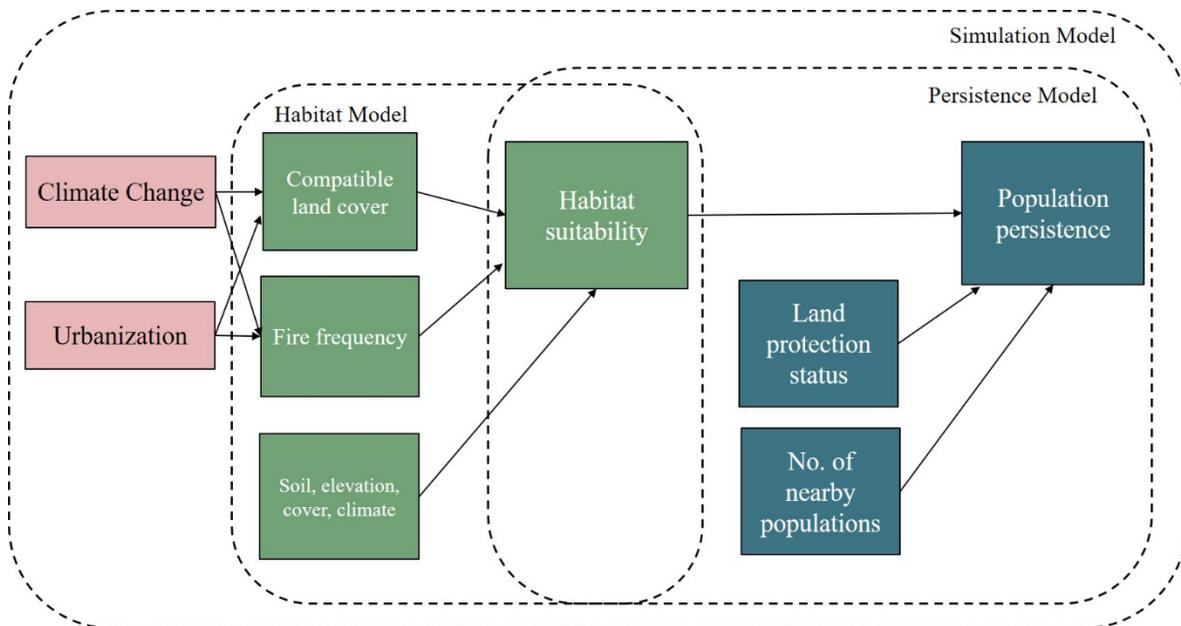
Figure 5-1. Conceptual model linking components included in the habitat suitability model (green), current persistence model (blue), and impacts of stressors (pink) in the simulation model for future conditions of the southern hognose snake.

How does the simulation model work? The simulation model took each southern hognose snake population's probability of persistence at the present (2023) and predicted the probability it will persist or become extirpated in the future, given varying levels of stressors that were captured in six different scenarios. Specifically, we selected the level of future urbanization and climate change associated with each scenario. Next, we modeled the effects of these conditions on the amount of compatible land cover and fire frequency within each population's boundary. We then calculated future habitat suitability based on these changing conditions. Finally, we used the persistence model described in Chapter 4 to estimate the probability each population would persist from one year to the next, through the year 2080, given changes in habitat suitability. We would expect populations that retain high levels of habitat suitability to have higher probabilities of persisting in the future; conversely, we would expect populations experiencing reductions in habitat suitability due to stressors to have lower future persistence probabilities.

We ran the model 10,000 times per scenario. In each run, the model estimated each population's probability of persisting one year to the next, based on changing conditions, and used that probability to randomly draw an outcome for each population in the next year. We can think of this as a coin flip determining whether a population persists or becomes extirpated. Because of this randomness (stochasticity), predictions varied between model runs.

We calculated each population's future persistence probability as the proportion of model runs where the population was still persisting each year through 2080. Additionally, we summed the number of populations still persisting each year within each representative unit and range-wide in each model run, and we used these to calculate the mean number of populations persisting at these scales in the future.

5.1.1 Stressors and Effects on Habitat Conditions

To predict future conditions, we selected stressors that were identified as factors influencing viability (Chapter 3; Figure 3-6) we anticipate will have an impact on southern hognose snake populations in the future, and for which we could reasonably access needed covariate projections that could be integrated into the persistence model. We selected urbanization, SLR, and predicted changes to fire frequency due to climate change as the stressors we could model through predicted effects on land cover and associated habitat suitability model (Section 4.1.1; Crawford et al., 2020a, entire). Changes in habitat suitability ultimately influenced population persistence, as predicted by the stochastic simulation model (Section 5.1.3; Figure 5-1; Appendix A). There are other stressors potentially affecting southern hognose snake populations that will continue into the future, but the availability of data and our understanding of these stressors' effects precluded their integration into the future persistence model. Below we describe the data sources we used for capturing stressors and spatial analysis methods used in ArcGIS to model the effects of stressors on habitat conditions.

We captured the extent and rate of urbanization using the FUTure Urban-Regional Environment Simulation (FUTURES) model (Meentemeyer et al., 2013, entire). Specifically, we used the probabilistic projections of urbanization by decade from FUTURES version 2.0 (Petrasova et al., 2023, unpaginated). These projections provide probabilities of new development ranging from 0-1, with higher values indicating areas more likely to be developed. The model specifies a 0% probability of urbanization for areas protected from development (e.g., conservation areas); however, some state conservation lands were omitted. Therefore, we set the probability of urbanization to 0 for any cell that overlapped our raster of currently protected areas. We used FUTURES projections from 2040, 2060, and 2080, and interpolated the annual extent of urbanization between those periods. We modeled the effect of habitat loss from urbanization by a given year by removing any area currently classified as compatible land cover that overlapped areas likely to be urbanized above a certain probability threshold (see scenario descriptions in Section 5.1.2). We then recalculated the proportion of compatible land cover for each population that subsequently affected overall habitat suitability.

The climate change projections used in this SSA report are based on Representative Concentration Pathway (RCP) scenarios. The RCPs are the current set of scenarios used for generating projections of climate change. We used climate change projections based on RCP 4.5 and RCP 8.5, the "medium-low" and "highest" scenarios, respectively. We captured potential habitat loss due to inundation from SLR. We obtained projections of SLR associated with RCPs from the Sixth IPCC Assessment Report (IPCC 2021, pp. 21–23) and used SLR inundation maps from the National Oceanic and Atmospheric Administration (NOAA, 2023, unpaginated). For each projected height of SLR associated with 2040, 2060, and 2080, we created a raster of inundated areas. Similar to modeling urbanization, we linearly interpolated the annual extent of inundation due to SLR between periods. We reduced the amount of compatible land cover for populations if currently compatible land cover was predicted to be inundated by SLR, given a certain inundation level and year.

We also wanted to capture the effects of urbanization on fire frequency to account for fire exclusion/suppression that often occurs in areas adjacent to developed lands. Studies have found evidence of fire exclusion/suppression in habitats within 600 m to 5 km (0.4 to 3.1 miles) of urban areas (Theobald & Romme, 2007, entire; Pickens et al., 2017, p. 105). Therefore, we chose a moderate value of 3.2 km (2 miles) to capture the interaction between urbanization and fire frequency. Using the predicted urbanized areas at each time period and urbanization probability level, we identified areas within 3.2 km of urban boundaries. We then projected future reductions in fire frequency by applying a distance-weighted reduction to any cell within 3.2 km of urban areas. Using this approach, fire frequency for any cell overlapping future urban areas was reduced by 100% (equaled 0) and any cell more than 3.2 km away from urban areas was reduced by 0% (unchanged). Any cell between 0 and 3.2 km away from urban areas was reduced by a percentage proportional to its distance; for example, a cell 1.6 km (1 mile) from an urban area was reduced by 50%. We recalculated the mean fire frequency for each population,

which subsequently affected overall habitat suitability. To account for changes in fire frequency from climate change, we used U.S. Geological Survey historical and future prescribed burn windows for the Southeast United States (Kupfer et al. 2021, unpaginated). This dataset included observed mean proportion of days with suitable weather conditions for burning by month for the periods of 2000-2009 and 2010-2017 and future projections of decadal mean proportions of days suitable for burning by season. To correspond with the fire frequency predictor used in our model of habitat suitability, which used annual fire detections from 2001-2016, for each cell we calculated an annual weighted average of the historical 2000-2009 and 2010-2017 data and weighted monthly data according to number of days per month. For future burn windows, we used data for each decade leading up to 2040, 2060, and 2080, and for each cell we calculated the decadal averages across seasons weighted by number of days per season. We calculated population means for each burn window data set and used the population averages to calculate proportional changes in fire windows for 2040, 2060, and 2080. We assumed that these would result in the same proportional changes in fire frequency and reduced each population's mean fire frequency accordingly, which subsequently affected overall habitat suitability.

5.1.2 Scenario development

We developed six plausible scenarios to simulate future conditions (Table 5-1). In each of the scenarios we varied the levels of urbanization and used two different RCPs for climate change. For all the scenarios we assumed management for the species would remain at the current status quo. For status quo management we assumed: (1) the amount of protected area for each population will remain constant through time (e.g., protected land will not be sold or urbanized); (2) compatible land cover will not increase; and (3) fire frequency will only change with urbanization and climate change as described in section 5.1.1 (e.g., managers will not increase prescribed fire).

Table 5-1. List of scenarios used to predict future conditions for the southern hognose snake, showing levels of urbanization and climate change RCP.

Scenario
Low Urbanization/RCP 4.5
Low Urbanization/RCP 8.5
Medium Urbanization/RCP 4.5
Medium Urbanization/RCP 8.5
High Urbanization/RCP 4.5
High Urbanization/RCP 8.5

For the scenarios, when analyzing a low rate of urbanization, we selected areas with a greater than 90% probability of being urbanized (only areas with high certainty of development), for a medium rate of urbanization we selected areas with a greater than 50% probability of being urbanized, and for a high rate of urbanization we selected areas with a greater than 10% probability of being urbanized (includes areas with a low probability of development). Where we used RCP 4.5, we used a SLR of 1 foot (ft) at years 2040 and 2060 and a SLR of 2 ft at year 2080. For RCP 8.5, we used a SLR of 1 ft at years 2040 and 2060 and a SLR of 3 ft at year 2080. Burn window reductions were also assessed for both an RCP 4.5 and RCP of 8.5.

5.1.3 Stochastic simulation model

To predict the probability of persistence for each population in the future, we developed a stochastic simulation model that was based on the current probability of persistence and future predicted changes in habitat suitability and land protection (introduced in Box above; Figure 5-1).

We built a multi-loop simulation model (McGowan et al., 2014, entire) that allowed us to simulate thousands of replicates of each population under the six different scenarios. This approach accounted for random year-to-year stochasticity as well as uncertainty around rates (i.e., annual persistence probability) estimated from the current persistence model. The model looped through 10,000 iterations for each of the scenarios. In each iteration, it looped through each of the 213 southern hognose snake populations within the analysis area and simulated persistence from the present (2023) to 2080.

The core of the simulation model was the persistence model used to estimate current conditions (see 4.1.3). For each population, the model selected its probability of currently persisting and randomly simulated it persisting or becoming extirpated in the next year (2024). From 2025 to 2080, the probability a population persisted from one year to the next was a function of its habitat suitability, proportion of land protected, and number of nearby populations, given the conditions of each scenario. For each year in a model iteration, it selected the annual values of land cover and fire frequency that were influenced by rates of urbanization and climate change. It then used these conditions, along with all other predictors used in the habitat suitability model (e.g., soil drainage, local elevation) that did not change in any scenario, to calculate mean habitat suitability for each population and year. Finally, it used the new values of a population's habitat suitability, along with the proportion of protected land and number of nearby populations, to estimate the probability a population persists each year in the future through 2080.

For this model, the primary output was the probability a population persists at a given year in the future through 2080, which we call "future persistence probability." We calculated the future persistence probability for each population as the proportion of model iterations where the population was persisting at a given year. The complement of future persistence probability can be interpreted as the probability a population has become extirpated by a given year. These

future persistence probabilities for populations are directly comparable to the current persistence probabilities estimated in Chapter 4. We characterized future conditions similarly to current conditions by summarizing the number of populations at or above certain persistence probability thresholds (50, 80, and 95%) in each representative unit and range-wide, given each of the six scenarios. Like in the current conditions analysis, in addition to a specific population's persistence probability, each model iteration recorded the number of populations persisting at each time step in each representative unit and range-wide. We used all model iterations to calculate the mean (the most likely prediction) and 95% confidence intervals for the number of persisting populations, in each representative unit and range-wide, each year. Like results for current conditions, for a population to be classified in the more than likely, very likely, or extremely likely categories, the lower 95% credible interval of the estimated future persistence probability had to be equal to or greater than 50%, 80%, or 95% respectively. We summarized these outputs for three future time horizons: 2040, 2060, and 2080. For more details on methods used in the future conditions analysis, see Appendix A. Importantly, a feature of this model is that it does not have any processes for colonization or recolonization. Therefore, persistence probabilities are invariably going to be <1 for each population, this means that it is inevitable that the model will predict some loss of populations over time. To address this inherent feature of the model, we also ran the model forward to 2040, 2060, and 2080 assuming no changes in urbanization or climate and SLR. This creates a null expectation for model projected population losses against which we could compare the models with projected changes in urbanization, climate, and SLR. In our results we refer to this as the null model.

5.2 Future Condition Results

5.2.1 Summary of analysis

Changes in habitat conditions used to predict future persistence varied slightly between scenarios (Table 5-2). Projected high urbanization and RCP 8.5 SLR across the Southeast for the year 2080 is shown in Figure 5-2. Under current conditions, the average population had compatible land cover of 50% (range = 9 – 92%), which decreased between 5.6% (Low Urbanization/RCP 4.5, which would be considered a best case) and 7.1% (High Urbanization/RCP 8.5, which would be considered a worst case) on average across all scenarios (Table 5-2). In terms of area, the average population had 77.5 km^2 (range = 1.5 – 1202.7 km^2) of compatible land cover under current conditions, which was reduced by 8.3 – 10.3 km^2 on average across future scenarios (Table 5-2). While some populations experienced no loss of land cover, others were predicted to lose as much as 60.8% of compatible land cover due to urbanization and climate change.
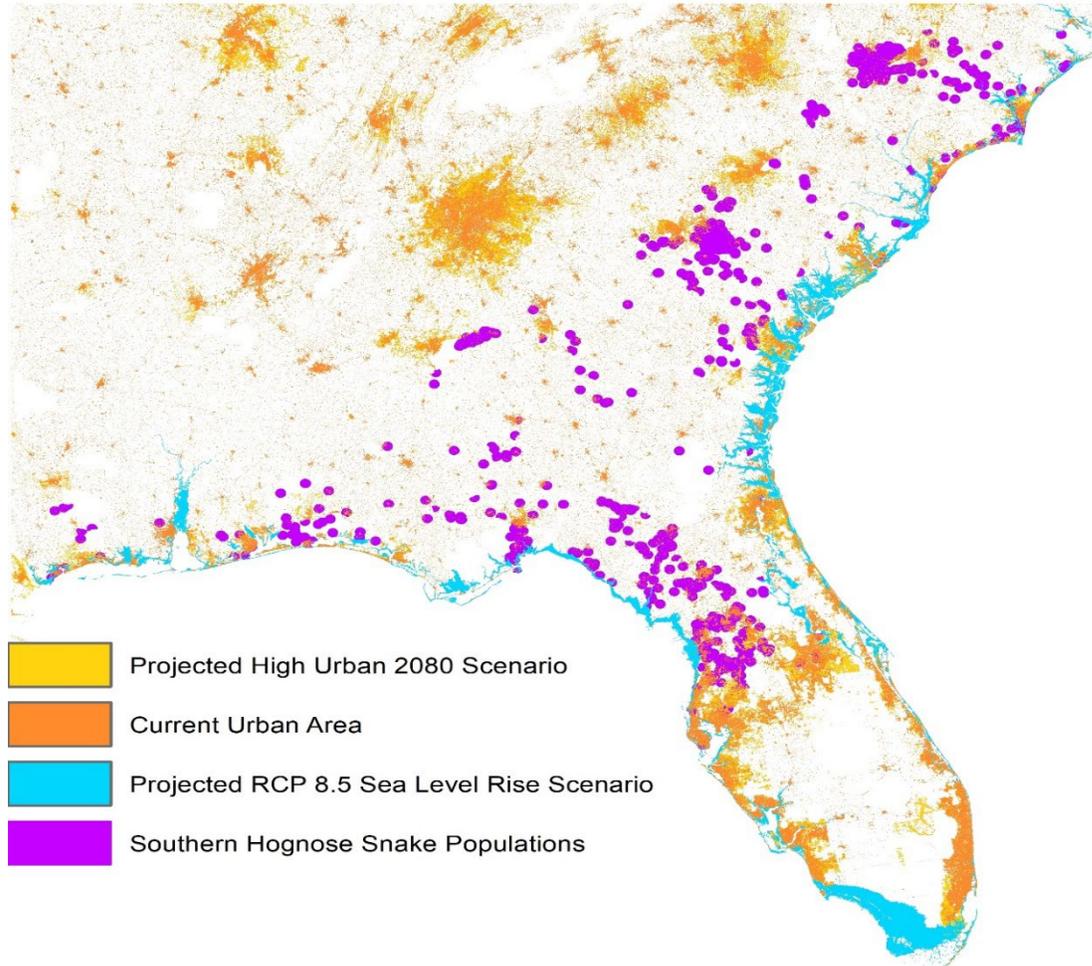
Figure 5-2. Projected high urbanization and SLR under RCP 8.5 for the year 2080 in the Southeast, United States. Certain southern hognose snake populations (purple), within the analysis area, were predicted to experience substantial habitat loss due to urbanization and SLR.

