A SPATIOTEMPORAL HABITAT FRAGMENTATION ANALYSIS FOR THE ENDANGERED HOUSTON TOAD *(BUFO HOUSTONENSIS)*

by

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TABLE OF CONTENTS

Page

LIST OF TABLES

LIST OF FIGURES

Figure **Page**

CHAPTER I

INTRODUCTION

Background

The loss of biodiversity worldwide is an issue of great concern and in the last quarter century amphibians declines have been at the front of this issue (Lannoo, 2005). Many amphibian species have large reproductive potential. However, if a species is under severe stress, as is the case with the endangered *B. houstonensis*, then the loss of a few individuals may reduce the future viability of a given population (Carroll, 2009). Tracking amphibian populations is complicated and a number of factors contribute to this: an individual and/or species may not be active while otherwise present; many amphibian species are explosive breeders and populations fluctuate substantially; clutch size and time to maturity are density and temperature dependent; recruitment of individuals and predation vary annually; and chorusing surveys account for adult males but not juveniles nor females (Carroll, 2009). The above factors contribute to the potential stochasticity reported for some amphibian populations, which adds to the difficulty of ascertaining the status of wild populations. Without repeated studies that spans several years and cover multiple habitats within the range of a species, the risk of misclassifying a species status increases (Collins, 2009).

Bufo houstonensis is a Texas endemic amphibian first discovered outside of Houston, Texas during the 1940's by amateur herpetologist John Wottring and later described as a species in 1953 by Ottys Sanders (Sanders, 1953). Since the 1950's *B. houstonensis* has been the subject of numerous studies, such as population assessments, morphometric, vocalization analysis, and habitat evaluations (Sanders, 1953; Blair, 1956; Kennedy, 1962; Brown, 1971; Hillis, et. al., 1984; Price, 1990; Dixon, 1990; Price, 1992; Yantis, et al., 1993; Forstner, 2000; Peterson, et. al., 2004; Jackson, et. al., 2006; Swannack, 2007; Buzo, 2008 Swannack, et. al, 2009). *B. houstonensis* was the first amphibian listed on the U.S. Endangered Species Act in 1970 (U.S. Fish and Wildlife Service). In 1977 the Office of Endangered Species designated critical habitat for the species in Bastrop, Burleson, and Harris counties. This action was controversial at the time and the critical habitat within Burleson and Harris counties was later rescinded, however, the Bastrop County critical habitat remained. The United States Fish and Wildlife Service established a Houston toad recovery team in 1977, and this group published the Houston toad Recovery Plan in 1984. In 1994 a group of experts met at the University of Texas at Austin and drafted the Houston toad Population and Habitat Viability Assessment, this document contains numerous recommendations which are still in effect today.

Today, the upland habitat of *B. houstonensis* is thought to be characterized by sandy, friable soils and substantial canopy cover. The species breeding habitat is proximal to lotic, ephemeral, and also permanent bodies of water. *B. houstonensis* dispersal habitat, or corridor habitat, is the least well characterized, although the maximum recorded distance the species has been observed to move is known (Seal et al. 1994; Andrew Price unpubl. data; Vandewge et al, 2013).

The species occurs in the following counties: Austin, Bastrop, Burleson, Colorado, Fort Bend, Harris, Lavaca, Lee, Leon, Liberty, Milam and Robertson (Dixon, 2013; Lannoo, 2005). Due to drought and urbanization the species became less present around the Houston area during the 1950's, and by the end of the 1970's experts believed the species to be extirpated from Harris County (Seal et al. 1994). The species is also thought to be extirpated from Fort Bend and Liberty counties. A recent literature review has found *B. houstonensis* records in Brazos, Freestone, and Grimes counties. However, these records are not yet published as part of the range of the species. To date, it is believed that Bastrop County has maintained the largest population since the 1970's.

Increased development (agricultural, residential, and commercial) has led to declines in amphibian populations worldwide (Phillips, 1990; Carey, 2001). The causes behind *B. houstonensis*' decline across the range are largely attributed to habitat destruction and degradation brought on by increased urbanization, agricultural practices, fire prevention practices, alteration of wetlands, ROW and roadway construction, drought, and wildfire (Seal et al. 1994). Landscape-level conversion of areas within the *B. houstonensis* range has likely contributed to local extirpation. Two severe droughts have occurred across the range of *B. houstonensis*. The first drought occurred between 1950 and 1957. The second drought occurred between 2005 and 2015 and contributed to the intensity of the 2011 Bastrop County Complex Wildfire. The recent drought and associated fire will have long term impacts for the species, particularly within Bastrop County.

Surveys for *B. houstonensis* during 2011 resulted in few detections, and are partially attributed to the consequences of severe drought. To compound this low detection rate, the 2011 Bastrop County Complex Wildfire altered the remaining *B. houstonensis* habitat in Bastrop County. One possible outcome of high intensity wildfire is forest stand replacement and habitat fragmentation (Miller, 2009; Pickett, 1985) and the Bastrop County Complex Wildfire of 2011 may have greatly affected small populations of species within Bastrop County. Furthermore, the five year status review for *B. houstonensis* (Forstner and Dixon, 2010) notes the trend of large chorusing events which decrease over time and eventually only a few males are heard for many years prior to final extirpation of an area. This pattern is seen at the county level with hundreds of chorusing detections in Harris County during the 1950's and the eventual effective extirpation of the Harris county population(s) by the 1970's. A more recent example of this temporal trend occurred in Lee County between 2001 and 2005 with numerous chorusing detections in 2001 and a single male heard by 2005 (Forstner per. comm.). By the late 1990s *B. houstonensis* was considered to be extirpated from Burleson County with a final detection in 1990; however a single male was detected by Dr. Jim Yantis in 2011 after a two decade hiatus (Forstner per. comm.)

In 2008 Buzo created a habitat suitability model derived from parameters important to the species, such as substantial forest canopy cover and deep, friable sandy soils. Buzo's model was later extended across the range of the species. In addition to this previous research on *B. houstonensis*, Buzo found that Lee County lost 11% canopy cover between the years 2001 and 2005 and 16% of habitat. During this same period *B. houstonensis* chorusing detections dropped off considerably in Lee County.

Using satellite imagery of the 2011 Bastrop County Wildfire Complex and a *B. houstonensis* habitat suitability model approximately 41% of *B. houstonensis*' habitat was altered within Bastrop County (Wallace et al., 2011; Wallace et al., 2012a; Wallace et al., 2012b). Given the habitat loss in Lee County and the predicted trend of habitat loss across the species' range it is possible habitat fragmentation currently is and will continue to affect the status of *B. houstonensis*. The extent of short-term habitat loss, fragmentation, and degradation requires we consider focusing recovery initiatives elsewhere while the Lost Pines ecoregion recovers. Thus, locating remaining viable habitat for *B. houstonensis* is critical for future conservation efforts, as is documenting habitat trends that have been occurring across the species range. It is imperative that other areas containing habitat within the range of *B. houstonensis* are assessed for suitability.

Objectives

I conducted this study to observe *B. houstonensis* habitat change throughout a thirty-nine year time span (1974-2013). The USFWS is considering implementing Focus Areas for conservation and recovery efforts for *B. houstonensis* and I targeted these proposed Focus Areas to assess the species habitat within each.

- Conduct a spatiotemporal analysis for *B. houstonensis* habitat within the USFWS-Focus Areas
- Characterize USFWS-Focus Areas for future management

Ultimately, this analysis characterized *B. houstonensis* habitat and aspects of how the habitat changed temporally. In order to assess how *B. houstonensis* habitat has changed, I produced and analyzed two landscape metrics and one fragmentation metric to characterize habitat within the USFWS-Focus Areas.

CHAPTER II

MATERIALS AND METHODS

Study Area

The study area was located in south-central Texas and covered the following counties: Austin, Bastrop, Burleson, Colorado, Lee, Leon, Milam, and Robertson. The range of *B. houstonensis* spans a number of ecoregions, which include the Post-Oak Savannah, Blackland Prairie, Gulf Coast Prairie, and the Lost Pines. The Lost Pines ecoregion is located within Bastrop County and is a disjunct, relic Loblolly pine (*Pinus teada*) and Post oak (*Quercus stellate*) forest. This is the westernmost portion of southern pines in the United States. The Lost Pines region is likely to be of particular importance to *B. houstonensis* due to the majority of detections found there. Soil type should also be evaluated when conducting studies of wildlife habitat. Experts suggest soils that biologically relevant to *B. houstonensis* are sandy, deep, and friable and this region of Texas contains a variety of soil series characterized as such. The eight USFWS-Focus Areas which are my study targets occur in South-Central Texas (Figure 1). These Focus Areas are roughly delineated by two natural boundaries, the Brazos River Valley and the Carrizo-Wilcox formation. They contain three of the largest detection clusters of *B. houstonensis* and also contain three of the largest contiguous areas of habitat (Buzo, 2008).

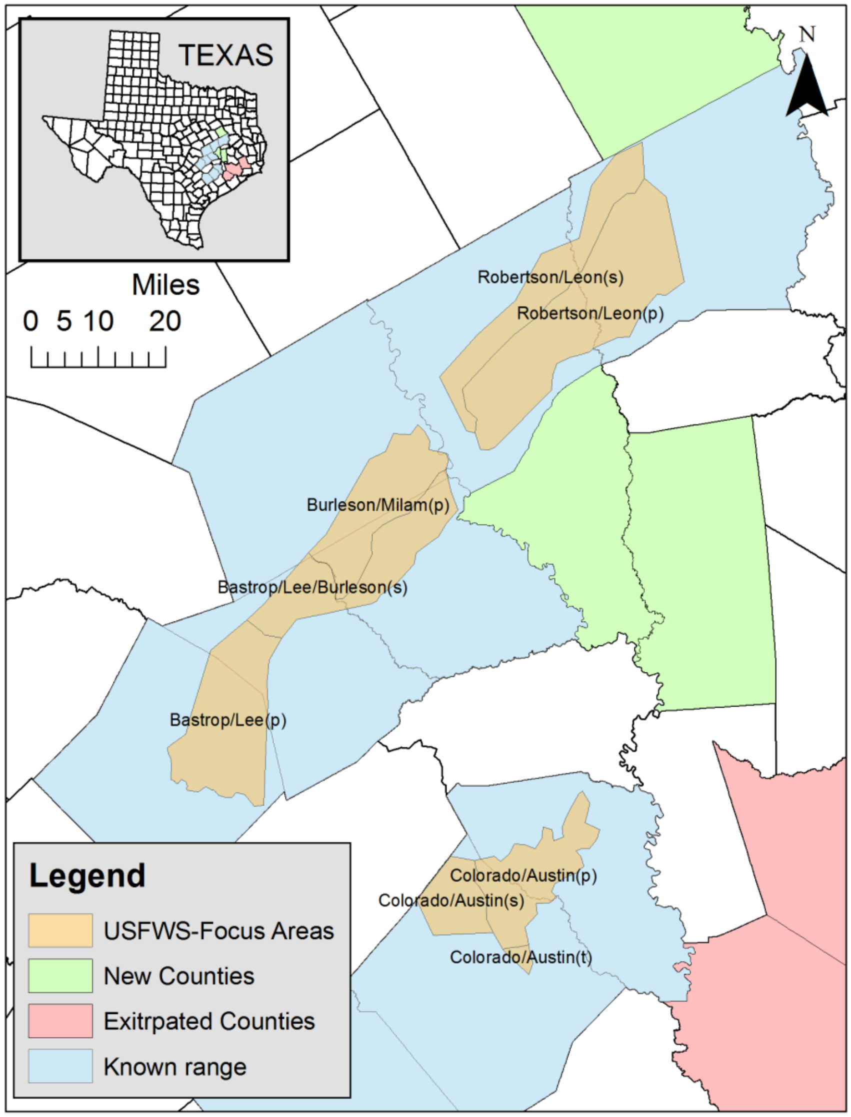

Figure 1. Eight Focus Areas proposed by the United States Fish and Wildlife Service (USFWS) for Houston toad (*Bufo houstonesis*) recovery planning. The Focus Areas occupy the following counties: Austin, Bastrop, Burleson, Colorado, Lee, Leon, Milam, and Robertson.

Satellite Data

I obtained Landsat 1 and 2 Multispectral Spectral Scanner (MSS), Landsat 5 Thematic Mapper (TM), and Landsat 8 Operational Land Imager (OLI) scenes through FTP download from the United States Geologic Survey-Earth Research Observation and

Science center (earthexplorer.usgs.gov). The satellite scenes arrived as 60x60 (MSS) and 30x30 (TM and OLI) meter ground sampling distance (GSD) GeoTIFF's, resampled using the cubic convolution (CC) method, and projected in Universal Transmercator-World Geodetic System 1984 (UTM-WGS84). I resampled the Landsat MSS scenes to 30x30 meter spatial resolution to match the TM and OLI data. I selected Landsat scenes if they met the following criteria: each scene maintained <10% cloud cover; was captured during or immediately after the breading season (February through April); both scenes for each time step came from the same year; and formatted with LT1 standard terrain correction (for geometric fidelity). Ultimately, I chose five steps in time between 1974 and 2013 and six Landsat scenes per time step for a total of 30 scenes.

Table 1. The 10 Landsat scenes used to derive canopy cover. All scenes were captured by one of three Landsat sensors: Multispectral Scanner (MSS); Landsat 5 Thematic Mapper (LT5); and Landsat 8 Operational Land Imager (OLI).

Scene path&row	Landsat sensor	Time Step 1	Time Step 2	Time Step 3	Time Step 4	Time Step 5
28_38	MSS	3/29/1974				
28_39	MSS	3/29/1974				
26_38	LT5		4/27/1987	5/19/1995	5/1/2006	
26_39	LT5		4/27/1987	5/19/1995	5/17/2006	
26_38	OLI					5/4/2013
26_39	OLI					5/4/2013

Image Classification

I pre-processed and classified all Landsat scenes using ERDAS Imagine 2013. Individual GeoTIFF files corresponding to reflective wavelength bands (blue through shortwave infrared) were stacked into a multi-layer composite for each year. I converted the pixel values (digital numbers) of Landsat scenes captured with MSS and TM sensors from DNs to at-sensor radiance and finally to top of atmosphere (TOA) reflectance using the radiometric calibration coefficients and conversion algorithms according to Chandler et al. (2009). The pixel values of Landsat scenes captured with the OLI sensor were converted from brightness values to the TOA reflectance using the radiometric calibration coefficients found in the metadata of each scene and conversion algorithms provided by USGS (landsat.usgs.gov). After individual scenes were stacked for each time step they were mosaicked to produce a seamless image of TOA reflectance. Each mosaicked scene was classified using an unsupervised classification method. Forty statistically separate clusters were generated by running the clustering algorithm ISODATA at 50 iterations with a convergence threshold of 0.95. Spectral clusters were manually assigned into one of two land cover classes: canopy and non-canopy (e.g. impervious areas, agriculture, and urban development).