Burn windows, which averaged 292 days/year (range = 248 – 327 days/yr) under current conditions, were reduced by 58 – 86 days on average across the two climate change scenarios (Table 5-2). These shorter burn windows, in combination with urbanization, resulted in fire frequencies (mean = 3.7%; range = 0 - 20.5% under current conditions) being reduced by 2.7 – 2.8% on average across scenarios (Table 5-2). Using the reduced fire frequencies, the total number of burns between 2023 – 2080 for an average population is expected to be reduced by 1 with a range of approximately 0 to 9 fewer burns across all populations (Table 5-2), compared to if burn frequency was not reduced from current levels (mean = 2; range = 0 – 12 burns from 2023-2080 under current levels). Finally, under current conditions, the average population had a mean HSI of 21.3% (Table 4-1), which decreased between 2.8% (best case) and 3.1% (worst case) on average across all scenarios (Table 5-2).

Table 5-2. Predicted changes in habitat variables (compatible land cover, fire frequency, burn windows, burn days, and Habitat Suitability Index [HSI]) between the present and 2080. Means (top value in each cell) represent the average change across populations, and minimums and maximums (bottom values in each cell) represent the lowest and highest changes, respectively, predicted for a single population.

Habitat variable	Scenario					
	Low Urbanization/ RCP 4.5	Med Urbanization/ RCP 4.5	High Urbanization/ RCP 4.5	Low Urbanization/ RCP 8.5	Med Urbanization/ RCP 8.5	High Urbanization/ RCP 8.5
Compatible land cover (%)	-5.6 (-59.0, 0.0)	-5.7 (-59.3, 0.0)	-7.0 (-60.8, 0.0)	-5.7 (-59.0, 0.0)	-5.7 (-59.3, 0.0)	-7.1 (-60.8, 0.0)
Compatible land cover (km^2)	-8.3 (-266.8, 0.0)	-8.3 (-266.8, 0.0)	-10.2 (-281.0, 0.0)	-8.4 (-269.7, 0.0)	-8.4 (-269.7, 0.0)	-10.3 (-284.0, 0.0)
Fire frequency (% of years burned)	-2.7 (-17.6, 0.0)	-2.7 (-17.6, 0.0)	-2.7 (-18.1, 0.0)	-2.8 (-17.9, 0.0)	-2.8 (-17.9, 0.0)	-2.8 (-18.4, 0.0)
Burn window days per year	-58 (-102, -5)	-58 (-102, -5)	-58 (-102, -5)	-86 (-123, -29)	-86 (-123, -29)	-86 (-123, -29)
Total burns (2023-2080)	-1.3 (-8.5, 0.0)	-1.3 (-8.5, 0.0)	-1.3 (-8.6, 0.0)	-1.3 (-8.6, 0.0)	-1.3 (-8.6, 0.0)	-1.3 (-8.7, 0.0)
HSI (%)	-2.8 (-30.4, 5.5)	-2.8 (-30.5, 5.5)	-2.9 (-37.8, 12.3)	-2.9 (-31.5, 5.5)	-2.9 (-31.5, 5.5)	-3.1 (-37.8, 12.3)

5.2.2 Future Population Resiliency

Using the simulation model, we predicted the future persistence probability for each of the 213 populations in the analysis area through the year 2080. As with current persistence we could not analyze the 20 populations outside the analysis area and considered the 18 populations with records found prior to or during 1990 to be likely extirpated and the remaining two populations with records in 2019 and 2021 to be "unknown". All six scenarios yielded nearly identical predictions of the number and percentage of persistence populations. These patterns were seen across all future time horizons (2040, 2060, and 2080). To simplify the reporting of our results since there was so little difference between the scenarios, we only show the results for the Low Urbanization/RCP 4.5 (best case) and High 8.5 (worst case) in our tables. We followed similar steps as in the current condition analysis to summarize population resiliency by reporting the number of populations at each persistence threshold under these two future scenarios in years 2040, 2060, and 2080 (Table 5-3, Figure 5-4). However, for future conditions report the number

of populations at each persistence threshold using the mean population persistence. This is because we recognize higher uncertainty exist about a prediction. We have also removed reporting populations that we have determine to be extirpated (n=144) in current conditions. In Figure 5-3, we display the distribution of populations by category of persistence probability across the species' range under current conditions and the Low Urbanization/RCP 4.5 (best case) scenario in 2080.

For all scenarios, future population persistence decreased from current conditions and a majority of populations that fell within the extremely likely on landscape (≥95%) threshold under current conditions were predicted to have lower persistence probabilities in the future and, thus, dropped to lower categories. The number and percentage of populations likely to be extirpated (<50%) increased for all scenarios and future time horizons, relative to current conditions. For example, the number of historical populations likely to be extirpated (<50%) in 2023 was 144 of the total 233 populations, leaving 87 extant. Under the Low Urbanization/RCP 4.5 scenario by 2040, 19 additional populations were predicted to be extirpated (Table 5-3). Between 2040 and 2060 an additional 25 populations were predicted to be extirpated, and between 2060 and 2080 an additional 12 populations were predicted to be extirpated for a total of 56 populations predicted to become extirpated by 2080. These numbers are very similar for the High Urbanization/RCP 8.5 (worst case) scenario. We also predicted future population persistence under the null model, where SLR, urbanization, and burn windows remained at current levels (i.e., HSI remained at the values used in the current conditions model). Population persistence was projected to be very similar under the null model as compared to the six scenarios of climate change/urbanization. Specifically, the number of populations likely to be extirpated under the null model was the same as the High Urbanization/RCP 8.5 scenario in 2040, one less population than in the High Urbanization/RCP 8.5 scenario in 2060, and one less population than in the High Urbanization/RCP 8.5 2080.

The similarity in results among each of the stressor scenarios and the null model suggest that future population declines predicted to occur are primarily a consequence of annual population persistence probabilities being <1 for each population and no processes included in our model for colonization or recolonization, rather than a consequence of decreased habitat suitability due to climate change and urbanization. This indicates that the changes captured by the future scenarios are not large enough to substantially affect future population persistence at the time scales considered (even though urbanization and climate change may affect persistence over longer time periods). Additionally, it indicates that a number of populations estimated to be persisting in 2023 are persisting under conditions that do not support long-term persistence. In other words, it suggests an extinction debt, where there is a lag between conditions causing extinction and the actual extinction events. Limited differences between the null model and future scenarios may also reflect a lack of available spatial data for other threats, which may cause larger declines if their effects were able to be included within the future scenarios (e.g., invasive species, disease, increases in soil temperature).
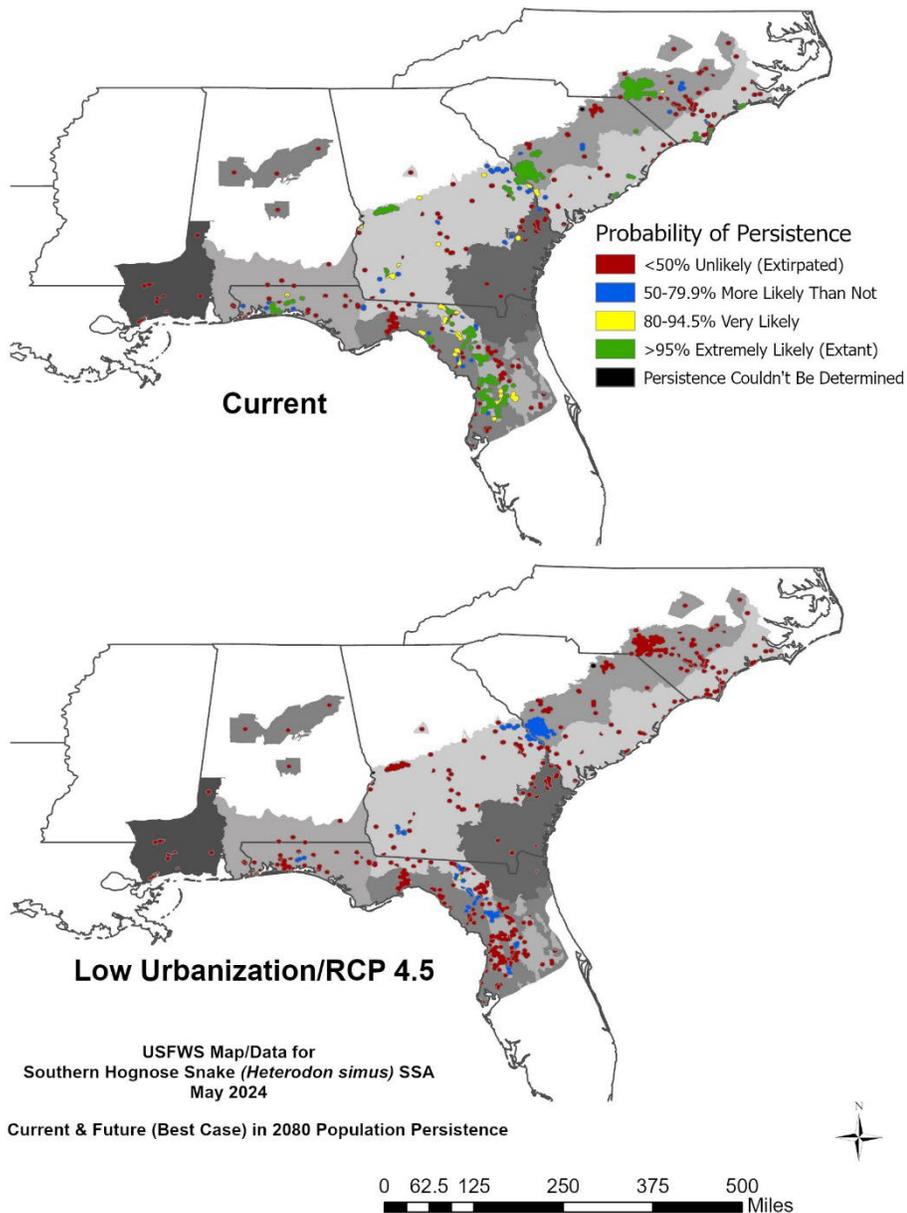
Figure 5-3. Spatial distribution of southern hognose snake populations by category of persistence probability across the species' range under current conditions and the low stressor scenario in 2080.

Table 5-3. Distribution of southern hognose snake populations in each category of population persistence in 2040, 2060, and 2080, for two scenarios. Numbers are reported as the number of populations in each category and as the cumulative number of populations at or above each threshold.

Population persistence category	Scenario					
	Current Condition		Low Urbanization/RCP 4.5		High Urbanization/RCP 8.5	
Year – 2040	Each category	Cumulative	Each category	Cumulative	Each category	Cumulative
*Extremely Likely on Landscape (Extant) 95-100%	33	33	2	2	2	2
*Very Likely on Landscape 80-94.9%	22	55	24	26	24	26
*More Likely than Not 50-79.9%	32	87	42	68	42	68
Unlikely (Extirpated) < 50%	144	-	19	-	19	-
Unknown	2	-	2	-	2	-
Year - 2060	Current in Each Category	Current Cumulative	Each Category	Cumulative	Each Category	Cumulative
*Extremely Likely on Landscape (Extant) 95-100%	33	33	0	0	0	0
*Very Likely on Landscape 80-94.9%	22	55	12	12	12	12
*More Likely than Not 50-79.9%	32	87	31	43	30	42
Unlikely (Extirpated < 50%	144	-	44		45	
Unknown	2	-	2	-	2	-
Year - 2080	Current in Each Category	Current Cumulative	Each Category	Cumulative	Each Category	Cumulative
*Extremely Likely on Landscape (Extant) 95-100%	33	33	0	0	0	0
*Very Likely on Landscape 80-94.9%	22	55	2	2	2	2
*More Likely than Not 50-79.9%	32	87	29	31	29	31
Unlikely (Extirpated) < 50%	144	-	56		56	
Unknown	2	-	2	-	2	-

To get at future resiliency, we summarized the future population resilience by using the currently extant populations and determining if they were resilient or not for the two scenarios (Table 5-4). We then summarized the future conditions for the moderate and high resiliency populations determined in current conditions (Table 5-5). Under both future scenarios there are 13 populations that remain at the highest level of resiliency in 2040 and by 2060 the number of high resiliency populations has decreased to 7 and by 2080 this has decreased to 2 populations (Table 5-6; Figures 5-5 thru 5-7). These are the same two populations that in 2040 are in the highest persistence category. We also predict that by 2040 one of the moderate resiliency populations could become extirpated and by 2060, 8 additional populations could become extirpated. Six of these potentially extirpated populations by 2060 currently have moderate resiliency, the other two currently have high resiliency. Further for future conditions under the low urbanization/RCP4.5 scenario, by 2060 and 2080, we have likely lost an additional 44 and 56 populations respectively.

Table 5-4. Future population summary for the currently extant populations with number considered currently resilient or not resilient due to suitable habitat and number of connected populations in current.

Population persistence category	Scenario					
	Low Urbanization/RCP 4.5			High Urbanization/RCP 8.5		
Year – 2040	Total	Resilient	Not Resilient	Total	Resilient	Not Resilient
*Extremely Likely on Landscape 95-100%	2	2	0	2	2	0
*Very Likely on Landscape 80-94.9%	24	11	13	24	11	13
*More Likely than Not 50-79.9%	42	12	30	42	12	30
Unlikely (Extirpated) < 50%	19	-	-	19	-	-
Year - 2060	Total	Resilient	Not Resilient	Total	Resilient	Not Resilient
*Extremely Likely on Landscape 95-100%	0	0	0	0	0	0
*Very Likely on Landscape 80-94.9%	12	7	5	12	7	5
*More Likely than Not 50-79.9%	31	10	21	30	10	20
Unlikely (Extirpated) < 50%	44	-	-	45	-	-
Year - 2080	Total	Resilient	Not Resilient	Total	Resilient	Not Resilient
*Extremely Likely on Landscape 95-100%	0	0	0	0	0	0
*Very Likely on Landscape 80-94.9%	2	2	0	2	2	0
*More Likely than Not 50-79.9%	29	14	15	29	14	15
Unlikely (Extirpated) < 50%	56	-	-	56	-	-

Table 5-5. Future conditions for the resilient populations (n=26) determined in current conditions under two scenarios.

Population persistence category	Current Conditions Resilient Populations	Scenario	
		Low Urbanization/RCP 4.5 Resilient Populations	High Urbanization/RCP 8.5 Resilient Populations
Year – 2040			
*Extremely Likely on Landscape 95-100%	13	2	2
*Very Likely on Landscape 80-94.9%	4	11	11
*More Likely than Not 50-79.9%	9	12	12
Unlikely (Extirpated) < 50%	-	1	1
Year – 2060			
*Extremely Likely on Landscape 95-100%	13	0	0
*Very Likely on Landscape 80-94.9%	4	7	7
*More Likely than Not 50-79.9%	9	10	10
Unlikely (Extirpated) < 50%	-	9	9
Year – 2080			
*Extremely Likely on Landscape 95-100%	13	0	0
*Very Likely on Landscape 80-94.9%	4	2	2
*More Likely than Not 50-79.9%	9	14	14
Unlikely (Extirpated) < 50%	-	10	10
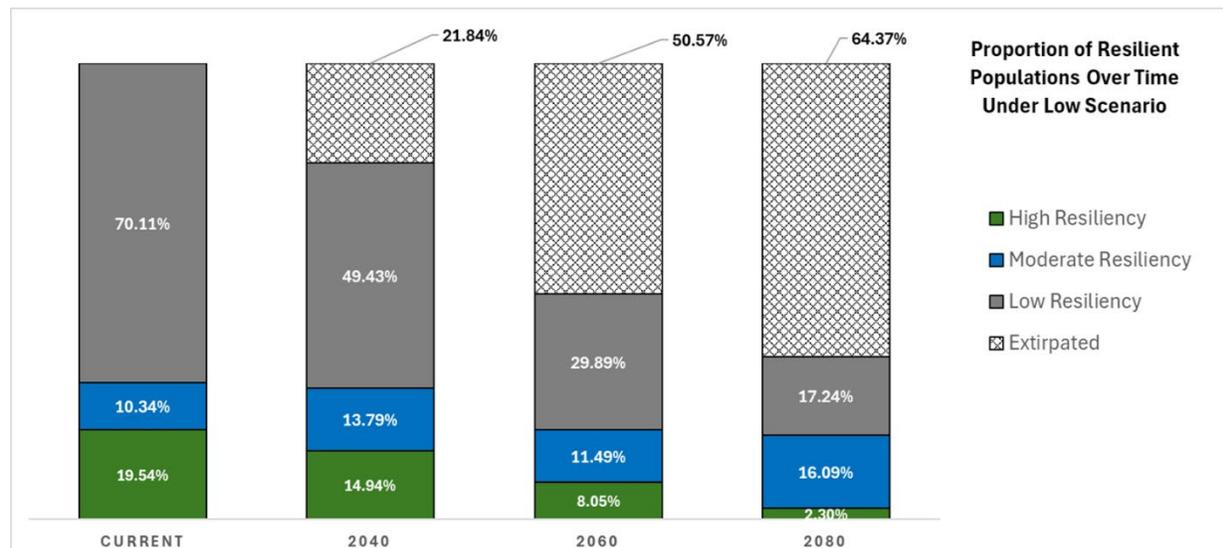
Figure 5-4. Percent of total southern hognose snake populations over time in each category of resiliency in 2040, 2060, and 2080, for best case scenario, showing how the percent of populations is predicted to change over time. Populations presented are the extant populations under current condition analysis. Populations in the highest resiliency are in green, followed by moderate resiliency populations represented in blue, and low resiliency populations in grey.