Accuracy Assessment

Accuracy was tested for the classified Landsat satellite imagery by randomly generating 25 points for each category within a classified Landsat image and comparing my classification with a reference image (Duarte et al., 2013; Hansen et al., 2001). Once the points were assessed for overall accuracy, producer accuracy, user accuracy, a Kappa Coefficient of Agreement (K_{hat}) was calculated to test agreement between my classified map and the reference imagery (Jensen, 2004; Stalmans, 2002).

Soil Data

I collected soil data for all fifteen counties via ftp download from the USDA-NRCS geospatial data gateway (datagateway.nrcs.usda.gov). The soil data arrived as shapefiles projected in North American Datum 1983 Universal Transverse Mercator Zones 14 and 15. The soil data for each county was then processed in ArcMap by reprojecting the Arcmap shapefile from the original format to USA Contiguous Albers Equal Area Conic USGS version, matching the extent of the study area with that of the soil shapefile, and then selecting soils that are at minimum biological relevant to *B. houstonensis*. Soil considered biological relevant to *B. houstonensis* are characterized as deep, friable sandy soils (Brown, 1971; Forstner, 2003) in the order Alfisols, and the Great Groups Hapludalfs, Paleudalfs, Haplustalfs, and Paleustalfs. I was interested in capturing all potential canopy change, and thus *B. houstonensis* habitat change, within a limited area (USFW-Focus Areas) so for my study I expanded the type of soils to include any soil series described as sandy, loamy, or both at the initial soil layer. This approach increased the types of all Orders, Suborders, Great Groups, and Subgroups used in my study.

Habitat Metrics

The results of the satellite image classification were incorporated into ArcMap and combined with the soil data. I used a weighted overlay function to produce my habitat model, which is where substantial canopy and suitable soils exist in the same location. Evaluation of landscape, class, patch metrics were performed with the program FRAGSTATS version 4.2 (McGarigal 2014) using my habitat model from each time step. I used the eight neighbor rule without any sampling strategy. Since I was targeting how *B. houstonensis* habitat changed within the USFWS-Focus Areas I choose metrics that most easily described change within a bounded area (total patch size, mean patch size, and total number of patches).

Detection Data

An existing database of 1724 *B. houstonensis* presence points was used. These presence points were obtained (typically during the breeding season) for *B. houstonensis* between 1953 and 2015 and represent chorus detections at breeding sites, individuals observed on site, and road kill data. The database was incorporated into a GIS database using ArcMap (ESRI), georeferenced and projected to USA Contiguous Albers Equal Area Conic USGS (Figure 2).

The metadata of the database consist of a variety of field surveys completed by various agencies, departments, and private entities (environmental firms). For earlier detections the exact geographic location of each *B. houstonensis* was not explicit due to the state of technology at the time. For example, *B. houstonensis* locations were determined by retracing of chorus survey routes, locating any existing ponds in the area, and using other additional information (e.g. cardinal directions). These points had more location ambiguity than more modern surveys that incorporated explicit geographic data from GPS units. The overall surveys were conducted by U.S. Fish and Wildlife Service (USFWS), Texas Parks and Wildlife (TPWD), Texas Department of Transportation (TxDoT), Lower Colorado River Authority (LCRA), various central Texas environmental firms, Dr. Jim Yantis, Dr. Andrew Price, Dr. James Dixon and his lab at Texas A&M University-College Station, Texas, and most recently Dr. Forstner and his lab at Texas State University, San Marcos, Texas (Buzo, 2008).

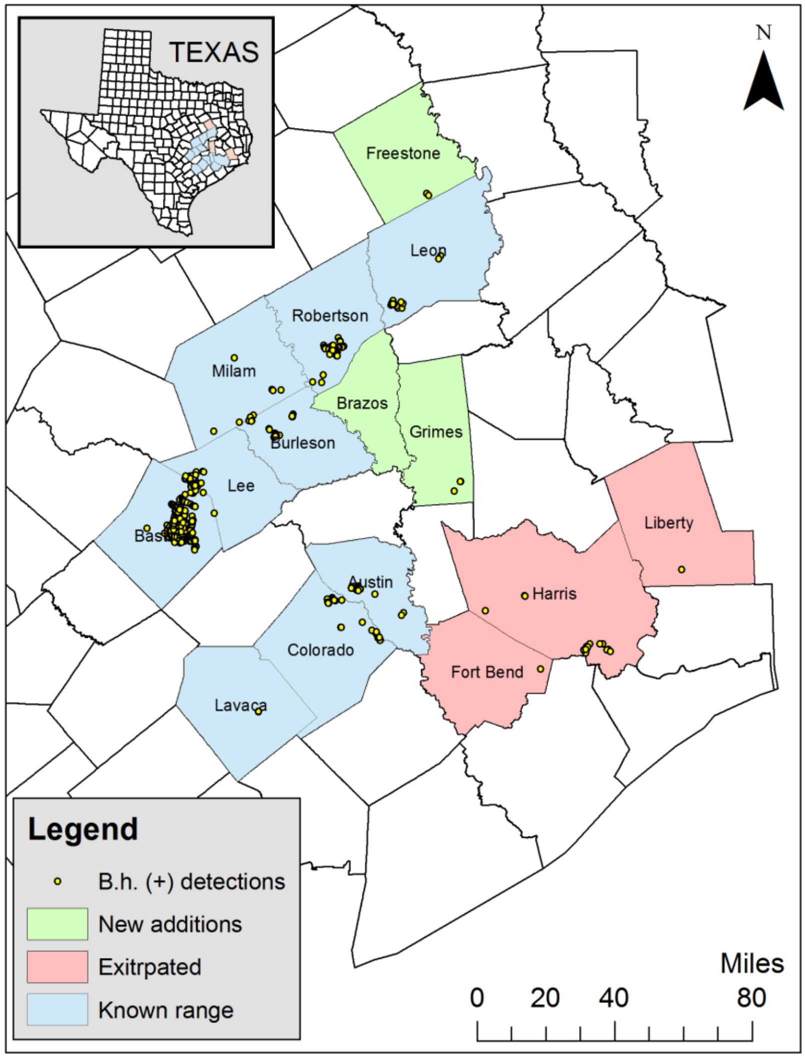

Figure 2. Houston toad (*Bufo houstonensis*) detections records from the earliest (1953) until the most recent records (2015). The Houston toad (*Bufo Houstonensis*) currently occupies the blue counties; the species is believed to be extirpated from the red counties; recently discovered historic records are in the green counties.

Evaluation

Ultimately, five time steps were created: 1974, 1987, 1995, 2006, and 2013. Each year corresponds to the year of each satellite image used in creating my habitat model (Table 1). Landscape and fragmentation metrics were generated from my habitat model and compared among all USFWS-Focus Areas. Specifically, I assessed how total patch size, mean patch size, and total number of patches changed across the time steps. I also assessed how much habitat occurred within each Focus Area of the total available habitat across all Focus Areas for each time step.

CHAPTER III

RESULTS

The objective of this study was twofold: Conduct a spatiotemporal analysis for *B. houstonensis* habitat within the USFWS-Focus Areas and to characterize these Focus Areas for future management. All metrics were successfully run for each time-step and each USFWS-Focus Area (Figures 3-7).

Habitat Metrics

The trends of the three metrics (total patch size area, mean patch size, and total number of patches) across all time steps were both positive and negative regarding *B. houstonensis* habitat. Total patch size initially decreased within all of the eight USFWS-Focus Areas, but later increased in six of the eight Focus Areas, the exceptions being the Bastrop-Lee (primary) Focus Area and the Colorado-Austin (tertiary) Focus Area (Figure 3). Mean patch size initially decreased across all USFWS-Focus Areas, but later increased in six of the eight Focus Areas, the exceptions being the Bastrop-Lee (primary) Focus Area, and the Bastrop-Lee-Burleson (primary) Focus Area (Figure 4). Total number of patches initially increased within all USFWS-Focus Areas, but decreased in six of the eight Focus Areas in later years, the exceptions being the Bastrop-Lee (primary) Focus Area, and the Bastrop-Lee-Burleson (primary) Focus Area (Figure 5). Except for Bastrop-Lee (primary) Focus Area, the total patch size and mean patch size increased across all Focus Areas at the last time step (Figures 3 and 4).