Table 5-6. Current and future condition summary of the number of high, moderate, low, and extirpated populations and their percentage of the total extant populations in 2040, 2060, and 2080. This is for the low urbanization/RCP 4.5 (best-case) scenario. This table shows how the number of populations in each of the resiliency categories is predicted to change over time.

Population status/resiliency	Current Condition		2040		2060		2080	
	Number of populations in each category	% of extant total	Number of populations in each category	% of extant total	Number of populations in each category	% of extant total	Number of populations in each category	% of extant total
High Resiliency	17	19.54%	13	14.94%	7	8.05%	2	2.30%
Moderate Resiliency	9	10.34%	12	13.79%	10	11.49%	14	16.09%
Low Resiliency	61	70.11%	43	49.43%	26	29.89%	15	17.24%
Extirpated	144	-	19	21.84%	44	50.57%	56	64.37%
Unknown	2	-	2	-	2	-	2	-
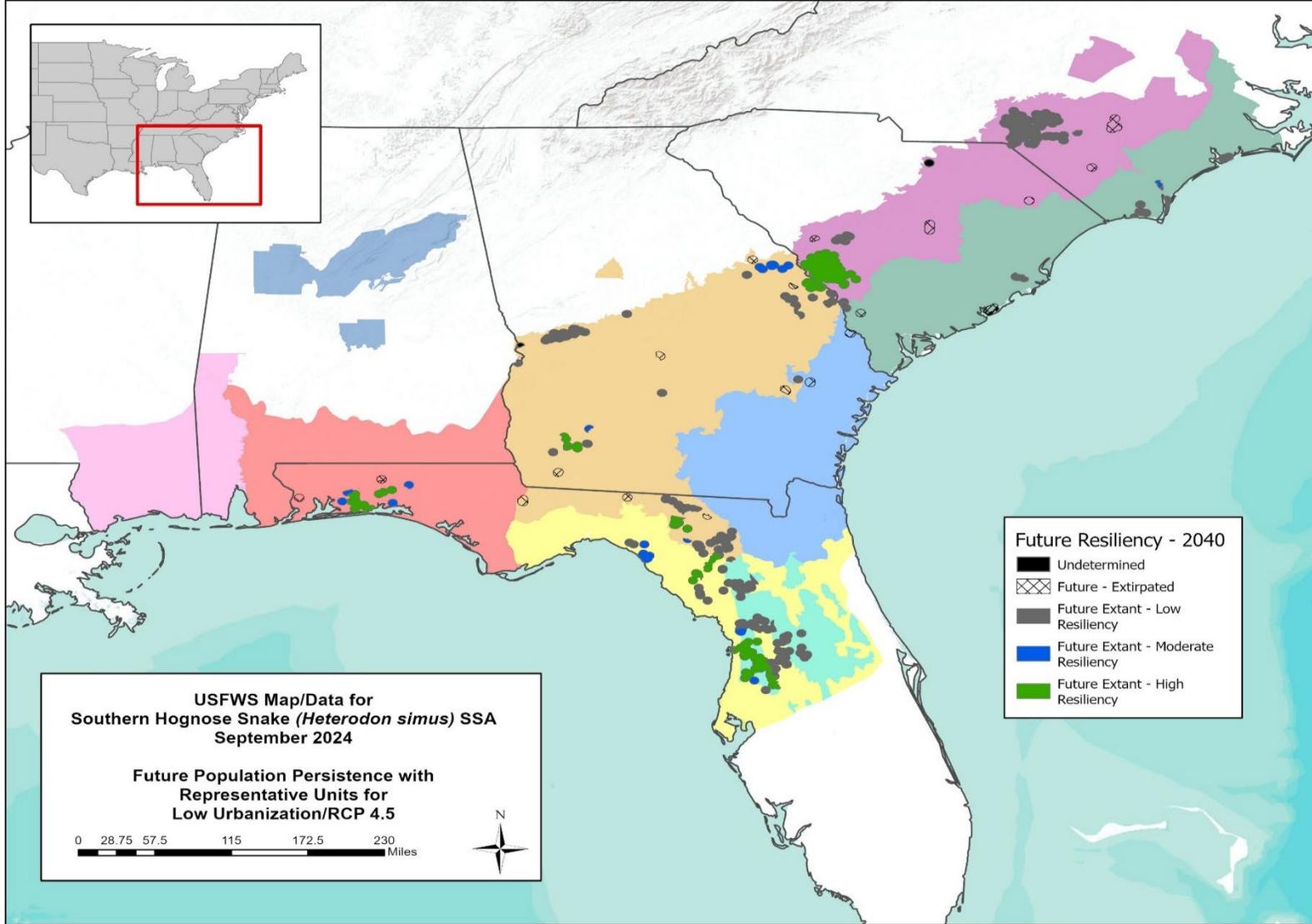
Figure 5-5. Map showing the future resiliency in 2040 under the low urbanization/RCP4.5 scenario. Populations in green indicate those with the highest resiliency, moderate in blue, and low in dark grey. Extirpated populations are hatched out.
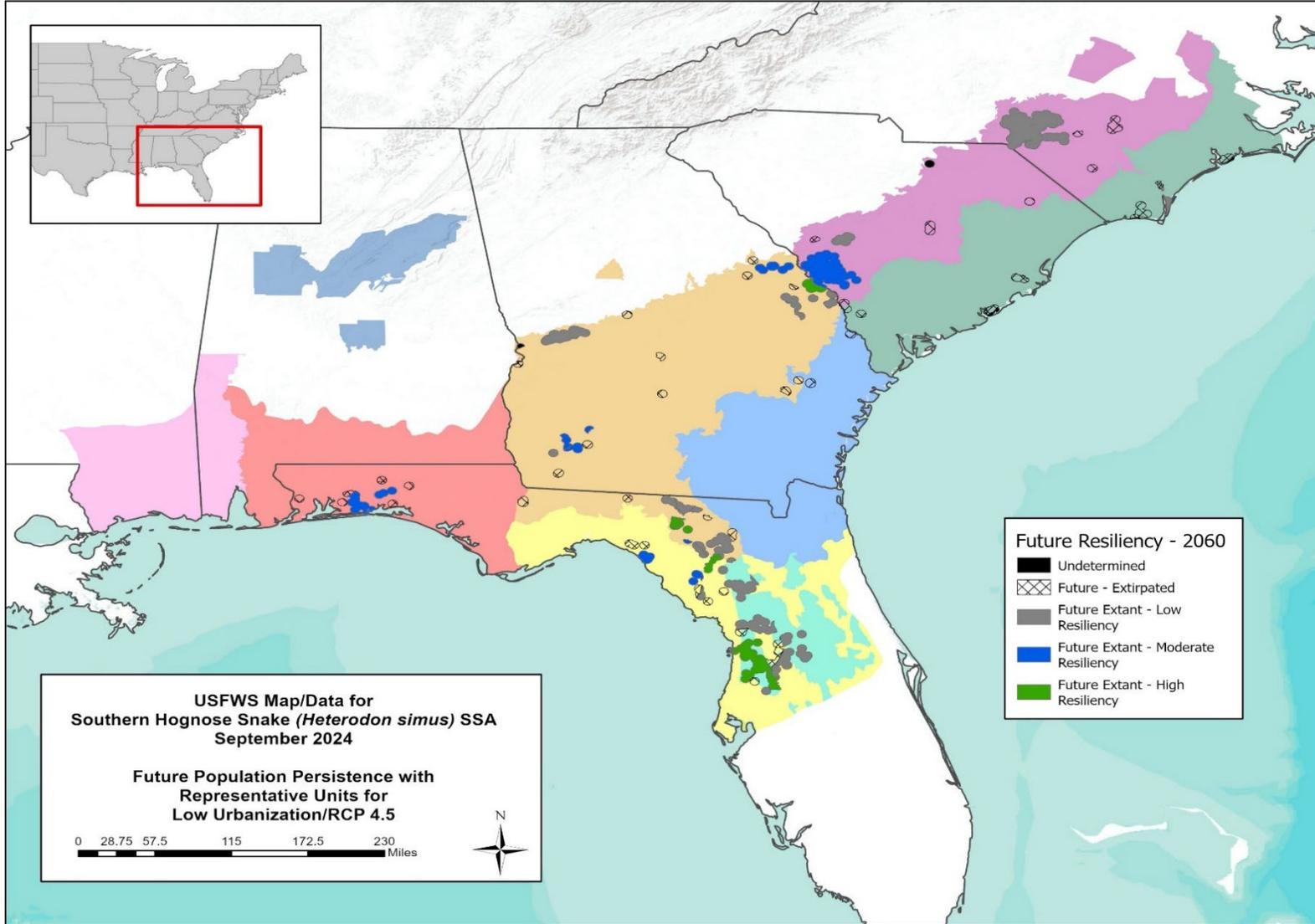
Figure 5-6. Map showing the future resiliency in 2060 under the low urbanization/RCP4.5 scenario. Populations in green indicate those with the highest resiliency, moderate in blue, and low in dark grey. Extirpated populations are hatched out.
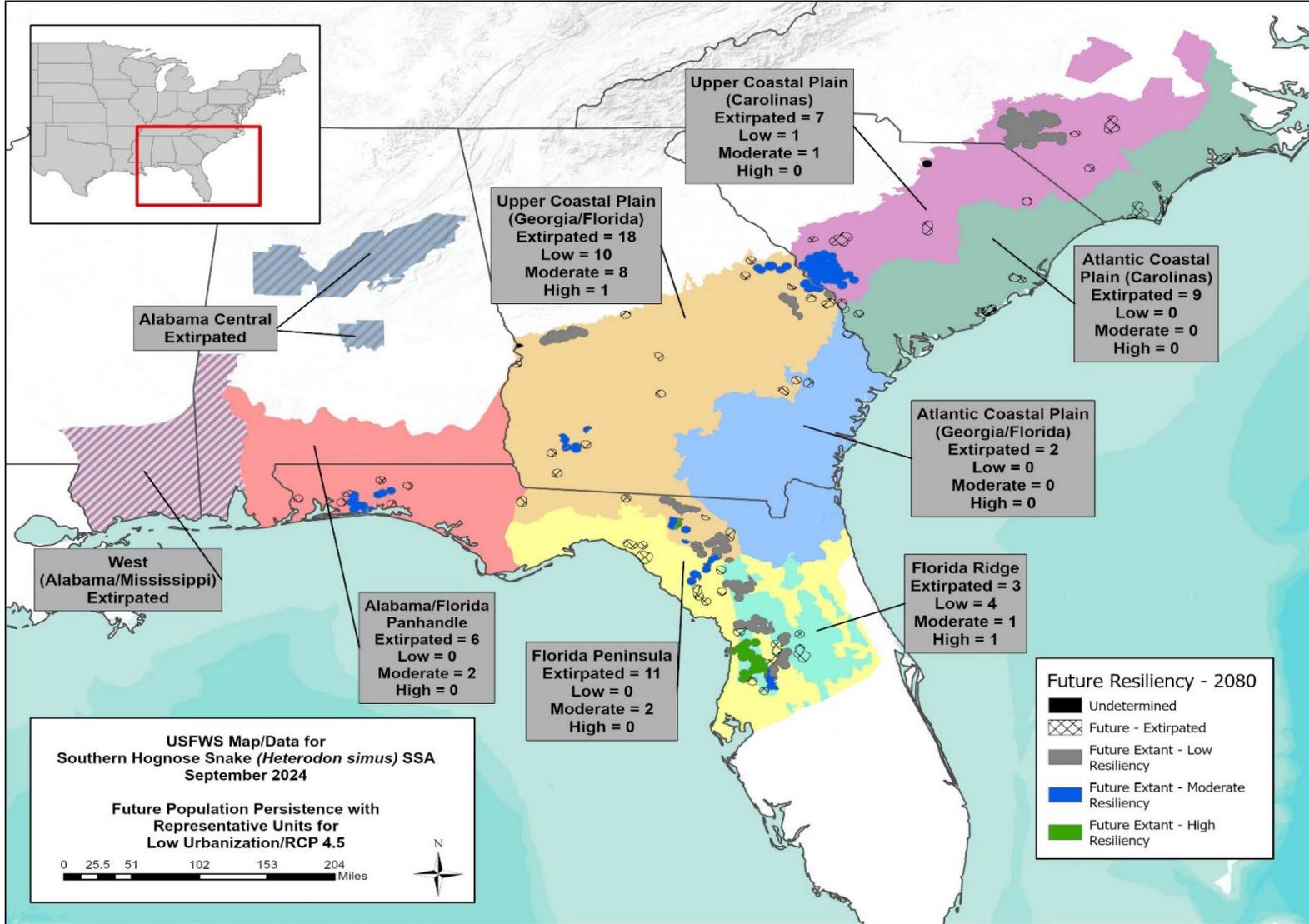
Figure 5-7. Map showing the future resiliency in 2080 under the low urbanization/RCP4.5 scenario. Populations in green indicate those with the highest resiliency, moderate in blue, and low in dark grey. Extirpated populations are hatched out.

5.2.3 Future Species Representation and Redundancy

We summarized trends in the future condition of the southern hognose snake for representation and redundancy using the number of populations likely to persist, their future resiliency, and their spatial distribution. Specifically, we report both the persistence probability thresholds, in each of the 9 representative units and across its range, in 2040, 2060, and 2080 (Table 5-7), as well as the mean number of populations predicted to persist with 95% confidence intervals (Tables 5-5).

We can assume that the risk of an entire representative unit becoming extirpated increases as the number of populations predicted to persist within that unit decreases. Therefore, we interpret a higher risk of loss of representation when a representative unit has zero populations above a certain persistence threshold, moderate risk when a unit has one or two populations above a certain threshold, and lower risk when a unit has three or more populations above a certain threshold. We discuss the risk for particular units in relative terms to other units.

Overall, we predicted future representation and redundancy to decrease from current conditions. The number of resilient populations and the number of representative units with resilient populations decreased under all scenarios. In our current condition analysis, we determined that the southern hognose snake has likely become extirpated in 2 of 9 representative units. The other 7 representative units had at least 1 population considered to have moderate to high resiliency. In 2040, under the low urbanization/RCP 4.5 scenario 5 representative units were predicted to be occupied by at least one population with high resiliency and one additional representative units was predicted to be occupied by at least one population with moderate resiliency (Table 5-7, Figure 5-5). By 2060, 5 representative units were predicted to be occupied by at least one population with moderate to high resiliency (Table 5-7, Figure 5-6). By 2080, only one representative unit (Upper Coastal Plain (GA/FL) was predicted to have more than 2 populations with moderate to high resiliency and the remaining four representative units have only one or two moderate to high resiliency populations. Two representative units were predicted to have no extant populations by 2080 (Atl. Coastal Plain (GA/FL) and Atl. Coastal Plain (Carolinas); Table 5-7, Figure 5-7).

Future representation is projected to decline from current conditions in the future, due to fragmentation of suitable habitat and decreased connectivity within and among representative units. We had previously predicted that the southern hognose snake has likely experienced a decrease in latitudinal and longitudinal variability (i.e., a range contraction) from its historical to current range extent. Future predictions showed that populations with moderate to high resiliency will be mainly located near and along the Florida Ridge and northward into the Upper Coastal Plain (Florida) with a few other isolated populations through the range (Figure 5-8). Large areas of the range will lack resilient populations (e.g., southern Alabama, middle Georgia, eastern Florida Peninsula, and coastal South Carolina, and all of North Carolina).

As mentioned under Current Condition, given the species' fossorial nature and habitat needs, the species may be limited in its capacity to shift in space in a changing environment. With the predicted declines in the future, the species is projected to have reduced adaptive capacity, and therefore, representation is low.

In addition to summarizing future conditions using the number of populations meeting a certain persistence probability threshold and assessing populations resiliency, we present the mean number of populations still persisting (and 95% confidence intervals), as predicted directly from the simulation model (Table 5-5). As discussed above, we again see that the Atlantic Coastal Plain (GA/FL) was the representative unit with the highest risk of losing representation, relative to other units, with a mean estimate of 0 populations persisting in 2040. Two other units (the Atlantic Coastal Plain (Carolinas) and AL/FL Panhandle) had a relatively high risk of losing representation as the mean number of populations was 3 for these units and the lower 95% confidence interval included 0 populations persisting in 2080. Additionally, 3 units (Upper Coastal Plain (Carolinas), FL Peninsula, and FL Ridge had a moderate risk of losing representation as the mean number of populations were 4, 6, and 6, respectively for these units but the lower 95% confidence intervals were 1, 1, and 2, respectively in 2080 Only the Upper Coastal Plain (GA/FL) unit is at low risk of losing representation with a mean of 20 populations persisting in 2080.

Redundancy, as measured by the number of populations with moderate to high resiliency (Table 5-7) and by the mean number of populations persisting (Table 5-8; Figure 5-8), decreased in all scenarios, time periods, and representative units, relative to current conditions. All scenarios yielded nearly identical predictions of the number of persisting populations. This is not surprising since there were only minimal differences between the scenarios in the amount of land cover loss and HSI for populations.

Similarly, we project declines in redundancy within representative units and throughout the species range, due to predicted population losses and resiliency decreases in the future. These predicted losses in populations, resiliency, and range will cause the species to be vulnerable to the effects of single catastrophic events, such as large-scale drought, wildfires, hurricanes, and disease outbreaks. In terms of distribution, the southern hognose snake was projected to have reduced distribution within and across multiple representative units, given the predicted extirpations and low resiliency populations. In addition, the distributions of remaining moderate to high resiliency populations within each representative unit are clustered, resulting in reduced connectivity. Given this, the species is projected to have low redundancy.

Table 5-7. Future high, moderate, and low resiliency populations and their representative unit. We only report the low urbanization/RCP 4.5 scenario for this table because the number of populations for the high urbanization/RCP 8.5 are the same.

Representative Unit	Current Conditions				Scenario			
					Low Urbanization/RCP 4.5			
	Extant	Low	Moderate	High	Extirpated	Low	Moderate	High
Year - 2040								
Upper Coastal Plain (Carolinas)	9	8	0	1	5	3	0	1
Upper Coastal Plain (GA/FL)	37	28	2	7	8	20	3	6
Atl. Coastal Plain (Carolinas)	9	8	1	0	2	6	1	0
Atl. Coastal Plain (GA/FL)	2	1	1	0	2	0	0	0
FL Peninsula	13	7	2	4	0	7	4	2
FL Ridge	9	7	0	2	0	7	0	2
AL/FL Panhandle	8	2	3	3	2	0	4	2
West (AL/MS)	0	0	0	0	-	0	0	0
AL Central	0	0	0	0	-	0	0	0
Range-wide	87	61	9	17	19	43	12	13
Year - 2060								
Upper Coastal Plain (Carolinas)	9	8	0	1	6	2	1	0
Upper Coastal Plain (GA/FL)	37	28	2	7	15	13	5	4
Atl. Coastal Plain (Carolinas)	9	8	1	0	7	2	0	0
Atl. Coastal Plain (GA/FL)	2	1	1	0	2	0	0	0
FL Peninsula	13	7	2	4	8	2	2	1
FL Ridge	9	7	0	2	0	7	0	2
AL/FL Panhandle	8	2	3	3	6	0	2	0
West (AL/MS)	0	0	0	0	-	0	0	0
AL Central	0	0	0	0	-	0	0	0
Range-wide	87	61	9	17	44	26	10	7
Year - 2080								
Upper Coastal Plain (Carolinas)	9	8	0	1	7	1	1	0
Upper Coastal Plain (GA/FL)	37	28	2	7	18	10	8	1
Atl. Coastal Plain (Carolinas)	9	8	1	0	9	0	0	0
Atl. Coastal Plain (GA/FL)	2	1	1	0	2	0	0	0
FL Peninsula	13	7	2	4	11	0	2	0
FL Ridge	9	7	0	2	3	4	1	1
AL/FL Panhandle	8	2	3	3	6	0	2	0
West (AL/MS)	0	0	0	0	-	0	0	0
AL Central	0	0	0	0	-	0	0	0
Range-wide	87	61	9	17	56	15	14	2
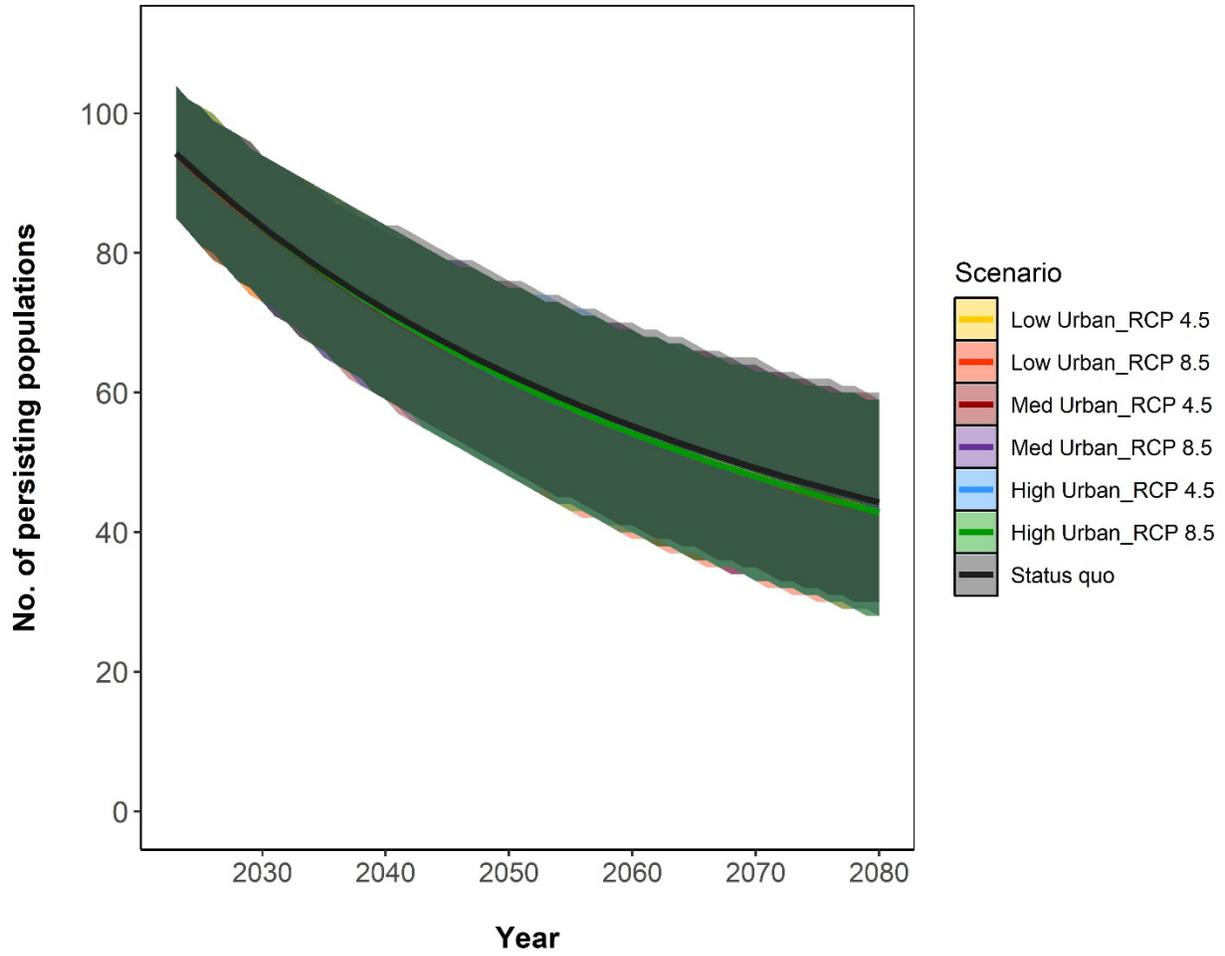
Figure 5-8. Predicted mean (± 95% credible intervals) number of persisting southern hognose snake populations between the present year (2023) and 2080, given two future climate change scenarios and three scenarios of urbanization.

Table 5-8. Mean number of southern hognose snake populations (Lower, Upper 95% confidence intervals) predicted to persist in 2040, 2060, and 2080, given the Low Urbanization/RCP 4.5 and High Urbanization/RCP 8.5 scenarios, across each representative unit and range-wide.

Representative Unit	Scenario		
Year - 2040	Current Condition	Low Urbanization/RCP 4.5	High Urbanization/RCP 8.5
Upper Coastal Plain (Carolinas)	12 (7, 18)	8 (4, 13)	8 (4, 13)
Upper Coastal Plain (GA/FL)	37 (26, 50)	30 (21, 38)	30 (21, 38)
Atl. Coastal Plain (Carolinas)	12 (8, 17)	8 (4, 12)	8 (4, 12)
Atl. Coastal Plain (GA/FL)	2 (0, 6)	0 (0, 2)	0 (0, 2)
FL Peninsula	13 (10, 17)	10 (6, 14)	10 (6, 14)
FL Ridge	10 (8, 12)	8 (5, 11)	8 (5, 11)
AL/FL Panhandle	9 (5, 13)	6 (3, 10)	6 (3, 10)
West (AL/MS)	1 (0, 3)	1 (0, 3)	1 (0, 3)
AL Central	0 (0, 0)	0 (0, 0)	0 (0, 0)
Range-wide	89 (74, 107)	71 (59, 84)	71 (59, 84)
Year - 2060			
Upper Coastal Plain (Carolinas)	12 (7, 18)	6 (2, 11)	6 (2, 11)
Upper Coastal Plain (GA/FL)	37 (26, 50)	24 (14, 35)	24 (13, 35)
Atl. Coastal Plain (Carolinas)	12 (8, 17)	5 (1, 9)	5 (1, 9)
Atl. Coastal Plain (GA/FL)	2 (0, 6)	0 (0, 1)	0 (0, 1)
FL Peninsula	13 (10, 17)	7 (3, 12)	7 (3, 12)
FL Ridge	10 (8, 12)	7 (4, 10)	7 (4, 10)
AL/FL Panhandle	9 (5, 13)	4 (1, 8)	4 (1, 8)
West (AL/MS)	1 (0, 3)	1 (0, 3)	1 (0, 3)
AL Central	0 (0, 0)	0 (0, 0)	0 (0, 0)
Range-wide	89 (74, 107)	54 (40, 69)	54 (40, 69)
Year - 2080			
Upper Coastal Plain (Carolinas)	12 (7, 18)	4 (1, 9)	4 (1, 9)
Upper Coastal Plain (GA/FL)	37 (26, 50)	20 (9, 32)	20 (9, 33)
Atl. Coastal Plain (Carolinas)	12 (8, 17)	3 (0, 7)	3 (0, 7)
Atl. Coastal Plain (GA/FL)	2 (0, 6)	0 (0, 1)	0 (0, 1)
FL Peninsula	13 (10, 17)	6 (1, 10)	6 (1, 10)
FL Ridge	10 (8, 12)	6 (2, 10)	6 (2, 10)
AL/FL Panhandle	9 (5, 13)	3 (0, 7)	3 (0, 7)
West (AL/MS)	1 (0, 3)	0 (0, 2)	0 (0, 2)
AL Central	0 (0, 0)	0 (0, 0)	0 (0, 0)
Range Wide	89 (74, 107)	43 (28, 59)	43 (28, 59)

5.2.4 Limitations

In any species status assessment, the process of modeling current conditions and projecting those into the future requires making strategic simplifications of reality using the best available data. We must account for multiple uncertainties and make informed assumptions when necessary. The level of uncertainty is especially high for a species that is difficult to detect and is as data limited as the southern hognose snake. Still, this assessment addressed some of the key

uncertainties and yielded useful predictions for characterizing the species' status. Quantitative models are essential tools for capturing the dynamics of complex, ecological systems, predicting species' outcomes, and informing conservation decisions for at-risk and listed species (Morris et al. 2002, entire; McGowan et al. 2017, entire). Through the use of predictive models and multiple scenarios, we captured a range of possible conditions in the future. We highlight and explain some of the key limitations and assumptions of the analyses below.

We developed three types of models in our analyses, (1) a habitat suitability model, (2) a current persistence model, and (3) a future persistence model. Each one, like all models, required simplifications and assumptions about the underlying ecological systems. The models generated specific quantitative results that should be recognized as our most reasonable estimates. For example, the results of the habitat suitability model represented areas of relatively high and low suitability based on a set of predictors; however, a specific site may have additional factors, such as presence of non-native invasive species or a history of over-collection, which we were not able to incorporate into the model.

We were not able to include all the factors that may be influencing viability for the southern hognose snake (Chapter 3) because spatial data for these stressors were not available across the species' range or at all, such as impacts from invasive feral hogs and red imported fire ants. These limitations likely did not hinder the reliability of results from the habitat suitability model since we included several of the most influential factors identified in the literature and by expert judgment as predictors – specifically, soil drainage, compatible land cover, and fire frequency. Simplifications were also made in the persistence model where we only included three predictors even though an infinite number of factors could influence population persistence locally. However, we developed all models in this assessment using the best available data and expert judgment for the southern hognose snake and its ecological systems. Despite simplifications, the results of this assessment tended to agree with expert judgment and previous studies characterizing trends in southern hognose snake habitat use and population persistence. We also projected population outcomes under multiple scenarios using the same model structure, and although there was uncertainty around all model predictions, one can consider and compare the range of plausible future conditions predicted across scenarios to effectively evaluate relative risks to the species.

We delineated 233 populations that served as the primary units for analyses, but creating these population boundaries required a set of assumptions that are important to consider when interpreting the results. Most importantly, we assumed that our full database of species records, which came from datasets maintained by State and Federal agencies and other researchers, adequately represented the distribution of southern hognose snake populations in the Southeast. While the full dataset likely captured most of the areas where southern hognose snakes occurred, it likely did not capture all locations where they occur due to the cryptic nature of the species and the lower search effort and data availability from private lands. This results in some uncertainty

around the actual number of populations. We employed a transparent and collaborative process to delineate populations and develop models, and while assumptions are unavoidable, they were based on best available scientific information.

Models used in current and future conditions hinged on an improved version of an approach developed in version 1.0 of this SSA to estimate persistence of populations, but we had to make several assumptions about how persistence probability was related to population resiliency. First, we assumed if the population is currently on the landscape, then it must display some level of resiliency for it to have persisted over time. Secondly, most likely larger populations will have a higher current persistence probability than smaller populations. Third, we assumed the more resilient populations are more likely to occur in highly suitable habitat, on protected lands and in proximity to other populations. Since we were able to account for these factors in our model, populations that meet these factors most likely have higher current persistence probabilities and greater resiliency.

While persistence probability is a reasonable indicator of resilience, we did not explicitly account for further dynamics within the population (e.g., increases in recruitment, abundance) or between populations (e.g., colonization rates between neighboring populations) that could influence viability. More complex models (e.g., population viability analysis) exist that directly estimate these biological processes; however, they require basic life history and demographic information that have not been estimated for southern hognose snakes. It is possible that our models are under- or overestimating persistence for certain populations by not explicitly estimating other processes like recruitment or colonization. However, biological processes like recruitment and colonization are represented, at least to some degree, in the set of predictors of annual persistence. We assume that the predictor of HSI, which was positively related to the annual persistence probability, is also positively related to recruitment and survival rates for a population as the habitat it occupies contains more compatible land cover and forage, and fewer anthropogenic threats. Similarly, we did not explicitly estimate colonization between populations, but this process was represented by including the number of nearby populations as a predictor of a population's annual persistence probability. Finally, colonization may be implicitly included in the model because of the long time scales considered. In other words, a population could be extirpated and recolonized, and this would be estimated as persistence in the model. We also acknowledge that many – or most – population boundaries include some proportion of unsuitable habitat that, in some cases, could be causing a single population defined in our study to be functioning as several isolated subpopulations. It is likely that smaller, isolated subpopulations would each have lower growth rates and persistence probabilities than a single large population. Directly accounting for fragmentation would require fine-scale information about southern hognose snake movement capabilities through different habitat types that is not currently available. However, we found in preliminary analysis for the habitat suitability models that mean HSI was related to the amount and connectivity of suitable habitat in populations; thus, we assume that including HSI as a predictor of persistence also partially

accounted for the influence of fragmentation within a boundary. Even without explicitly estimating recruitment or colonization rates, the model structure allows for populations to be stable (i.e., persist and not become extirpated over time) over time, which is useful for assessing the degree and distribution of risk of extinction for populations across the species' range. Still, improving the quality and quantity of data for southern hognose snakes in the future will greatly improve predictions of population outcomes using additional types of models.

Finally, as previously stated, the habitat suitability model was based on a set of predictors, but there are likely other important climate-related factors that were not included in the model but are likely to affect habitat suitability and population persistence. Although we did include the projected impacts of SLR to habitat suitability, there are other probable climate change-related impacts that we were not able to model, such as projected increases in mean temperature and decreases in precipitation. An increase in mean temperature will result in increases in soil temperature, which has the potential to negatively impact burrowing species such as the southern hognose snake. Additionally, there is a great amount of uncertainty in how the longleaf pine ecosystem will respond to climate change (e.g., range contraction vs. shifting range), and any changes in the total acreage or distribution of longleaf pine will likely impact the southern hognose snake.

5.3 Summary of Future Conditions and Viability based on Resiliency, Representation, and Redundancy

For the southern hognose snake to maintain *viability*, it needs to have resilient populations that are able to withstand stochastic events and maintain ecological and genetic diversity, which will help preserve the breadth of adaptive capacity, and hence, the evolutionary flexibility of the species. In addition, the populations need to be spread across its range in a way that reduces the chance that a catastrophic event is not likely to lead to the species extinction.

Our analysis shows that future resiliency, for the southern hognose snake is predicted to decline from current conditions under all our scenarios. For all scenarios, populations that fell within the extremely likely on landscape (≥95%) threshold under current conditions were predicted to have lower persistence probabilities in the future and, thus, dropped to lower categories. Under the Low Urbanization/RCP 4.5 scenario by 2040, 19 additional populations were predicted to be extirpated (Table 5-3). Between 2040 and 2060 an additional 25 populations were predicted to be extirpated, and between 2060 and 2080 an additional 12 populations were predicted to be extirpated for a total of 56 populations predicted to become extirpated by 2080. Our analysis shows that future representation, as measured by the number and distribution of resilient populations across representative units in the species' range, will also be reduced from current conditions, due to fragmentation of suitable habitat and decreased connectivity within and among representative units. Given the species' fossorial nature and habitat needs, the species may be limited in its capacity to shift in space in a changing environment in the future. With the predicted declines, the species is projected to have reduced adaptive capacity, and therefore,

representation is low. Our analysis shows that future redundancy, as measured by the number and distribution of resilient populations within representative units and across the range of the species, will be reduced from current conditions in all representative units and under all scenarios tested. These predicted losses in populations, resiliency, and range will cause the species to be vulnerable to the effects of single catastrophic events, such as large-scale drought, wildfires, hurricanes, and disease outbreaks. In term of distribution, the southern hognose snake was projected to have reduced distribution within and across multiple representative units, given the predicted extirpations and low resiliency populations. In addition, the distributions of remaining moderate to high resiliency populations within each representative unit are clustered, resulting in reduced connectivity. Given this, the species is projected to have low redundancy.