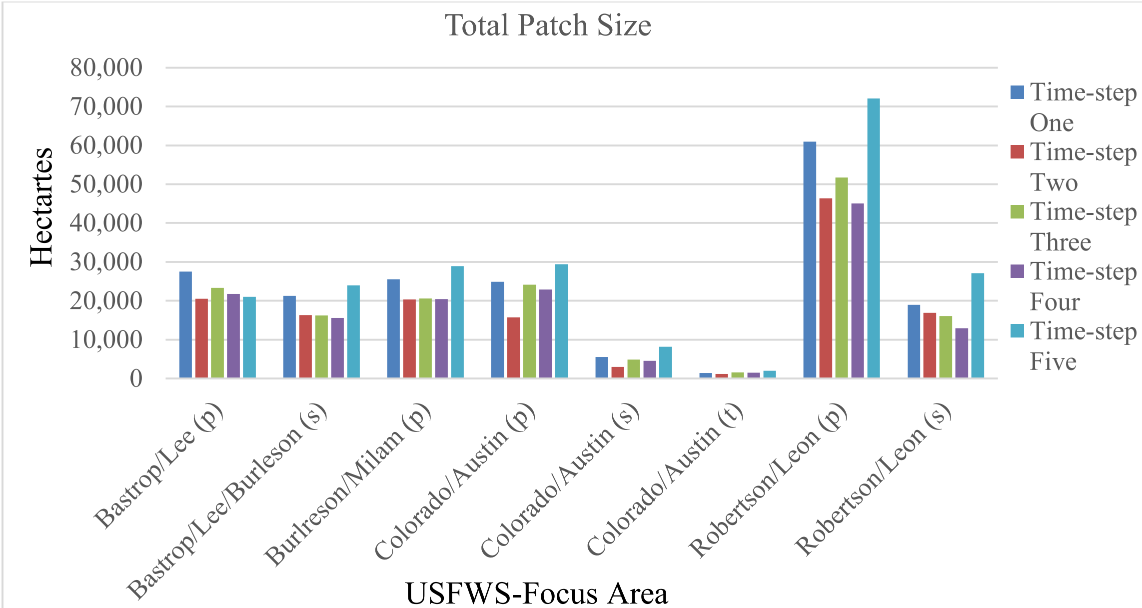

Figure 3. Total patch size within each of the eight USFWS-Focus Areas for the Houston toad (*Bufo houstonensis*) at each time step. This landscape metric summates all area determined to be habitat by my model for each Focus Area at each time step.

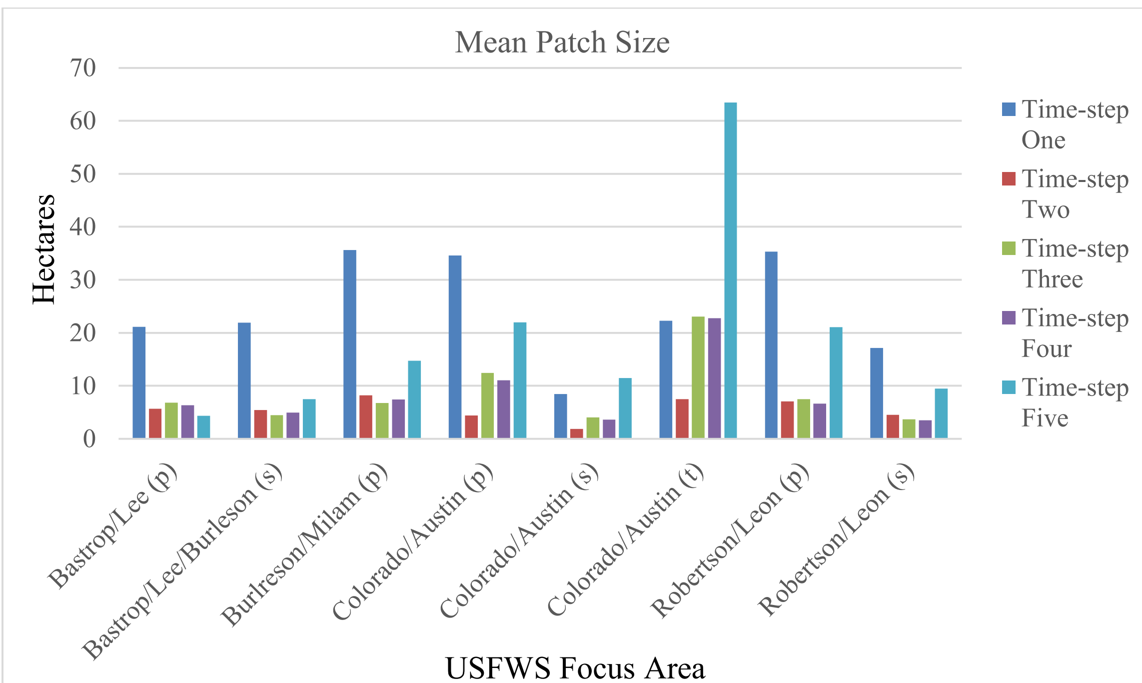

Figure 4. Mean patch size within each of the eight USFWS-Focus Areas for the Houston toad (*Bufo houstonensis*) at each time step. This landscape metric is the product of dividing the total patch size by the total number of patches for each Focus Area at each time step.

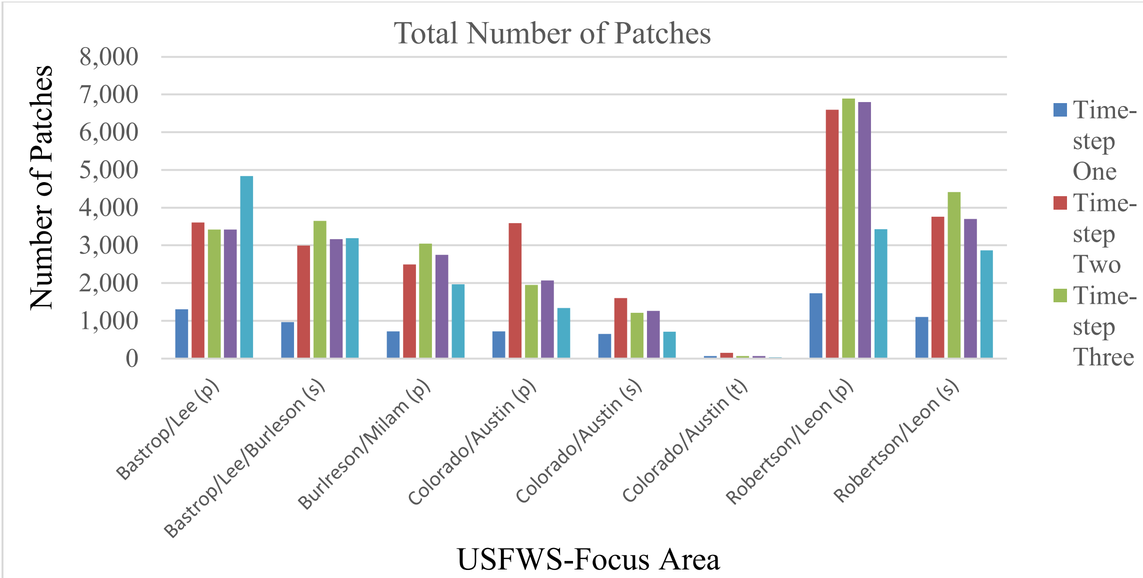

Figure 5. Total number of patches within each of the eight USFWS-Focus Areas for the Houston toad (*Bufo houstonensis*) at each time step. This fragmentation metric summarizes all patches determined to be habitat by my model within each Focus Area at each time step.