The purpose of this assessment was to assess viability of the southern hognose snake. Our assessment shows that there have been range-wide declines for this species from its historical to current conditions, which has previously been suggested in the literature (Tuberville et al. 2000, entire). Our analysis indicates that future resiliency, representation, and redundancy, as measured by future population persistence, for the southern hognose snake is predicted to further decline from current conditions under all scenarios considered.

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APPENDIX A: POPULATION PERSISTENCE ANALYSIS REPORT

Population persistence analysis for southern hognose snake (*Heterodon simus*)
Species Status Assessment (SSA)
July 2024

> **In a nutshell:**
>
> ☒ We used southern hognose snake locality records and spatial habitat/landscape data layers to estimate persistence for 233 southern hognose snake populations across the species' range under current conditions and future scenarios representing climate change and urbanization.
>
> ☒ We used locality records of 14 other snake species commonly observed in southern hognose snake habitats, obtained from HerpMapper.org and other partners, as information about relative search effort across populations in order to improve persistence estimates.
>
> ☒ Current persistence varied considerably by population but was positively influenced by mean habitat suitability and number of populations within 10 km and was negatively related to time since last observation.
>
> ☒ Currently, out of 233 populations, 87 were more likely than not to persist currently (probability of persistence greater than 50%), while 144 were more likely than not to be extirpated.
>
> ☒ Under the six future scenarios 66 to 67 additional populations are likely to be extirpated by 2080.
>
> ☒ Of the 9 representative units, it is extremely likely that 2 units (AL Central and West of the Mobile River in AL and MS) have become extirpated by 2023, and 6 other units are at moderate to high risk of extirpation by the year 2080.
>
> ☒ Collectively, the number of persisting southern hognose snake populations has declined from historic conditions, and these declines are predicted to continue in the future. Redundancy (number of persisting populations within a representative unit) has decreased and is predicted to decrease further in the future. Representation (number of units with persisting populations) has decreased, as 2 of 9 units are likely extirpated at the present, and multiple additional units are at risk of extirpation by 2080.

1. Methods

We sequentially went through the following steps when conducting this analysis and describe each step in more detail in the sections below. First, we gathered a comprehensive dataset of southern hognose snake locality records and delineated population boundaries based on clusters of these records (Section 1.1). Second, we gathered locality records for other snake species commonly observed in southern hognose snake habitats that were found within population boundaries to represent search effort (Section 1.2). Third, we extracted metrics of site-level conditions at the present for each population to use as predictors of persistence (Section 1.3). These predictors included mean habitat suitability index that was estimated as part of the habitat suitability model (Crawford et al., 2020a, entire). Fourth, we constructed a persistence model to estimate current population persistence (in 2023) that leveraged information from the southern hognose snake and other snake species locality datasets and accounted for imperfect detection (Section 1.4). Fifth, we created six scenarios of stressors to evaluate a range of plausible future conditions for the species; we then performed spatial analyses to capture predicted changes in land cover and fire frequency under each scenario, and we extracted these conditions to populations (Section 1.5). Sixth, we built a simulation model that used habitat conditions and current persistence to forecast population persistence through 2080 under each scenario (Section 1.6). Lastly, we summarized results by representative unit and range-wide currently (in 2023), in 2040, 2060, and 2080 (see Section 2 Results).

The core of this analysis – the persistence model – used a novel structure to estimate current population persistence, given data limitations of the southern hognose snake (Crawford et al., 2020b, entire). Specifically, we adapted the Cormack-Jolly-Seber model (Cormack 1964, entire; Jolly 1965, entire; Seber 1965, entire), designed to estimate survival of individual animals based on mark-recapture data, to analogously estimate persistence ("survival") of populations based on detection-non-detection data within each population boundary. Aggregating and analyzing southern hognose snake records by populations can overcome challenges associated with low probability of recapture and allows for estimating processes occurring at the population-level. We performed spatial analyses in ArcGIS version 10.8 (ESRI, Redlands, CA) and statistical analyses in R version 4.3.3 (R Core Team 2016, unpaginated).

1.1 Collecting southern hognose snake records & delineating populations

To develop population persistence models, we first compiled a geospatial database of occurrence records for southern hognose snakes and created population boundaries around clustered records. We compiled species records from datasets maintained by Natural Heritage Programs, USFWS, USFS, DoD, state agencies, academic researchers, and HerpMapper – an online platform where species records are reported by the public and validated by professional herpetologists (HerpMapper 2023, unpaginated). Records included opportunistic sightings, as well as observations from systematic research and monitoring studies. From the full location dataset, we removed 30 records, contained in 20 populations, that fell outside of the analysis area (all were found prior to or during 1990). We performed analyses on the remaining 213 populations.

We performed the following steps to delineate populations around all species locations. We:
1) Buffered species locations by 5 km and joined buffers that overlapped. Ideally, we would have selected a buffer distance using a reported maximum annual movement, or dispersal, distance, but this information does not exist for the southern hognose snake. NatureServe suggests a separation distance for colubrid snakes of 10 km (6.2 miles) for suitable habitat and 1 km for unsuitable habitat (NatureServe 2018, unpaginated). This recommendation is based on a limited number of studies of movement and home range in colubrid snakes but was selected by NatureServe for the colubrid group because it seems generally unlikely that two locations separated by less than 10

km of suitable habitat would represent distinct occurrences. Very little information about dispersal distances and home range sizes exists for this species, so this buffer size was chosen with the input of species experts and based off of NatureServe recommendations for small terrestrial snakes (NatureServe 2018, unpaginated).

2) Split the polygons from step 1 with ecologically-relevant barriers. Movement of individuals across these barriers is believed to be extremely unlikely, and thus, areas on either side of a barrier should be considered separate populations (expert team, pers. comm.). Specifically, we used:

    a. Large rivers of the 6th or higher order from the National Hydrography Dataset (https://www.sciencebase.gov/catalog/item/62c6050cd34eeb1417baff15), and

    b. Primary roads classified as Route Type (RTTYP) "I" (i.e., Interstate) from the TIGER/Line 2023 Primary Roads dataset (https://catalog.data.gov/dataset/tiger-line-shapefile-2023-nation-u-s-primary-roads).

3) Removed any polygons from step 2 that now did not have any species records within them and modified final boundaries to reflect 5-km buffers around locations within a population. We also clipped final population boundaries by the U.S. Coastline.

After we delineated populations, we associated the population ID number and representative unit for each southern hognose snake record in ArcGIS. Using the southern hognose snake record dataset, we created observation histories (denoted as $y_{i,t}$) describing if at least one individual was observed in a population (i) in a given year (t) ($y_{i,t} = 1$, 0 otherwise). These observation histories were used to model persistence (see Section 1.4).

1.2 Collecting non-target snake species records

Models similar to our approach rely on absence information – i.e., when searches occurred but the target species was not observed – to estimate survival, abundance, and persistence (Kéry et al. 2009, entire; Kéry and Schaub 2012, p. 171-239; MacKenzie et al. 2002, entire). However, robust search effort and absence data do not exist for the southern hognose snake. Therefore, we developed a search effort index from occurrence records of southern hognose snakes and other snake species commonly observed in southern hognose snake habitats (hereafter search effort dataset) obtained from HerpMapper.org and other partners. We used the search effort dataset to account for imperfect detection of the southern hognose snake and improve the precision of persistence estimates. Records of other (non-target) snake species that fall within a given population boundary indicate that the area was searched by an individual in a given year and inform the likelihood a population is still persisting. For example, imagine two populations: A and B. Southern hognose snakes have not been observed in both Populations A and B since 1990. Population A has been frequently searched since then, and other species of common snakes continue to be reported in the area. Population B has only been searched once since then. Assuming everything else is equal, there is more evidence that Population A has become extirpated of southern hognose snakes while Population B is more uncertain. In using non-target species data, we made the following assumptions: 1) non-target records indicate an event when an area known to have southern hognose snakes at some time was searched, 2) the search was performed in a way that southern hognose snakes could be observed (e.g., road surveys), and 3) when a person submitted non-target records but not southern hognose records to HerpMapper after a search, this indicated the area was searched but no southern hognose was found (i.e., we assumed southern hognose snakes would be reported if found).

We developed a list of 14 non-target species most commonly observed while surveying for southern hognose snakes that are active during the same months of peak activity (May, June, September, and October): *Agkistrodon contortrix subspp.*, *Agkistrodon piscivorus subspp.*, *Cemophora coccinea subspp.*, *Coluber constrictor subspp.*, *Crotalus adamanteus*, *Crotalus horridus*, *Heterodon platirhinos*, *Lampropeltis getula subspp.*, *Masticophis flagellum subspp.*, *Opheodrys aestivus subspp.*, *Pantherophis*

guttatus, *Pantherophis obsoletus subspp*, *Pituophis melanoleucus subspp.*, and *Thamnophis sirtalis subspp.* (multiple experts, pers. comm.). We queried Natural Heritage Programs, USFWS, U.S. Forest Service, DoD, State agencies, academic researchers, and HerpMapper and accessed 16,448 records of these snake species that fell within boundaries of the 213 southern hognose populations in the analysis area and occurred between 1880-2023. We added our full dataset of southern hognose records since these indicate search events as well. While HerpMapper launched in 2013, there were records included in this and the other snake datasets used to create a search effort index that were collected between 1880 and 2023.

We associated the population ID number for each record in the search effort dataset in ArcGIS. Some records that had been previously shared among partners were duplicated across data sets. Thus, in order to create an index of search effort, we filtered the search effort dataset to remove duplicate records. We did this by checking for records that shared the same species, date, and location. Thus, the dataset represented unique records to the best of our knowledge and included 19,080 records in total. We then followed the same process used to create observation histories of southern hognose snakes to create search effort histories for each population. Search effort histories ($s_{i,t}$) described the number of records for population (i) in year (t).

1.3 Extracting current site-level conditions for populations

Using the population boundaries, we summarized population-specific metrics for several spatial variables that likely influence persistence and used these as predictors in the persistence model. We included three metrics representing site-level conditions in the analysis: 1) average Habitat Suitability Index (HSI), estimated in the habitat analysis, 2) proportion of the population area protected, and 3) number of additional populations within 10 km.

We used the Zonal Statistics tool in ArcGIS to calculate mean HSI within each population boundary. HSI can be thought of as a measure of habitat quality between 0 (most unsuitable, lowest quality) to 100% (most suitable, highest quality). Predicted HSI for the southern hognose snake was positively related to the amount of well-drained, sandy soils, compatible landcover (e.g., mixed/evergreen forest, scrub/shrub, grasslands, flatwoods), and fire frequency.

We used the Zonal Statistics tool to calculate proportion of a population boundary currently in protected lands. We created a protected lands raster where areas included in the U.S. Geological Survey Protected Areas Database (http://www.protectedlands.net/data/), Florida Natural Areas Inventory Conservation Lands Database (https://www.fnai.org/publications/gis-data) , Georgia Department of Natural Resources Conservation Lands 2019 Database (https://data.georgiaspatial.org), North Carolina Natural Heritage Program Natural Heritage Areas and Managed Areas Databases (https://ncnhde.natureserve.org/content/data-download), The Nature Conservancy Conserved Lands of South Carolina Database (https://tnc.maps.arcgis.com/apps/dashboards/e2214b443c65483091cb744b13fed253), and Alabama Department of Conservation and Natural Resources Wildlife Management Areas, State Lands, State Parks, and Forever Wild Tracts Databases (https://conservationgis.alabama.gov/adcnrweb/rest/services) were given a value of 1. These areas include publicly-owned and managed lands as well as private lands registered in state or federal programs where natural resource conservation is one of the management goals. All other area was given a value of 0. Therefore, calculating the mean of the protected lands raster within each population boundary yielded the proportion of protected land.

Lastly, we used the buffer and spatial join tools in ArcGIS to calculate the number of populations found nearby (within 10 km). Although experts believed movement between two populations was unlikely if they were greater than 5 km apart, we recorded populations within 10 km because they may provide

opportunities for "rescue" where recolonization can occur after a catastrophe; alternatively, nearby populations could provide a signal that there are localized conditions (e.g., geological, climatic) that promote population persistence that have not been otherwise captured in our analyses.

1.4 Current persistence model

We used a modified version of the model developed in version 1.0 of this SSA and subsequently published in the peer-reviewed literature (hereafter, persistence model; Crawford et al., 2020b, entire) to estimate trends in southern hognose snake populations and derive probabilities that each population in the species' range persists currently in 2023. This model is adapted from the Cormack-Jolly-Seber model (Brooks et al. 2000, entire; Lebreton et al. 1992, entire), designed to estimate survival of individual animals based on mark-recapture data. Analogous to the Cormack-Jolly-Seber model, we structured the persistence model to estimate persistence ("survival") of populations based on their observation histories. Under this framework, persistence can also be thought of as 1 – the probability of extinction for each population.

We developed the persistence model using a state-space formulation fitted in a Bayesian framework (Kéry and Schaub, 2011, pp. 171–239). State-space models explicitly model how the state of a system changes over time (e.g., population persistence and extirpation) as well as the process of observing an individual, given the population has not become extirpated. Thus, they are helpful in separating real biological signals from error in observation data.

We modeled the state history ($z_{i,t}$) of a population over the period from 1880 to 2023. We modeled state histories of populations as a function of an annual population-specific persistence probability $\varphi_{i,t}$, where a population could either persist ($z_{i,t} = 1$) or become extirpated ($z_{i,t} = 0$), given that it still persisted the year before ($z_{i,t-1} = 1$). Using this approach with our Bayesian formulation, we provided the model with information about the known state of populations, which helped it estimate parameters. For example, a population where southern hognose snakes were first detected in 1980 and last detected in 2000 indicates that it persisted at least between 1980 and 2000, and we would supply known states ($z = 1$) for that population between these years (but the model would predict z states each year after 2000). In all years, the prediction of a z state in any year is a random outcome of the model (0 or 1) when no snake was observed in the population that year and is a deterministic outcome (1) for years when snakes were observed. In order to characterize current population resilience, we derived the probability that each population still persisted in 2023 by calculating the proportion of model iterations where a $z_{i,2023} = 1$. We interpret this value as the probability a population has persisted through the entire time period modeled and still exists (which we refer to as current persistence), and we note that this value differs from $\varphi_{i,t}$ estimated in the model that reflects the probability a population will persist into the next year (which we refer to as annual persistence). We modeled observation histories ($y_{i,t}$) for a population as a function of the probability of detecting at least one individual, $p_{i,t}$, given that the population had not become extirpated.

We included additional effects on persistence and detection parameters. For persistence, we included a fixed effect for the population's representative unit (φ_{rep}). This allowed for a different baseline persistence probability for each unit. We also included three fixed effects for each of the predictors indicating conditions measured at each population: mean Habitat Suitability Index (β_{HSI}), proportion of a population protected ($\beta_{protect}$), and number of nearby populations ($\beta_{connect}$). This allowed for estimating the relationships between each predictor and persistence probabilities across the species' range. For detection, we included an intercept (p_0). We included a trend effect (p_{beta}) that allowed mean detection to change over time, given that the amount of search effort in our dataset substantially increased between 1880 and 2023 and the quality of search effort may be higher in recent years due to more easily

accessible information on where and how to search for this species. We also included a fixed effect of search effort (p_{effort}), using the search effort index data, and a fixed effect for the total area within each population boundary that was within 2 km of a major road (p_{road}). Major roads included primary and secondary roads from the 2023 TIGER/Line Roads National Geodatabase (https://www.census.gov/geographies/mapping-files/time-series/geo/tiger-geodatabase-file.html). This was used to account for the effect of roads on re-detection probability, given that many observations of southern hognose snakes occurred on roads.

We used standard practices for fitting Bayesian models following Kéry and Schaub, (2011, pp. 171–239). We fit the persistence model with Markov chain Monte Carlo (MCMC) methods in Jags called from R via the R2jags package (Su and Yajima 2012, entire). We assigned diffuse prior distributions for all parameters, and we generated three MCMC chains using 500,000 iterations where we retained every third iteration from the last 400,000 iterations, yielding a final set of 349,998 samples from posterior distributions of the parameters. We assessed convergence for all models by visually inspecting chain mixing in MCMC trace plots and posterior distribution plots for evidence of unimodality. To assess goodness-of-fit, we conducted posterior predictive checks (Gelman et al. 2000, entire) where we simulated datasets using parameters estimated in the model, calculated the mean number of populations with simulated detections of southern hognose snake in four time periods (1920-1929, 1950-1959, 1980-1989, and 2014-2023), and compared mean observations in these periods from the real dataset with values from simulated datasets. We based parameter inferences on posterior means and 95% Bayesian credible intervals (BCIs; 2.5th – 97.5th percentile of the distribution).