The Robertson-Leon (primary) Focus Area contained approximately 32% of available habitat across all time steps, the largest proportion of all Focus Areas (Figure 6). This is followed by the Bastrop-Lee (primary), Colorado-Austin (primary), Robertson-Leon (secondary), and Burleson-Milam (primary) Focus Areas (Figures 6 and 7). Of these four Focus Areas, Burleson-Milam (primary) and Robertson-Leon (secondary) do not show a decline in the proportion of habitat between the last two time steps (Figures 6 and 7). The Bastrop-Lee (primary) Focus Area shows a decline in proportion of available habitat between the last two time steps which is likely the result of the 2011 Bastrop County Complex Wildfire. The other two Focus Areas, Colorado-Austin (secondary) and Colorado-Austin (tertiary), contain a small proportion of available habitat across all time steps (<%5).

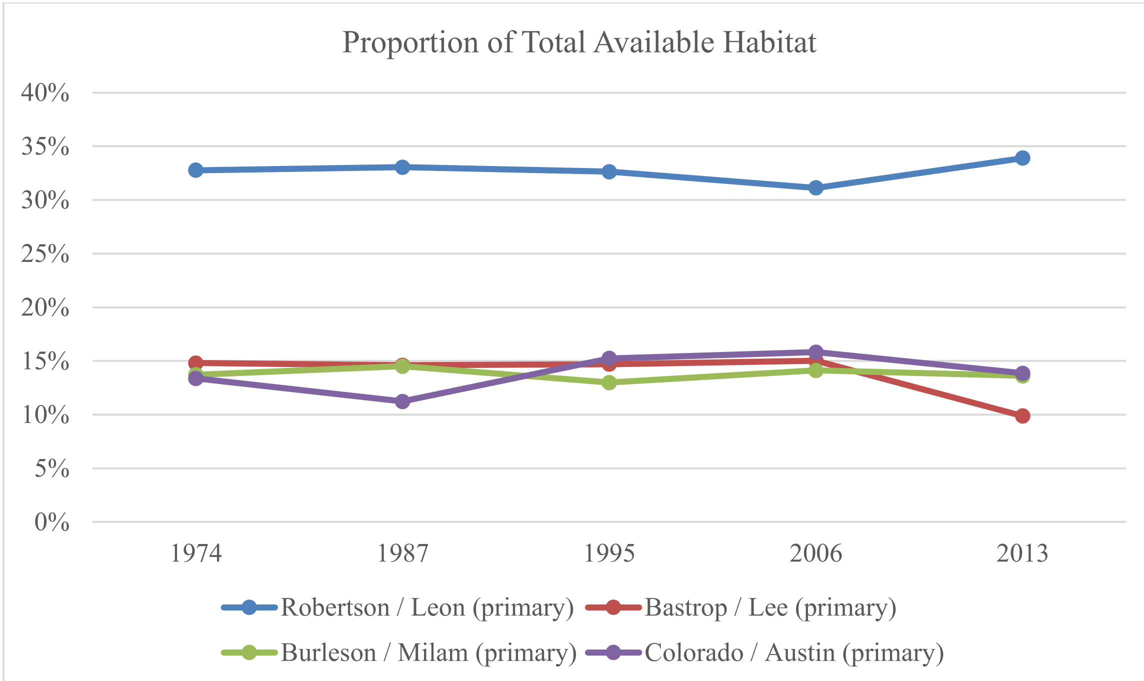

Figure 6. The proportion of total available habitat each USFWS-Focus Areas for the Houston toad (*Bufo houstonensis*) contains at each time step. The Y-axis represents proportion of total available habitat; the X-axis represents each time step.

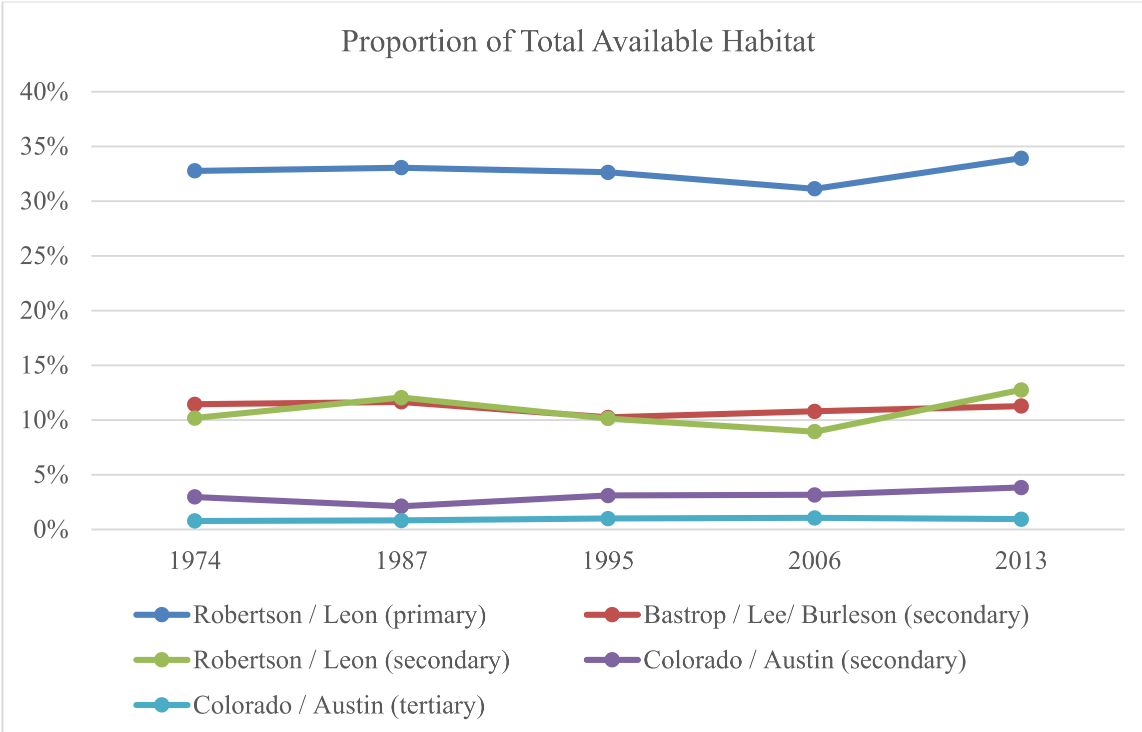

Figure 7. The proportion of total available habitat each USFWS-Focus Areas for the Houston toad (*Bufo houstonensis*) contains at each time step. The Y-axis represents proportion of total available habitat; the X-axis represents each time step. Robertson-Leon (primary) Focus Area added for comparison.

The overall accuracy for each mosaicked scene was 92% for time-step one, 96% for time-step two, 90% for time-step three, 86% for time-step four, and 94% for time-step five (Table 2) An overall accuracy of 85% or higher is generally accepted as successful or acceptable classification. The kappa statistic for each mosaicked scene was 84% for time-step one, 92% for time-step two, 80% for time-step three, 72% for time-step four, and 88% for time-step five (Table 2).

Table 2. Producer’s accuracy, Users’ accuracy, Overall accuracy, Kappa statistic, and Overall Kappa statistic for each classified Landsat scene used in building my habitat model within the USFWS-Focus Areas for the Houston toad (*Bufo houstonensis*). Landscape classifications were either canopy, or non-canopy.

Landsat Scenes	Producer's Accuracy	User's Accuracy	Kappa coefficient of agreement	Overall Accuracy	Overall Kappa statistic
1974				0.9200	0.8400
Non-canopy	0.9565	0.8800	0.7778		
Canopy	0.8889	0.9600	0.9130		
1987				0.9600	0.9200
Non-canopy	0.9600	0.9600	0.9200		
Canopy	0.9600	0.9600	0.9200		
1995				0.9000	0.8000
Non-canopy	0.8846	0.9200	0.8333		
Canopy	0.9167	0.8800	0.7692		
2006				0.8600	0.7200
Non-canopy	0.9091	0.8000	0.6429		
Canopy	0.8214	0.9200	0.8182		
2013				0.9400	0.8824
Non-canopy	0.9259	1.0000	1.0000		
Canopy	1.0000	0.8800	0.7857		

CHAPTER IV

DISCUSSION

As with any project there exist many potential sources of uncertainty. This study provided useful information in order to understand how habitat has changed temporally (1974-2013) for *B. houstonensis* within the USFWS-Focus Areas. The practicality and cost-effectiveness of using GIS data, satellite imagery, and other forms of medium-to-large scale spatial data has provided practical approaches for answering questions regarding *B. houstonensis* conservation. In order to effectively protect *B. houstonensis* and make sound conservation decisions it is necessary to understand what has happened to the species environment. Furthermore, it is important to identify how habitat changed in the USFWS-Focus-Areas when extirpation of the *B. houstonensis* occurred, such information could be used for future conservation efforts. Unfortunately, with the 2011 Bastrop County Complex Wildfire, *B. houstonensis* lost a large proportion of habitat in Bastrop County and it is important to expand conservation efforts across the species known range. Ultimately, this study provides additional information to guide government agencies, and other groups involved in conservation for the species, in deciding where to focus future conservation efforts.

The spatiotemporal analysis of *B. houstonensis* habitat was a success but the process of using satellite imagery to build habitat models is not without issues. Canopy cover across the time steps was not assessed for actual loss or gain of canopy, but change in total patch size, mean patch size, and total number of patches. Many amphibian species are known to be spatially distributed across the landscape in a metapopulation structure (e.g. Levin's classical model, mainland-island model, and patchy isolation model). Bradford et al. (2003) studied *Bufo punctatus* (the Red Spotted toad) across the Mojave Desert and found that patch occupancy increased with patch size and that occupancy was not related to patch isolation. Hokit's study (2003) of *Sceloperus woodi* (Florida Scrub Lizard) found that habitat patch size positively correlated with species abundance, survivorship, and recruitment and growth rate of males. Therefore, only looking at the three metrics I provided may not provide a comprehensive assessment for the status of *B. houstonensis*. Furthermore, it's important to note that the landscape and fragmentation metrics used in the analysis are not directly comparable across USFWS-Focus Areas due to the variety of sizes and shapes of the Focus Areas. It is worth assessing each Focus Area across the time steps and learn how the *B. houstonensis* habitat changed throughout the years and then use this information to characterize the Focus Areas for management (Duarte et al., 2013). It's worth noting that when determining what was canopy from the Landsat scenes the density of canopy within a pixel was not determined.

Soil Data

Since my entire analysis was bounded by USFWS-Focus Areas it would be prudent to fully understand how canopy was changing within these pre-designated areas. To better understand canopy change, it is necessary that soil was not a limiting factor in creating *B. houstonensis* habitat. In previous studies suitable soils were limited to one Order, two Suborders, four Great Groups, and 16 Subgroups (Buzo, 2008). To better understand how *B. houstonensis* habitat has undergone change, I included any soils that are described as sandy, loamy, or both within the initial soil layer. This is a liberal application, but, it was prudent to assess the potential canopy that would be used in my habitat suitability model. However, including more soil series can create problems, and not being a soil scientist I may be in error to include more soils. The 12 Orders, 64 Suborders, 300 Great Groups, and 2400 Subgroups of NRCS Soil Taxonomy are general categorized based on soil genesis, processes that affect soil genesis, the assemblage of soil horizons, and lesser processes of the above mentioned. It is likely that including soils of various Orders, not to mention the lower divisions, is erroneous when assuming biological relevance to *B. houstonensis*. However, it's necessary in order to capture the most canopy within the limited space that are the USFWS-Focus Areas, because it is canopy that changes over short periods of time, not soils. A final assessment of the correlation among the newly completed presence data matrix of Houston toad detections should subsequently enable a much more complete determination of soils useful in the description of Houston toad habitat delineation.

Habitat Classification

The process of image classification starts with a geographically corrected satellite image (Landsat satellite) and ends with a selection of pixels from the original satellite image determined to be canopy. The salient steps of my image classification include satellite image band stacking, image correction to top-of-atmosphere (TOA) reflectance and then radiance, mosaicking all post-TOA images, clustering of like pixels with the ISODATA algorithm (twice for difficult clustering of pixels), and manually assigning each cluster of pixels to a specific landscape class (canopy, or non-canopy). The most likely source of error in the above process would occur in the manual assignment of clusters due to the reliance of this step on the human eye in determining differences among varying colors of each pixel. The process of manually assigning each cluster of pixels to a particular class (canopy, or non-canopy) was tedious and eye straining, which also increased the probability of incorrectly assigning a cluster of pixels to the wrong class. However, since all pixel clusters were eventually assigned to two classes the likelihood of misclassifying a cluster of pixels was reduced, but, regardless, misclassification is still an issue.

The Landsat 8 (OLI) satellite imagery presented another issue. Total patch size for seven of the eight Focus Areas increased (Figure 3) and there are a few potential reasons for this phenomenon. The Landsat 8 satellite sensor has an increased radiometric sensitivity and is more sensitive to the energy reflected by features on the landscape. Increased sensitivity of a sensor may not appear to be a problem. However, if smaller landscape features that are not biologically relevant for *B. houstonensis* are represented as habitat the overrepresentation of habitat may have occurred.

Accuracy assessment consisted of using a program built into ERDAS IMAGINE to manually assess the accuracy of my classified image and produce measurements of accuracy: users' accuracy, producers' accuracy, overall accuracy, and the kappa coefficient of agreement. The overview of the process involved comparing my classified image with that of an unclassified satellite image at 25 randomly assigned locations. Performing an effective accuracy assessment is crucial for the overall process, since potential errors in previous steps will emerge here, and if unaddressed may compound any errors going forward. Ideally, when performing an accuracy assessment with a classified image it is recommended not to rely on the original satellite image used in the creation of the classified image (e.g. don't use the same satellite image), and most experts recommend using higher resolution aerial imagery to check accuracy. However, the circumstances of my analysis are not ideal and higher resolution aerial images were not available for the extent of my study area and for all time steps. So, given the conditions I worked with, a major potential source of misclassification may have persisted even post-accuracy assessment if the classification of the satellite images were in error.

Habitat Metrics

The uses of landscape and fragment metrics are essential to the process of determining how *B. houstonensis* habitat changed temporally. I used the program FRAGSTATS to determine metrics in each of the eight USFWS-Focus Areas, specifically: total patch size, mean patch size, and total number of patches. A potential problem when performing and evaluating these metrics is the misclassification of pixels during previous steps (classification). This potential problem may have a cascading effect on my study and ultimately the results of my analysis. The process of pixel classification started with creating 40 statistically separate clusters, after which I visually (naked eye) assessed each of the 40 clusters and assigned all to two categories: canopy, or non-canopy. This is where major, range-wide pixel misclassification may occur since a particular statistical cluster may cover all eight USFWS-Focus Areas. Also, if a statistical cluster is misclassified all three of the metrics used in my analysis would be affected. The effects of misclassification may be large, as seen in the above descriptions, or relatively minor if a particular statistical cluster contained only minor amount pixels. However, even smaller statistical clusters can cause major issues further along if they are misclassified.