We measured southern hognose snake population resiliency by using current persistence probabilities (between 0 and 100%), and we summarized results by grouping populations into categories representing ranges of persistence probabilities. The categories we chose were unlikely or extirpated (< 50%), more likely than not on landscape (50 – 79%), very likely on landscape (80 – 94%), and extremely likely on landscape or extant (95 – 100%). For a population to be classified in the more than likely, very likely, or extremely likely categories, the lower 95% credible interval of the estimated current persistence probability had to be equal to or greater than 50%, 80%, or 95% respectively. This criterion allowed us to say that we were 97.5% certain that a population was in that persistence category. A population was classified as unlikely or low likelihood of persisting if the lower limit of the 95% credible interval for current persistence probability was below a probability of 0.5 even if the mean estimate for that population exceeded 0.5. This means that our classification of persistence was conservative and unlikely to over-represent the current resilience of a population or range-wide status of the species. For a population to be highly resilient, it must have a relatively high current persistence probability.

To characterize representation and redundancy, we captured predictions of the number of resilient populations within a representative unit and range-wide in two ways. First, we summed the number of populations within a unit and range-wide with current persistence probabilities at or above each category (threshold) as described above for characterizing population resiliency. Second, we recorded the number of populations predicted to persist in 2023 within each unit and range-wide using direct outputs from the model. Each model iteration recorded the number of populations persisting in 2023 in each representative unit and range-wide, and we used all model iterations to calculate the mean (the most likely prediction) and 95% confidence intervals for the predicted number of persisting populations in 2023.

One can think of the difference between a specific population's probability of persistence and the mean number of populations persisting within a representative unit by considering a set of four fair coins. Each has a 50% probability of getting a heads – this is a population's persistence probability. If we flip all four coins many times, the most likely outcome, on average, is getting two heads and two tails – this is the mean number of persisting populations predicted in a model iteration. The specific coins that yield a heads may change each trial, but we still expect two out of four heads most commonly. Therefore, when

assessing representation and redundancy at the scale of a representative unit and range-wide, it may be helpful to consider the two types of results alongside each other. One can interpret the mean number of persisting populations as the most likely outcome then further assess the current resiliency of populations within a representative unit and range-wide using the number of populations above a certain persistence threshold (e.g., 80%). When comparing these two metrics, it is important to remember that for a population to be classified above a certain persistence threshold, the lower 95% credible interval of the estimated current persistence probability had to be equal to or greater than the respective threshold (as described in section 4.1.3).

We measured representation using the number and distribution of resilient populations (i.e., those above a certain persistence probability threshold) across representative units in the species' range as well as assessing the spatial distribution (latitudinal and longitudinal variability) of resilient populations. To have high representation the species must have multiple highly resilient populations located in each of the representative units, and those occupied units should span the latitudinal and longitudinal extent of historical populations. We measured redundancy using the current number and distribution of resilient populations within representative units and across the range of the species. To have high redundancy, the southern hognose snake would need to have multiple resilient populations within a representative unit and throughout its range.

1.5 Future scenarios and spatial analysis

We considered processes that may influence future habitat suitability and population persistence of the southern hognose snake and grouped these into six plausible scenarios to simulate future conditions. We used spatial analyses performed in ArcGIS to capture changes in land cover and fire frequency due to future urbanization and the effects of climate change on sea level rise and on opportunities for prescribed fire. Changes in these spatial predictors subsequently influenced future habitat suitability, as predicted by the habitat suitability model, and population persistence, as predicted by the stochastic simulation model. We describe spatial analyses of future stressors below.

We captured the effects of future urbanization and sea level rise on compatible land cover for southern hognose snake populations. First, we mapped areas predicted to be urbanized in the future using the FUTure Urban-Regional Environment Simulation (FUTURES) model (Meentemeyer et al., 2013, entire) Our use of this model replaced the Slope, Land cover, Exclusion, Urbanization, Transportation, and Hillshade (SLEUTH) model, which we used to predict urbanization in version 1.0 of this SSA. Specifically, we used the probabilistic projections of urbanization by decade from FUTURES version 2.0 (Petrasova et al., 2023, unpaginated). These projections provide probabilities of new development ranging from 0-1 with higher values indicating areas more likely to be developed. The model specifies a 0% probability of urbanization for areas protected from development (e.g., conservation areas); however, some state conservation lands were omitted. Therefore, we set the probability of urbanization to 0 for any cell that overlapped our raster of currently protected areas. We used FUTURES projections from 2040, 2060, and 2080 and selected all cells with a ≥ 90% (most conservative), ≥ 50%, and ≥ 10% (most liberal) probability of urbanization to represent low, medium, and high levels of urbanization, respectively. In addition to urbanization, we captured potential loss of habitat due to inundation from sea level rise. We obtained projections of sea level rise associated with Representative Concentration Pathways (RCPs) from the Sixth IPCC Assessment Report (IPCC, 2021, p. 21-23) and used SLR inundation maps from the National Oceanic and Atmospheric Administration (https://coast.noaa.gov/slrdata/). Based on the IPCC report, for RCP 4.5 we assumed sea level rise of 1 ft at years 2040 and 2060 and 2 ft at year 2080 and for RCP 8.5 we assumed sea level rise of 1 ft at years 2040 and 2060 and 3 ft at year 2080. For each projected height of sea level rise, we created a raster of inundated areas. Finally, we captured the reduction in compatible land cover from urbanization and sea level rise for each time period and stressor level by removing areas predicted to be urbanized or inundated from the current compatible land cover

layer using the Raster Calculator tool and calculated the proportion of compatible land cover in each population boundary using the Zonal Statistics tool.

We also captured the effects of urbanization on fire frequency. This was done to account for fire exclusion/suppression that often occurs in habitat adjacent to urban areas, known as the wildland-urban interface, due to safety and smoke management restrictions (Theobald and Romme 2007, entire). Studies have found evidence of fire exclusion/suppression in habitats within 600 m to 5 km of urban areas (Pickens et al. 2017, entire; Theobald and Romme 2007, entire). Therefore, we chose a moderate value of 3.2 km (2 mi) to capture the interaction between urbanization and fire frequency. Using the predicted urbanized areas at each time period and urbanization probability level, we identified areas within 3.2 km of urban areas using the Euclidian Distance tool. We then projected future reductions in fire frequency starting with the current fire frequency raster and applying a distance-weighted reduction to any cell within 3.2 km of urban areas. Using this approach, fire frequency for any cell overlapping future urban areas was reduced by 100% (equaled 0) and any cell more than 3.2 km away from urban areas was reduced by 0% (unchanged). Any cell between 0 and 3.2 km away from urban areas was reduced by a percentage proportional to its distance – i.e., a cell 1.6 km from urban areas was reduced by 50%. We then recalculated the mean fire frequency for each population.

To account for changes in fire frequency from climate change, we used U.S. Geological Survey historical and future prescribed burn windows for the Southeast United States (Kupfer et al. 2021, unpaginated). This dataset included observed mean proportion of days suitable for burning by month for the periods of 2000-2009 and 2010-2017 and decadal mean future proportions of days suitable for burning by season. To correspond with the fire frequency predictor used in our model of habitat suitability, which used annual fire detections from 2001-2016, for each cell we calculated an annual weighted average of the historical 2000-2009 and 2010-2017 data and weighted monthly data according to number of days per month. For future burn windows, we used data for RCPs 4.5 and 8.5 and each decade leading up to 2040, 2060, and 2080. For each cell we calculated the decadal averages across seasons weighted by number of days per season. We calculated population means for each burn window data set and used the population averages to calculate proportional changes in fire windows for 2040, 2060, and 2080 for each RCP. We assumed that these would result in the same proportional changes in fire frequency and reduced each population's mean fire frequency accordingly, which subsequently affected overall habitat suitability. Two populations did not have data for observed fire window, so we used values from the nearest populations.

Our six future scenarios included all possible combinations of urbanization (low, medium, high) and climate change (RCP 4.5, RCP 8.5). For each scenario, we used the resulting land cover and fire frequency layers as inputs for predicting future habitat suitability and population persistence. We also compared a seventh scenario that included no changes in urbanization or climate and SLR from the current conditions. This created a null expectation for projected population losses against which we could compare the models with projected changes in urbanization and climate.

1.6 Future simulation persistence model

We used a stochastic simulation model that used a Markovian process to predict the probability of persistence in the future for each population in the analysis area based on the current probability of persistence and future predicted changes in habitat suitability and land protection. The primary output metric for this model was the probability a population persists at a given year in the future (2040, 2060, and 2080), which we call "future persistence probability." We calculated the future persistence probability for each population as the proportion of model iterations where the population was persisting at a given year. The complement of future persistence probability can be interpreted as the probability a population has become extirpated by a given year.

We built a multi-loop simulation model (following McGowan et al. 2014, entire) that allowed us to simulate thousands of replicates of each population under different scenarios. This approach accounted for random year-to-year stochasticity as well as uncertainty around rates (i.e., annual persistence probability) estimated from the current persistence model. The model looped through 10,000 iterations for each of the six scenarios. It then looped through each of the 213 southern hognose snake populations within the analysis area and simulated persistence from the present (2023) to 2080. We briefly discuss the model framework, inputs, and outputs below.

In short, the model calculated inputs from the spatial analysis (compatible land cover, fire frequency, and proportion of protected area), predicted habitat suitability, selected a set of parameter estimates from the current persistence model, used inputs and the parameter estimates to predict annual probabilities of persistence in the future, and used the annual persistence probabilities to predict the state of each population (persisting or extirpated) each year through 2080. It accomplished this through a series of steps.

Step 1) Each iteration of the model began by calculating annual values of land cover and fire frequency by interpolating the values of these predictors calculated in the spatial analysis in 2040, 2060, and 2080. These input values were scenario-dependent.

Step 2) The model then used inputs of land cover and fire frequency, along with all other predictors used in the habitat suitability model (e.g., soil drainage, local elevation) that did not change in future scenarios, to calculate mean habitat suitability for each population and year, given conditions of each scenario. This was done using the habitat suitability model and the predict.glm function in R.

Step 3) Each iteration of the simulation selected a single set of parameter estimates ("posterior estimates") generated from one iteration of the current persistence model. These parameters included mean current persistence probability for each population and the estimated effects of all predictors of the annual persistence probability (mean representative unit persistence, habitat suitability, proportion of protected land, and number of populations within 10 km). This was done in order to account for the uncertainty around parameters (parametric uncertainty) estimated in the current analysis, as well as year-to-year stochasticity in the simulation model. Therefore, the simulation model results varied between iterations based on which parameter estimates were randomly selected.

Step 4) Once we had a sample of posterior estimates and scenario-, population-, and year-specific inputs, the model calculated annual probabilities of persistence using the same model structure as the persistence analysis. Annual persistence probability was a function of mean representative unit persistence, habitat suitability, proportion of protected area, and number of populations within 10 km. The model simulated the state of each population each year through 2080. The probability of persistence in 2024 was equal to the mean current persistence probability for each population multiplied by the annual persistence probability for that population that was randomly selected from the estimates generated in the current persistence model ($j_{current}*j_t$). The state of the population (persisting or extirpated) in the next year was drawn from a Bernoulli trial using that probability. For years 2025 through 2080, the state of a population was drawn from a Bernoulli trial using the annual persistence probability, given that the population had persisted in the previous year. Thus, as in our current persistence model, extirpation was an absorbing state (i.e., recolonization was not allowed).

Step 5) The model recorded summary outputs useful for characterizing resiliency, redundancy, and representation. For this model, the primary output was the probability a population persists at a given year in the future through 2080, which we call "future persistence probability." We calculated the future persistence probability for each population as the proportion of model iterations where the population was

persisting at a given year. The complement of future persistence probability can be interpreted as the probability a population has become extirpated by a given year. These future persistence probabilities for populations are directly comparable to the current persistence probabilities. We characterized future conditions similarly to current conditions by summarizing the number of populations at or above certain persistence probability thresholds (50, 80, 90, and 95%) in each representative unit and range-wide, given each of the six scenarios. Like in the current conditions analysis, in addition to a specific population's persistence probability, each model iteration recorded the number of populations persisting at each time step in each representative unit and range-wide. We used all model iterations to calculate the mean (the most likely prediction) and 95% confidence intervals for the number of persisting populations in each representative unit and range-wide each year. We summarized these outputs for three future time horizons: 2040, 2060, and 2080.

2. Results & Discussion

2.1 Current and historical populations

We obtained 2,262 southern hognose snake records from years 1880-2023. Many of the early occurrence records were for the county only and no coordinates were available for these records. The occurrence records were spread throughout the species range, but a majority of the records came from the Upper Coastal Plain (Carolinas) representative unit. From these records, we identified 233 potential populations of southern hognose snakes with a mean area of 13,360 ha (range = 1,248 – 236,477 ha). Of the total pool of records and populations, we used 2, 632 occurrence records grouped into 213 populations within the analysis area to fit the persistence model and simulate future persistence. The remaining 30 occurrence records that fell outside of the analysis area were grouped into 20 populations. All but two of these records were found prior to or during 1990 and likely represent extirpated populations, and thus are included in our resiliency analysis as extirpated. The remaining two records located outside of the analysis area, representing two populations, were found within the last five years (2019 and 2021). Since we were unable to estimate current persistence probability for these two populations, we consider their status to be unknown.

2.2 Predictor effects on current persistence

Out of the 144 years we modeled (1980-2023), the mean number of years southern hognose snakes were found in a population was 3.08 (range = 1 to 48). From the search effort dataset, the number of records per year per population ranged from 0 to 548 (mean = 0.622), and records of non-target species came from 174 of 213 (81.7%) populations within the analysis area.

The persistence model showed adequate convergence, as assessed with traditional practices (MCMC chains were mixing well, Brooks-Gelman-Rubin statistics < 1.1 for all parameters). Posterior predictive checks indicated that the model fit the data adequately in the first and last time periods assessed but had poorer fit in the two intermediate time periods assessed (Figure A-1). This lack of fit in the intermediate time periods likely indicates that the detection model failed to capture some non-linearity between effort and re-detection probability through time, and that detection is likely underpredicted. Consequently, persistence estimates may be biased high. Efforts to improve model fit included soliciting non-target species records from partners that provided southern hognose snake records but no non-target species records for version 1.0 of this SSA. We were able to obtain a much larger non-target species data set, better representing search effort within more southern hognose snake populations. This effort did improve model fit but did not fully resolve the issue.

As estimated in the persistence model, persistence varied considerably by population (Table A-1) but was positively and significantly influenced by mean habitat suitability and number of populations within 10

km (Table A-2, Figure A-2). Mean annual persistence rates were similar across representative units (Table A-2). Detection was positively and significantly influenced by time (i.e., trend effect), search effort index, and area of the population within 2 km of a major road (Table A-2, Figure A-2).

Relationships between persistence and site predictors agree with expert judgment that the species generally uses and survives best in fire-dependent, xeric habitat (e.g., longleaf pine sandhills) – attributes that are associated with a higher Habitat Suitability Index. The strong relationship between number of populations within 10 km and persistence could support that nearby populations may provide opportunities for "rescue" where recolonization can occur after a catastrophe. It may also be an artifact of large core areas of high-quality habitat that support multiple populations or subpopulations over large geographic areas.

2.3 Current conditions

As mentioned previously, we used the model to derive the probability that each population was still persisting in 2023 (current persistence), and we summarized range-wide patterns of resiliency using the proportion of populations at or above a certain persistence threshold. Overall, resiliency, as measured by number of extant populations, has decreased for this species range-wide. Across the species' range, 87 of 233 (37.3%) delineated populations had a probability of current persistence greater than 50%, 55 (27.9%) had a probability of current persistence greater than 80%, and 33 (14.2%) had a probability of current persistence greater than 95%. We have likely lost at least 61.8% of southern hognose snake populations (i.e., populations with a less than 50% probability of current persistence). We report mean persistence estimates and 95% credible intervals for each population in Table A-1.

Current representation, as measured by the number and distribution of resilient populations (i.e., those above a certain persistence probability threshold) across representative units in the species' range has also decreased from historical conditions. To have high representation the species must have highly resilient populations located in each of the representative units, and those occupied units should span the latitudinal and longitudinal extent of historical populations. The southern hognose snake has experienced a complete loss of two representative units, one additional representative unit is at risk of becoming extirpated, and all the remaining units are showing declines in the number of resilient populations. There has been a loss of latitudinal and longitudinal variability within the range as all of the populations at the northeastern and western extent of its range have been extirpated.

Current redundancy, as measured by using the current number and distribution of resilient populations within representative units and across the range of the species has been reduced from historical conditions. To have high redundancy the species needs to have multiple resilient populations within representative units and throughout its range. Each of the 9 representative units has likely lost at least 37.7% –100% of its populations. Range-wide, the number of populations more likely than not to currently persist has decreased by 61.8%, relative to the historical number of populations. The southern hognose snake has experienced a decline in the number of resilient populations within each of the representative units and across its entire range. Additionally, the distribution of resilient populations within each unit and across the range has become clustered, leaving portions of each representative unit and overall range-wide lacking resilient populations.

2.4 Future conditions

Under current conditions, the average population had compatible land cover of 50% (range = 9 – 92%), which decreased between 5.6% (Low Urbanization/RCP 4.5 - best case scenario) and 7.1% (High Urbanization/RCP 8.5 - worst case scenario) on average across all scenarios. In terms of area, the average population had 77.5 km^2 (range = 1.5 – 1202.7 km2) of compatible land cover under current conditions,

which was reduced by 8.3 – 10.3 km^2 on average across future scenarios. While some populations experienced no loss of land cover, others were predicted to lose as much as 60.8% of compatible land cover due to urbanization and climate change. Burn windows, which averaged 292 days/year (range = 248 – 327 days/yr) under current conditions, were reduced by 58 – 86 days on average across the two climate change scenarios. These shorter burn windows, in combination with urbanization, resulted in fire frequencies (mean = 3.7%; range = 0 - 20.5% under current conditions) being reduced by 2.7 – 2.8% on average across scenarios. Using the reduced fire frequencies, the total number of burns between 2023 – 2080 for an average population is expected to be reduced by 1 with a range of approximately 0 to 9 fewer burns across all populations, compared to if burn frequency was not reduced from current levels (mean = 2; range = 0 – 12 burns from 2023-2080 under current levels). Finally, under current conditions, the average population had a mean HSI of 21.3%, which decreased between 2.8% (best case scenario) and 3.1% (worst case scenario) on average across all scenarios.

We used the simulation model to predict the future persistence probability for each of the 213 populations in the analysis area through the year 2080. As with current persistence we could not analyze the 20 populations outside the analysis area and considered the 18 populations with records found prior to or during 1990 to be likely extirpated and the remaining two populations with records in 2019 and 2021 to be "unknown". We followed similar steps to the current conditions analysis to summarize population resiliency across the species' range by reporting the number of populations in each category of persistence probability (50%, 80%, and 95%).

For all scenarios, future population persistence decreased from current conditions and all populations that fell within the extremely likely on landscape (≥95%) threshold under current conditions were predicted to have lower persistence probabilities in the future and, thus, dropped to lower categories. The number and percentage of populations likely to be extirpated (<50%) increased for all scenarios and future time horizons, relative to current conditions. For example, the number of historical populations likely to be extirpated (<50%) in 2023 was 144 of the total 233 populations, leaving 87 populations across the more likely than not on landscape (50 –79%), very likely on landscape (80 – 94%), and extremely likely on landscape or extant (95 – 100%) categories. Under the Low Urbanization/RCP 4.5 scenario by 2040, 39 additional populations were predicted to be extirpated. Between 2040 and 2060 an additional 19 populations were predicted to be extirpated and between 2060 and 2080 an additional 9 populations were predicted to be extirpated for a total of 67 populations predicted to become extirpated between 2023 and 2080. These numbers are very similar for the High Urbanization/RCP 8.5 (worst case) scenario. The very small difference in resiliency between the scenarios was consistent with the minimal differences between the scenarios in the amount of land cover loss and change in habitat suitability for populations. The similarity in results between the stressor scenarios and the null model suggest that future population declines predicted to occur are primarily a consequence of population persistence probabilities being <1 for each population and no processes included in our model for colonization or recolonization, rather than a consequence of decreased habitat suitability due to climate change and urbanization.

Overall, we predicted future representation and redundancy to decrease from current conditions. The number of resilient populations and the number of representative units with resilient populations decreased under all scenarios. In our current condition analysis, we determined that the southern hognose snake has likely become extirpated in 2 of 9 representative units. Six of the other 7 representative units had at least 1 population extremely likely to be on the landscape (persistence probability ≥ 95%). In 2040, no representative units were predicted to be occupied by at least one population at the ≥95% threshold and 5 of 9 representative units were predicted to be occupied by at least one population at the ≥80% threshold. By 2060, between 1 and 2 of 9 representative units were predicted to be occupied by a single population at the ≥80% threshold and 6 of 9 representative units were predicted to be occupied at least population at the ≥50% threshold. By 2080, 1 of 9 representative units was predicted to be occupied by a single population at the ≥80% threshold and 5 of 9 representative units were predicted to be occupied at

least population at the ≥50% threshold. Additionally, by 2080, only 3 of 9 representative units had at least 2 populations at the ≥50% threshold and only 2 representative units had at least 3 populations at the ≥50% threshold.

One representative unit, Atlantic Coastal Plain (GA/FL), was predicted to have no remaining populations more likely than not to persist (≥50%) by 2040 in all scenarios. Thus, the Atlantic Coastal Plain (GA/FL) was predicted to be at the highest risk of extirpation, relative to the other units, and indicates a high potential for losing representation of the species in this unit in the future.

In addition to summarizing future conditions using the number of populations meeting a certain persistence probability threshold, we present the mean number of populations still persisting (and 95% confidence intervals), as predicted directly from the simulation model. As discussed above, we again see that the Atlantic Coastal Plain (GA/FL) was the representative unit with the highest risk of losing representation, relative to other units, with a mean estimate of 0 populations persisting in 2040. Two other units (the Atlantic Coastal Plain (Carolinas) and AL/FL Panhandle) had a relatively high risk of losing representation as the mean number of populations was 3 for these units and the lower 95% confidence interval included 0 populations persisting in 2080. Additionally, 3 units (Upper Coastal Plain (Carolinas), FL Peninsula, and FL Ridge had a moderate risk of losing representation as the mean number of populations were 4, 6, and 6, respectively for these units but the lower 95% confidence intervals were 1, 1, and 2, respectively in 2080. Only the Upper Coastal Plain (GA/FL) unit is at low risk of losing representation with a mean of 20 populations persisting in 2080.

Redundancy, as measured by the number of populations above the 50, 80, and 95% persistence threshold and by the mean number of populations persisting, decreased in all scenarios, time periods, and representative units, relative to current conditions. All scenarios yielded nearly identical predictions of the number of persisting populations. This is not surprising since there were only minimal differences between the scenarios in the amount of land cover loss and HSI for populations.

Looking at redundancy within the representative units, we see that one representative unit (Upper Coastal Plain (GA/FL)) was predicted to have at least 1 population above the 80% persistence probability threshold and at least 12 populations above the 50% threshold in 2080. The Upper Coastal Plain (GA/FL) currently has the highest number of populations and was predicted in the future to maintain the highest level of redundancy in the future, relative to the other units. All other units had highly reduced redundancy, with the second highest redundancy projected for the FL Ridge unit, with 3 populations above the 50% threshold in 2080. Lastly, we note that it is very likely that the two Western representative units (West and Alabama Central) are no longer occupied by the species and additional units are predicted to become unoccupied in the future.

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Table A-1. Southern hognose snake population summary statistics for populations within the analysis area including site-level conditions, survey effort, number of years with ≥ 1 southern hognose snake observation, last year observed, mean and lower and upper 95% Bayesian credible intervals for current persistence – the probability of a population being extant in 2023.

Population ID	Habitat Suitability Index (0 – 100)	Proportion protected	No. of pops within 10 km	Representative unit [1]	Area within 2 km of roads (ha)	Total effort	No. years with southern hognose snake observation(s)	Last year observed	Current Persistence prob. (%) Mean	Lower 95%	Upper 95%
1	0.9	0.25	0	6	7,235	6	3	1981	0.23	0.20	0.28
2	3.7	0.00	0	6	4,002	2	1	1931	0.08	0.06	0.11
3	5.5	0.39	1	7	3,053	3	1	1952	0.02	0.01	0.05
4	7.3	0.59	2	7	4,566	6	1	1904	0.01	0.00	0.02
5	55.3	0.02	1	7	4,930	24	3	1969	0.30	0.26	0.35
6	56.6	0.75	4	7	2,838	49	1	1994	0.08	0.06	0.11
7	42.4	0.74	4	7	2,175	13	2	2015	0.81	0.77	0.85
8	69.4	0.90	4	7	10,422	107	11	2023	1.00	1.00	1.00
9	27.8	0.38	1	7	4,148	20	1	2008	0.43	0.38	0.48
10	4.6	0.56	1	6	2,451	31	2	1980	0.02	0.01	0.03
11	26.8	0.63	1	7	7,052	24	2	2008	0.26	0.21	0.30
12	23.0	0.01	2	7	2,479	6	3	1967	0.13	0.10	0.16
13	26.6	0.03	2	7	3,932	2	1	1967	0.18	0.15	0.22
14	74.1	1.00	3	7	2,729	18	1	2011	0.76	0.71	0.80
15	26.2	0.02	2	7	4,855	3	1	2008	0.55	0.51	0.60
16	80.3	1.00	1	7	587	3	1	2005	0.71	0.67	0.76
17	0.6	0.69	1	6	2,225	2	1	1975	0.19	0.15	0.23
18	79.0	1.00	4	7	8,953	25	3	2022	0.99	0.98	1.00
19	26.6	0.00	0	6	7,640	15	1	1931	0.05	0.03	0.08
20	67.5	0.97	4	7	1,157	44	1	1995	0.28	0.24	0.33
21	3.2	0.03	2	7	6,332	10	2	1959	0.01	0.00	0.02
22	36.9	0.42	1	2	1,181	77	3	2012	0.58	0.54	0.63
23	17.2	0.00	1	7	-	3	1	2008	0.35	0.31	0.40
24	44.9	0.01	1	7	7,219	7	2	2022	0.97	0.95	0.98
25	0.0	0.91	0	6	8,190	27	3	1976	0.01	0.00	0.02
26	22.4	0.00	1	7	1,006	7	1	2020	0.87	0.84	0.90
27	0.8	0.00	3	7	3,014	3	1	1978	0.13	0.10	0.17
28	0.4	0.00	0	7	5,885	10	3	1969	0.02	0.01	0.04
29	0.5	0.04	1	7	5,924	20	1	1964	0.01	0.00	0.03
30	4.3	0.20	0	2	3,438	3	1	1956	0.12	0.09	0.16
31	10.8	0.62	0	7	-	16	1	1966	0.00	0.00	0.01
32	1.1	0.00	0	7	7,322	6	1	1970	0.01	0.01	0.03
33	3.5	1.00	0	7	3,953	780	2	1970	0.00	0.00	0.95
34	9.5	0.00	0	2	5,570	1	1	1957	0.25	0.20	0.31
35	0.6	0.00	0	7	6,939	9	1	1944	0.00	0.00	0.01
36	12.2	0.25	1	2	5,533	1	1	1960	0.34	0.29	0.39
37	10.9	0.06	1	2	317	1	1	2015	0.86	0.83	0.89

38	56.4	0.26	0	2	45,864	216	14	2023	1.00	1.00	1.00
39	4.8	0.54	1	4	1,619	4	1	1968	0.02	0.01	0.04
40	34.9	0.56	2	4	64,364	456	19	2018	0.14	0.11	0.17
41	14.1	0.02	2	2	3,649	4	1	1968	0.42	0.35	0.48
42	9.6	0.01	1	2	7,123	7	1	1933	0.08	0.05	0.11
43	6.9	0.37	0	2	5,508	41	1	1970	0.04	0.02	0.06
44	13.2	0.01	0	2	7,179	3	2	2010	0.75	0.70	0.79
45	24.8	0.08	2	2	915	1	1	1997	0.75	0.71	0.79
46	45.6	0.44	2	2	10,004	3,854	19	2022	0.99	0.98	1.00
47	41.1	0.06	3	2	10,394	5	3	2013	0.94	0.92	0.96
48	10.3	0.05	2	2	7,868	2	2	2000	0.73	0.69	0.77
49	57.6	0.27	2	2	89	1	1	2000	0.87	0.83	0.90
50	30.5	0.05	1	2	3,319	1	1	1959	0.50	0.45	0.55
51	9.7	0.93	3	4	-	22	1	2004	0.04	0.03	0.07
52	24.3	0.00	4	4	1,017	5	1	2011	0.77	0.72	0.81
53	32.4	0.58	6	4	2,802	27	2	2019	0.94	0.91	0.96
54	22.6	0.49	6	4	650	53	1	2016	0.69	0.65	0.74
55	69.7	0.14	6	4	4,227	24	1	1960	0.12	0.09	0.16
56	66.2	0.19	5	4	1,994	13	1	1972	0.54	0.49	0.59
57	66.6	0.03	5	4	7,867	10	3	2020	0.97	0.95	0.98
58	15.6	0.32	1	4	3,182	34	1	1969	0.00	0.00	0.01
59	38.6	0.52	2	4	-	48	1	1983	0.01	0.00	0.02
60	6.4	0.09	1	2	10,616	19	2	2016	0.77	0.72	0.81
61	31.0	0.06	6	2	24,153	49	8	2023	1.00	1.00	1.00
62	60.7	0.09	7	4	6,948	27	4	2020	0.99	0.97	0.99
63	43.1	0.02	3	4	-	51	5	2022	0.98	0.96	0.99
64	26.9	0.15	4	2	3,024	14	3	2013	0.92	0.89	0.94
65	26.0	0.11	4	2	8,618	29	3	2015	0.93	0.90	0.95
66	31.5	0.13	2	4	132	21	2	2018	0.86	0.83	0.89
67	44.4	0.00	2	4	3,607	7	1	2013	0.77	0.73	0.81
68	58.4	0.08	3	2	1,524	4	1	1973	0.78	0.73	0.82
69	10.9	0.00	2	4	3,931	6	1	1976	0.06	0.04	0.09
70	47.3	0.00	4	2	3,039	1	1	2018	0.98	0.96	0.99
71	13.8	0.31	3	2	1,843	31	5	2020	0.97	0.95	0.98
72	20.6	0.15	7	2	2,511	15	1	1973	0.34	0.29	0.39
73	13.6	0.05	4	2	5,428	12	3	2014	0.85	0.81	0.88
74	34.9	0.14	5	2	7,193	15	4	2018	0.98	0.96	0.99
75	62.4	0.07	6	2	881	4	1	2014	0.98	0.96	0.99
76	51.4	0.11	6	2	1,882	72	5	2017	0.93	0.90	0.95
77	16.3	0.08	1	2	6,975	7	1	1984	0.32	0.28	0.37
78	7.4	0.23	2	2	1,881	2	1	2003	0.64	0.59	0.69
79	19.3	0.21	0	2	-	8	1	2005	0.70	0.65	0.74

80	27.0	0.17	1	2	3,403	4	1	1953	0.43	0.38	0.48
81	3.3	0.16	0	2	6,637	1	1	1953	0.19	0.16	0.23
82	5.3	0.00	0	2	9,458	4	2	1957	0.20	0.16	0.24
83	25.8	0.21	0	2	4,450	14	1	1994	0.17	0.13	0.21
84	6.2	0.04	0	2	5,095	5	1	2021	0.95	0.92	0.97
85	3.6	0.04	1	2	5,061	2	1	1999	0.52	0.47	0.57
86	4.1	0.00	1	2	5,016	1	1	1948	0.28	0.24	0.33
87	7.8	0.04	1	2	6,019	2	2	2000	0.64	0.59	0.69
88	4.2	0.10	1	2	8,954	2	2	1980	0.44	0.38	0.51
89	5.1	0.15	0	2	4,990	1	1	1941	0.18	0.14	0.24
90	9.4	0.01	0	2	5,478	2	2	2017	0.86	0.82	0.89
91	8.8	0.02	0	2	6,863	1	1	1957	0.26	0.20	0.32
92	5.7	0.00	0	2	5,034	2	1	1961	0.27	0.23	0.32
93	7.8	0.00	1	2	6,390	2	2	2019	0.92	0.89	0.94
94	42.6	0.44	3	2	21,641	35	5	2015	0.83	0.79	0.86
95	16.3	0.03	1	2	4,401	1	1	1998	0.67	0.62	0.71
96	5.5	0.03	0	4	4,310	36	1	1969	0.00	0.00	0.01
97	12.9	0.06	0	4	4,756	9	1	1969	0.00	0.00	0.01
98	37.8	0.13	1	4	3,853	4	1	1979	0.17	0.13	0.21
99	40.8	0.64	1	4	3,854	32	1	1996	0.08	0.06	0.11
100	11.0	0.11	5	5	30,246	29	8	2023	1.00	1.00	1.00
101	44.1	0.19	5	5	13,394	34	7	2021	0.99	0.98	1.00
102	13.1	0.33	6	4	10,920	29	3	2017	0.90	0.87	0.93
103	42.7	0.28	9	5	57,578	237	24	2023	1.00	1.00	1.00
104	9.4	0.00	7	5	10,699	10	5	2021	0.99	0.97	1.00
105	35.2	0.15	3	4	5,081	18	1	1984	0.15	0.12	0.19
106	4.5	0.21	5	5	20,118	137	10	1970	0.00	0.00	0.01
107	22.6	0.20	6	5	19,263	74	14	2023	1.00	1.00	1.00
108	40.3	0.07	3	4	324	22	4	2023	1.00	1.00	1.00
109	1.4	0.27	3	4	27,026	988	21	1975	0.00	0.00	0.95
110	24.0	0.09	5	5	27,698	257	17	2022	0.99	0.97	0.99
111	38.1	0.02	2	4	3,752	1	1	2016	0.84	0.80	0.87
112	30.8	0.02	5	4	4,189	19	2	2021	0.97	0.95	0.98
113	33.6	0.00	4	5	3,690	6	1	1969	0.35	0.30	0.41
114	37.2	0.13	4	2	3,166	9	2	2019	0.98	0.96	0.99
115	1.7	0.03	0	8	1,273	1	1	1969	0.03	0.02	0.05
116	4.5	0.35	1	2	4,656	19	1	2016	0.68	0.63	0.72
117	11.0	0.03	1	2	2,610	15	1	1988	0.35	0.31	0.40
118	16.5	0.11	3	2	16,860	37	5	2021	0.98	0.96	0.99
119	46.5	0.15	4	2	6,748	74	5	2020	0.98	0.96	0.99
120	40.3	0.45	5	1	72,556	543	48	2022	0.97	0.95	0.98
121	20.5	0.01	2	2	2,843	1	1	1973	0.56	0.51	0.61