Conservation Efforts

Survey efforts for *B. houstonensis* have not been systematic, comprehensive, or uniform by any measure. Previous surveys have varied by year, by county, and by the number of surveys per year. Absence of detections requires that we presume extirpation for the species at a particular locality. However, there are three counties where making such assumptions is problematic: Burleson, Austin, and Lavaca. In Burleson County the last two years when detections were documented are 1990 and 2011, a period of over 20 years. A similar event occurred in Lavaca County, the last two years when detections were documented are 1994 and 2011. Another example occurred in Austin County, where the last detections were recorded in 1990 and the next detection occurred in 2008. This lack of uniformity has led to an incomplete dataset of *B. houstonensis* records, especially the lack of absence points, which reduces how this dataset can be implemented. The USFWS has had protocols for conducting *B. houstonensis* surveys and in 2007 these protocols were improved upon, ultimately increasing the probability of detecting the species when present by 80% (Jackson et al., 2006).

With over 95% of land in Texas privately owned, surveys are also limited by a lack of public lands. Thus, the majority of surveys are limited to a few large tracts of lands (Bastrop State Park, Griffith League Ranch), utility right of way access, and public roads. Of all the *B. houstonensis* records in our dataset, over 95% represent individuals that were heard during a survey, thus, the majority of all surveys represent breeding habitat. Maximum distances of adults and juvenile *B. houstonensis* has been documented, and it is possible this species enters breeding habitat from other habitats, which would bias all habitat models. However, we do have individuals recorded from other surveys (which were not dependent on chorusing) in our database that do not seem to conflict with habitat models derived from chorusing surveys. Regardless, surveys need to be designed and conducted in such a way to identify the other two types of habitats (upland, and dispersal). The only surveys I know to have done so occurred in 2008 when Buzo and Forstner identified a *B. houstonensis* in an isolated patch of habitat in northeast Bastrop County, and again in 2013 were Buzo's model identified suitable habitat in southwest Colorado County where and individual was detected and there were no previous records of the species in that isolated habitat patch. So, these models seem to work even considering the inherent biases and we do seem to have a working understanding of how to define *B. houstonensis* habitat.

The preponderant abundance of the species is considered to exist within in Bastrop County. However, work done in 2014 within Robertson County found a significant number of individuals and chorusing locations where there had been few previous records of the species. This is better understood by looking at the disparity of the number of years in which a survey was conducted within Bastrop and Robertson counties. Between 1980 and 2015 surveys were conducted in Bastrop in 24 of the years and in Robertson seven of the years, a discrepancy of 17 additional years where a survey took place. This has led to a very good understanding of where the species occurs in Bastrop County, but a very poor understanding everywhere else. This represents an inconsistency of efforts, and a lack of conservation efforts outside of Bastrop County, which can be clearly seen when looking again at Robertson County. In 1973 a *B. houstonensis* was found in Robertson County, but wasn't reported until 1990 when Dr. Jim Yantis found the specimen in a museum collection and confirmed their occurrence by audio survey. So, 23 years of conservation efforts were lost within Robertson County and during this same timespan approximately 33% of habitat within both Robertson-Leon Focus Areas was altered to some degree. To further highlight this failure of efforts, within the last five years there have been 47 new chorusing locations found in Robertson County and in more than a dozen chorusing locations, where previously only three locations were reported for the taxon in the County.

USFWS-Focus Areas

Within the data produced by my study there are several things about the USFWS-Focus Areas that may be useful going forward. In six of the eight Focus Areas, there are some indications of recovery from past habitat fragmentation. This may be an artifact of the Landsat 8 (OLI) issue in the classification of landscape, but it’s probably not all due to this issue. Unfortunately, of these 6 Focus Areas that do show signs of recovery, two have no *B. houstonensis* records. As for the other four Focus Areas that seem to be recovering from fragmentation and also have *B. houstonensis* records, all four show positive trends in all three metrics: total patch size, mean patch size, and total number of patches. When thinking about how these three metrics work together to describe the habitat and potential fragmentation of habitat within a given boundary larger total patch size is better, larger mean patch size is better, and fewer total patches is also better. This isn’t always the case, and it depends on the species in question and the type of habitats a species occupies. But, in the case of *B. houstonensis*, and in the context of these bounded USFWS-Focus Areas in which to assess these three metrics, more total habitat, coupled with larger patches, and fewer patches indicate less fragmentation.

I suggest directing efforts to annual evaluation of the following four key USFWS-Focus Areas: Robertson/Leon (primary); Robertson/Leon (secondary); Austin Colorado (primary); and Burleson/Milam (primary). All four of these key Focus Areas show increased total patch size; mean patch size; while also a decrease of total number of patches and this indicates recovery from past fragmentation. A key aspect of directing attention to these four key Focus Areas is that three of the four Focus Areas have *B. houstonensis* detections within the last 10 years. The Robertson-Leon (secondary) Focus Area has no history of detections, but it is directly adjacent to the Robertson-Leon (primary) Focus Area where 47 *B. houstonensis* detections occurred in the past five years.

Future Directions

Some future studies that may provide useful information for conservation of *B. houstonensis* include expanding my study to cover the known range of the species, and not only targeting the Focus Areas. These proposed USFWS-Focus Areas are by no measure small, however, many *B. houstonensis* detections records exist outside of these Focus Areas (145 detections as of 06/10/2015). Ultimately, in order to evaluate my habitat suitability model surveys should be designed to assess *B. houstonensis* presence and absence within these Focus Areas and conducted over enough time and with consistency.

The large gap in the number of years between detections suggests a few things: lack of conservation efforts and lack of consistency of efforts. For these reasons prior sites need extensive surveys, and audio loggers appear to be a suitable way to do this. These surveys should be directed in areas identified as habitat but without detections in the last 10 years.

Finally, clarification of the influence of soils on *B. houstonensis* could be useful for habitat modeling. Previous studies have focused on a narrow breadth of soil types thought to be biologically relevant to *B. houstonensis*, but this may be an error of omission. Mahato and Forstner (2011) found that many *B. houstonensis* detections occurred outside the soils series previously described as biologically relevant. It may be that we should not look for soils that are the most suitable for *B. houstonensis* rather that we exclude soils least suitable (Dr. Michael Forstner per. comm.). The eventual recovery or extinction of this and other endangered species requires that we learn from the past and apply our better informed understanding of mistakes and successes to improving our future conservation work with rare taxa.

APPENDIX SECTION

The following are maps illustrating United States Fish and Wildlife Service Focus Areas for the Houston toad (*Bufo houstonensis*). The maps are sorted first by Focus Area and then in chronological order (from earliest to latest). Each map provides a representation of the habitat at each time step produced by my model. The sizes and shapes of each Focus Area are variable, creating different scales across the representations, thus attention to each individual map's scale is critical.