122	13.0	0.00	0	1	4,068	2	1	2014	0.67	0.62	0.71
123	8.1	0.99	0	8	1,004	2	1	1946	0.01	0.00	0.02
124	6.0	0.00	2	2	4,989	1	1	2005	0.76	0.71	0.79
125	11.4	0.00	4	2	5,991	1	1	1987	0.74	0.70	0.78
126	34.8	0.00	1	1	14,579	5	3	1934	0.22	0.18	0.26
127	12.9	0.46	2	4	2,004	5	1	2003	0.21	0.18	0.26
128	13.6	0.19	2	4	8,382	57	1	1963	0.00	0.00	0.01
129	12.1	0.00	2	4	4,780	15	1	1994	0.31	0.26	0.35
130	43.7	0.16	3	4	112	1	1	2011	0.80	0.76	0.84
131	3.2	0.15	3	4	15,929	164	5	1983	0.00	0.00	0.95
132	28.0	1.00	3	8	3,702	174	4	2020	0.85	0.82	0.89
133	36.1	0.26	2	8	2,552	10	1	1985	0.04	0.03	0.07
134	7.5	0.00	1	2	5,137	3	2	1974	0.40	0.35	0.45
135	10.9	0.07	3	2	5,594	4	2	2010	0.78	0.73	0.81
136	16.4	0.04	5	2	-	10	2	2017	0.96	0.94	0.98
137	29.3	0.01	2	1	13,559	11	6	2023	1.00	1.00	1.00
138	32.6	0.02	2	5	3,486	2	1	2013	0.90	0.86	0.92
139	6.9	0.04	3	5	18,511	66	10	2018	0.87	0.84	0.90
140	6.4	0.10	3	5	693	3	1	2022	0.98	0.97	0.99
141	2.4	0.24	3	5	841	9	1	1914	0.15	0.12	0.19
142	8.8	1.00	2	5	2,353	88	3	1970	0.00	0.00	0.01
143	5.6	0.55	1	4	-	55	1	1919	0.00	0.00	0.95
144	0.4	1.00	1	4	672	10	1	1975	0.01	0.00	0.03
145	17.6	0.04	0	8	3,665	19	1	1959	0.00	0.00	0.02
146	11.4	0.02	0	8	1,387	4	1	1946	0.00	0.00	0.02
147	20.8	1.00	1	8	4,531	22	2	2000	0.06	0.04	0.09
148	19.1	0.62	2	8	1,659	83	1	2000	0.03	0.02	0.05
149	7.7	0.01	3	8	14,337	12	5	1984	0.11	0.08	0.14
150	14.0	0.00	2	8	7,602	2	2	1987	0.25	0.21	0.29
151	24.3	0.48	2	8	6,074	11	3	2000	0.20	0.16	0.24
152	13.9	0.01	2	8	6,944	9	2	1974	0.02	0.01	0.04
153	32.1	0.48	2	3	2,817	172	4	1996	0.01	0.01	0.03
154	41.7	0.06	2	8	-	2	2	2008	0.68	0.63	0.72
155	20.5	0.03	1	8	5,584	1	1	1975	0.15	0.11	0.18
156	21.3	0.05	1	3	6,032	1	1	2007	0.64	0.59	0.69
157	34.5	0.69	3	3	8,166	29	3	2021	0.96	0.94	0.98
158	8.1	0.02	1	1	7,228	2	1	1974	0.20	0.17	0.24
159	14.8	0.01	1	5	6,236	27	1	1969	0.29	0.25	0.33
160	13.6	0.04	1	5	12,974	56	2	1950	0.01	0.00	0.02
161	6.7	0.02	0	5	5,441	18	1	1950	0.17	0.14	0.21
162	16.7	0.13	0	3	5,218	3	1	1975	0.12	0.09	0.15
163	38.8	0.24	0	3	6,757	50	2	2017	0.38	0.34	0.43

164	16.6	0.02	0	3	4,201	1	1	1977	0.21	0.17	0.25
165	27.1	0.00	0	3	3,523	1	1	1958	0.16	0.12	0.19
166	8.0	0.40	0	3	1,997	9	1	1976	0.02	0.01	0.04
167	7.1	0.58	0	3	5,515	1	1	1938	0.02	0.01	0.04
168	12.7	0.30	0	3	4,728	2	1	2000	0.31	0.26	0.35
169	3.4	0.37	1	1	120	1	1	1954	0.13	0.10	0.16
170	34.4	0.73	1	1	10,999	4	3	2002	0.56	0.51	0.61
171	50.0	0.94	0	1	2,950	108	2	1995	0.07	0.05	0.11
172	43.9	0.75	1	1	22,606	75	9	2011	0.04	0.02	0.06
173	49.3	0.03	1	1	6,147	2	1	1974	0.46	0.41	0.51
174	37.0	0.41	5	1	91,709	1,965	42	2023	1.00	1.00	1.00
175	8.1	0.13	0	3	10,964	10	3	2023	1.00	1.00	1.00
176	33.5	0.99	0	3	2,778	889	12	2023	1.00	1.00	1.00
177	0.0	0.01	0	1	3,844	1	1	2023	1.00	1.00	1.00
178	40.2	0.54	0	3	3,318	8	1	1986	0.15	0.12	0.19
179	18.0	0.04	0	3	5,085	4	1	1973	0.09	0.06	0.12
180	26.6	0.94	0	3	6	84	1	1997	0.08	0.06	0.11
181	7.9	0.26	1	3	5,096	144	1	1972	0.00	0.00	0.01
182	6.0	0.12	1	3	6,635	2	1	2000	0.31	0.27	0.36
183	10.0	0.10	1	3	5,283	4	1	2009	0.31	0.26	0.35
184	13.0	0.34	2	3	13,739	24	4	2023	1.00	1.00	1.00
185	29.1	0.26	3	3	7,451	101	17	2022	0.98	0.95	0.99
186	33.3	0.89	3	3	8,195	35	2	2009	0.21	0.17	0.25
187	24.7	0.68	4	3	1,248	17	5	2023	1.00	1.00	1.00
188	22.1	0.09	5	3	11,301	16	2	1977	0.11	0.08	0.14
189	41.4	0.69	3	3	3,621	19	5	2014	0.74	0.69	0.78
190	0.6	0.00	3	1	4,085	3	1	1983	0.23	0.19	0.28
191	1.2	0.00	2	1	4,724	2	1	2013	0.66	0.61	0.70
192	4.3	0.21	4	3	6,629	145	1	1977	0.01	0.00	0.02
193	12.2	0.09	6	3	4,803	5	1	1973	0.31	0.27	0.36
194	11.9	0.26	2	3	3,057	36	2	2012	0.29	0.24	0.33
195	13.5	0.37	2	3	2,197	7	1	2002	0.14	0.11	0.18
196	14.5	0.13	0	3	4,290	16	1	1983	0.01	0.00	0.02
197	0.4	0.39	5	1	14,780	160	3	1981	0.01	0.00	0.02
198	0.5	0.01	5	1	7,286	2	1	1968	0.39	0.34	0.44
199	9.0	0.00	3	3	6,341	5	1	2007	0.43	0.38	0.47
200	4.2	0.44	5	1	3,682	579	1	2018	0.19	0.15	0.23
201	9.5	0.11	5	3	14,949	1,906	6	2018	0.00	0.00	0.01
202	8.3	0.18	4	3	5,163	2,039	4	2019	0.00	0.00	0.01
203	2.1	0.02	1	1	6,817	3	1	1989	0.18	0.14	0.22
204	1.0	0.07	4	1	1,405	2	1	1989	0.48	0.43	0.53
205	2.1	0.05	3	1	4,097	6	1	1989	0.22	0.18	0.26

206	37.5	0.87	0	3	6,763	70	3	2023	1.00	1.00	1.00
207	7.2	0.05	3	1	3,751	2	1	2020	0.91	0.88	0.94
208	0.0	0.02	1	1	981	3	1	2007	0.49	0.44	0.54
209	2.1	0.04	1	1	14,533	6	4	2016	0.68	0.64	0.73
210	0.0	0.00	1	1	5,379	2	1	1974	0.15	0.12	0.19
211	13.3	0.01	1	1	3,306	1	1	1991	0.43	0.39	0.48
212	12.1	0.52	0	3	4,804	2	1	1968	0.06	0.04	0.09
213	22.2	0.03	1	1	2,252	1	1	1969	0.36	0.31	0.40

[1] Representative units: 1 – Upper Coastal Plain (Carolinas); 2 – Upper Coastal Plain (GA/FL); 3 – Atlantic Coastal Plain (Carolinas); 4 –FL Peninsula; 5 – FL Ridge; 6 – West; 7 – AL/FL Panhandle; 8 – Atlantic Coastal Plain (GA/FL)

Table A-2. Parameter estimates (means and 95% Bayesian credible intervals) for the persistence model predicting the probability of persistence and detection between 1880 and 2023 for 213 populations of southern hognose snakes. Posterior parameter estimates that do not overlap zero are interpreted as ecologically important.

Parameter	Mean	Lower 95%	Upper 95%
Persistence			
φ_{UCPC}	0.954	0.908	0.985
φ_{UCPG}	0.969	0.932	0.993
φ_{ACPC}	0.946	0.906	0.974
φ_{ACPG}	0.901	0.788	0.969
φ_{PEN}	0.909	0.834	0.959
φ_{RID}	0.963	0.910	0.991
φ_{PAN}	0.912	0.829	0.967
φ_{W}	0.959	0.898	0.991
β_{HSI}	2.184	0.585	3.865
$\beta_{protect}$	-0.202	-1.106	0.731
$\beta_{connect}$	2.588	0.953	4.326
Detection			
p_0	0.100	0.051	0.169
p_{road}	0.239	0.172	0.308
p_{beta}	0.013	0.008	0.019
p_{effort}	0.015	0.008	0.024

Parameter notations: φ – representative unit effects on annual persistence; β – site condition effects on persistence; p – intercept, road, trend, and effort effects on detection. Representative unit codes: UCPC – Upper Coastal Plain (Carolinas); UCPG – Upper Coastal Plain (GA/FL); ACPC – Atlantic Coastal Plain (Carolinas); ACPG – Atlantic Coastal Plain (GA/FL); PEN – FL Peninsula; RID – FL Ridge; PAN – AL/FL Panhandle; W – West (AL/MS).
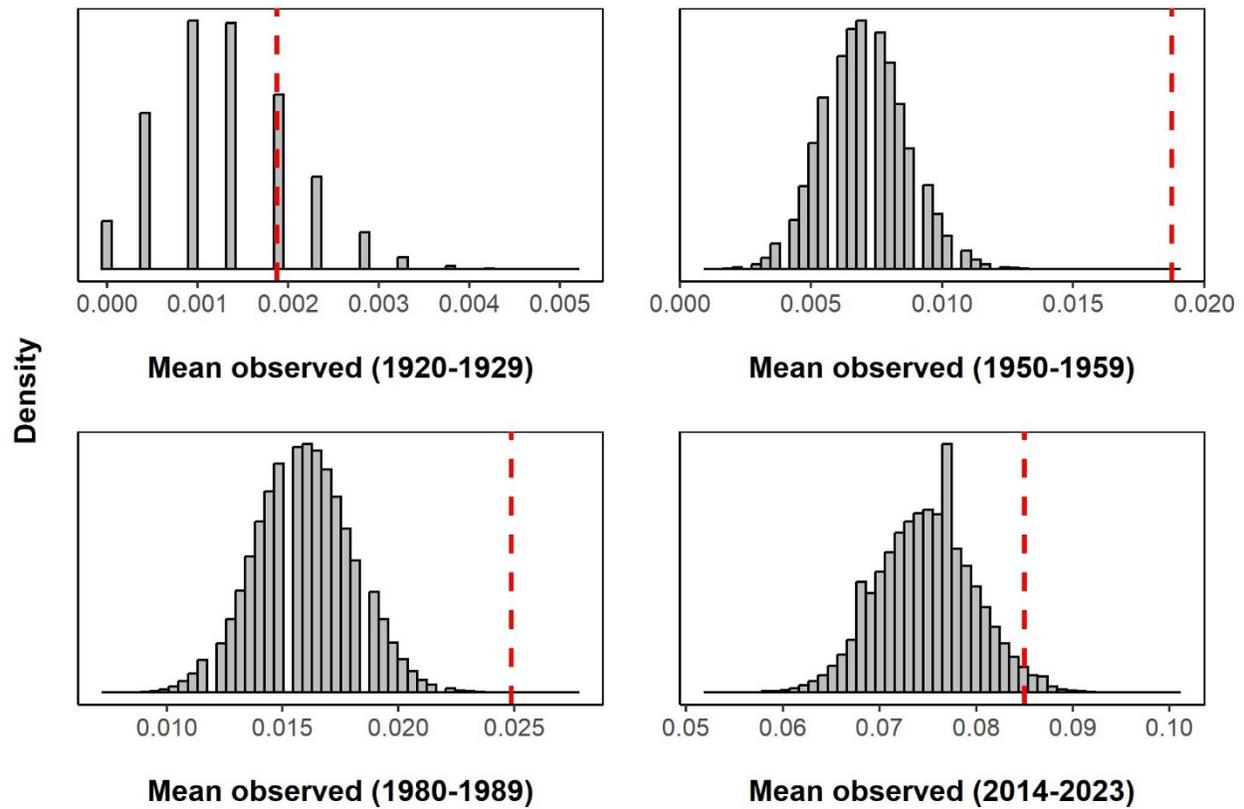
Figure A-1. Results of posterior predictive checks used to assess goodness-of-fit where we simulated datasets using parameters estimated in the model, calculated the mean number of populations with simulated detections of southern hognose snakes in four time periods (1920-1929, 1950-1959, 1980-1989, and 2014-2023), and compared mean observations in these periods from the real dataset with values from simulated datasets. Gray bars represent the distribution of mean observations simulated within each period (n = 349,998 MCMC samples) and red dashed lines represent the mean observations in these periods from the real dataset.
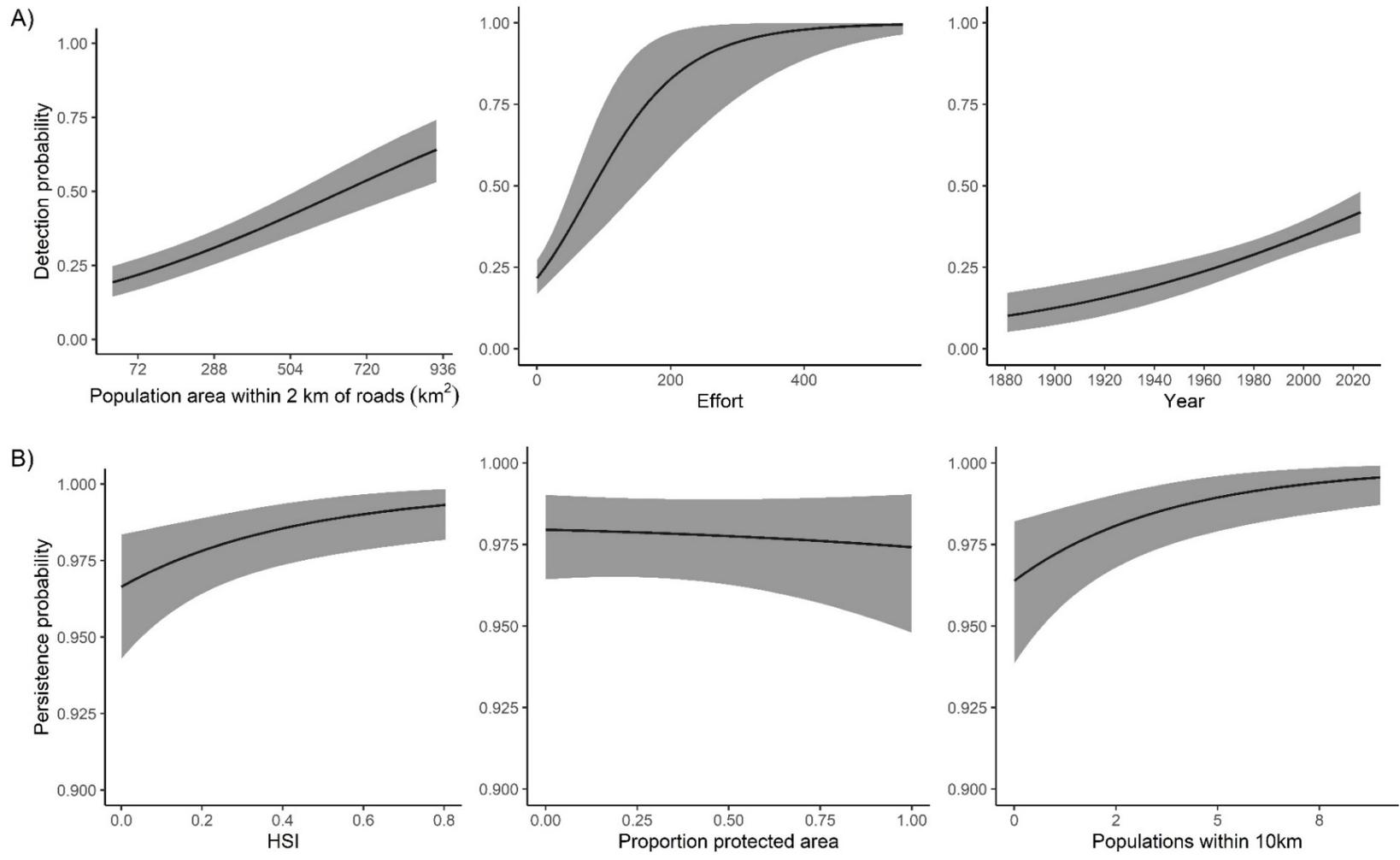
Figure A-2. Effects of each predictor variable on (A) detection probability and (B) annual persistence probability, holding values of other predictor constant at their respective means. For persistence probability, results are displayed for the Atlantic Coastal Plain (Carolinas) representative unit, which has a mean persistence estimate similar to that of most other representative units.