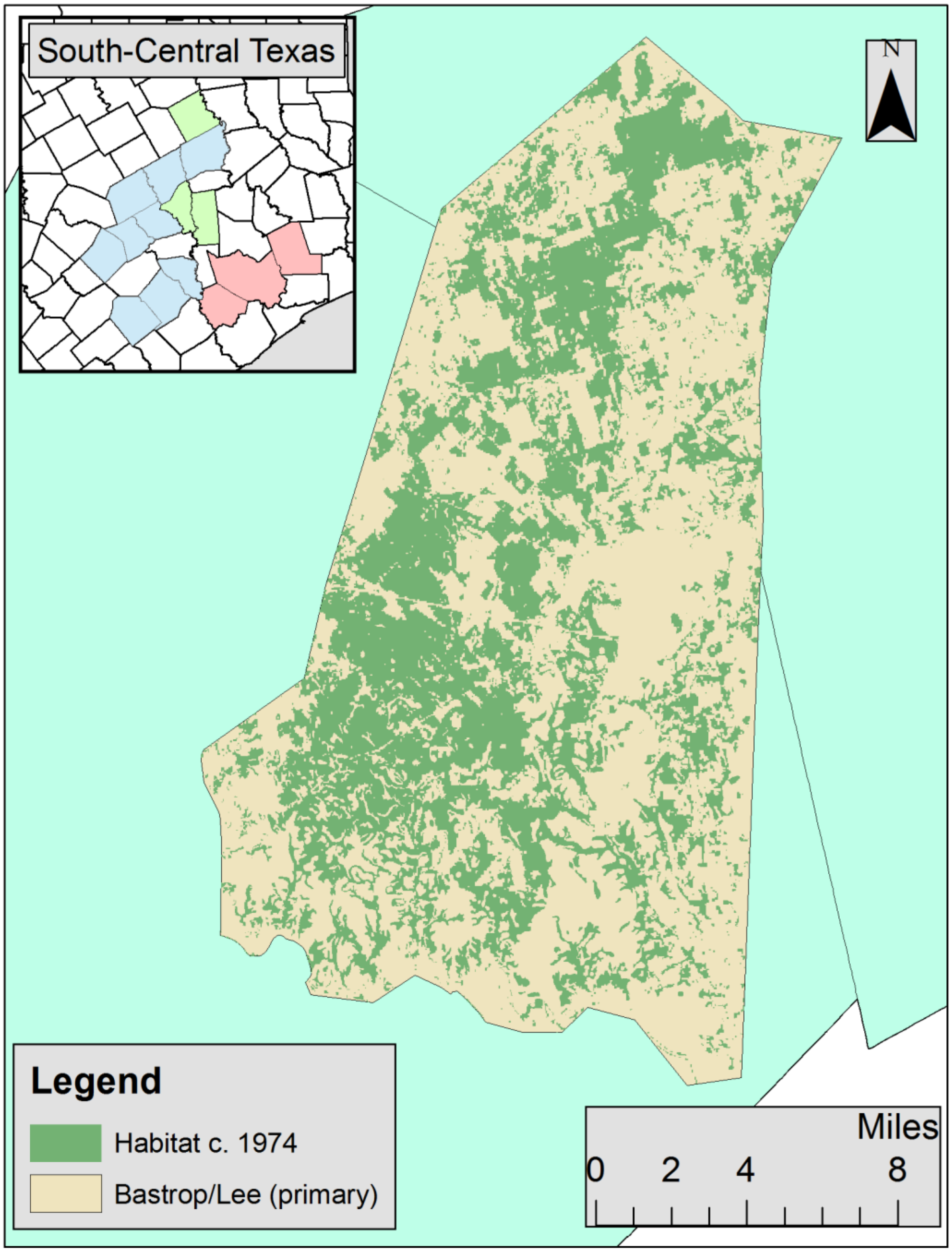

Figure 8. Bastrop/Lee (primary) USFWS-Focus Area for the Houston toad (*Bufo houstonensis*) with habitat (c. 1974). The areas in green represent habitat derived in part from satellite imagery captured on March 19, 1974. This Focus Area spans Bastrop and Lee counties.

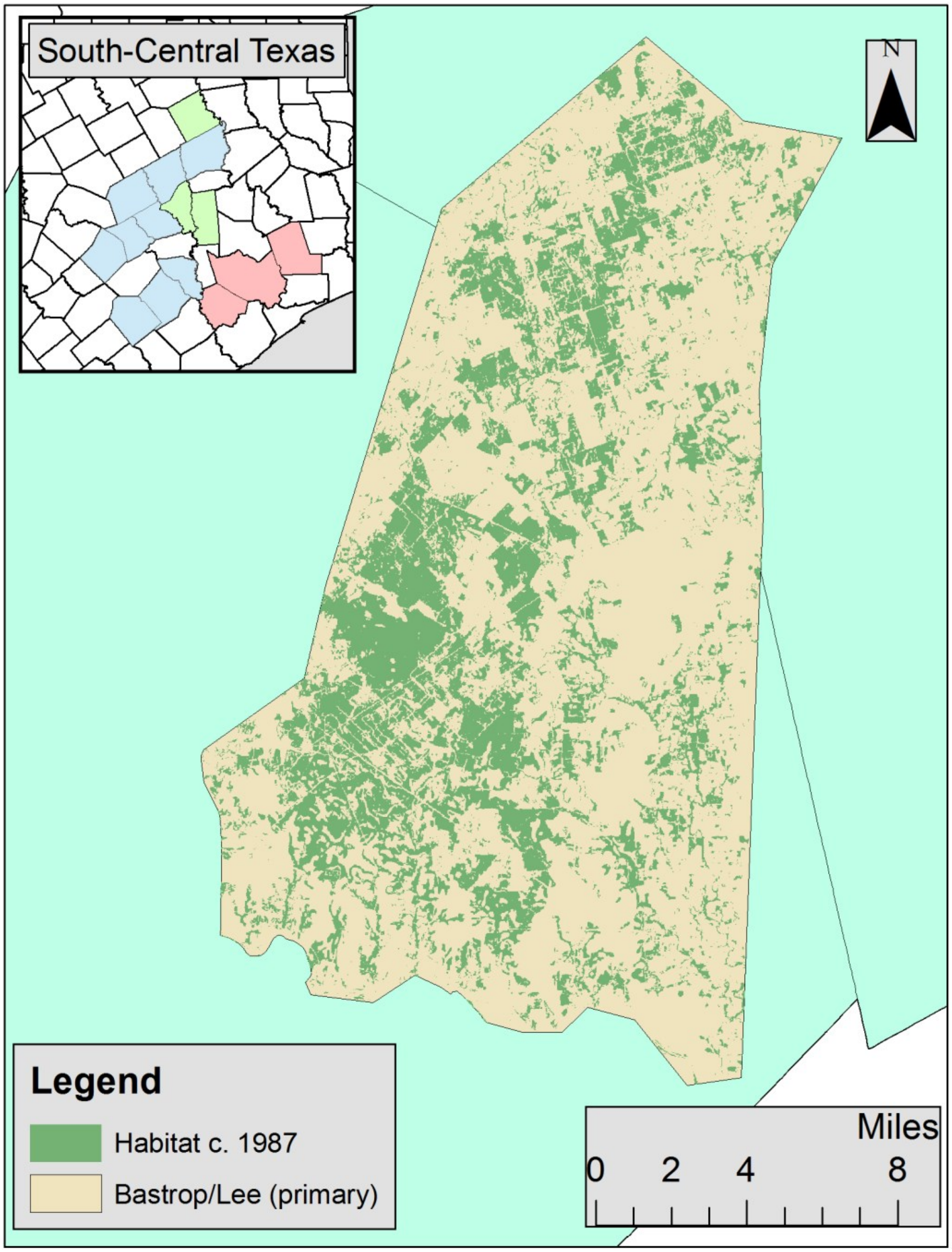

Figure 9. Bastrop/Lee (primary) USFWS-Focus Area for the Houston toad (*Bufo houstonensis*) with habitat (c. 1987). The areas in green represent habitat derived in part from satellite imagery captured on April 27, 1987. This Focus Area spans Bastrop and Lee counties.

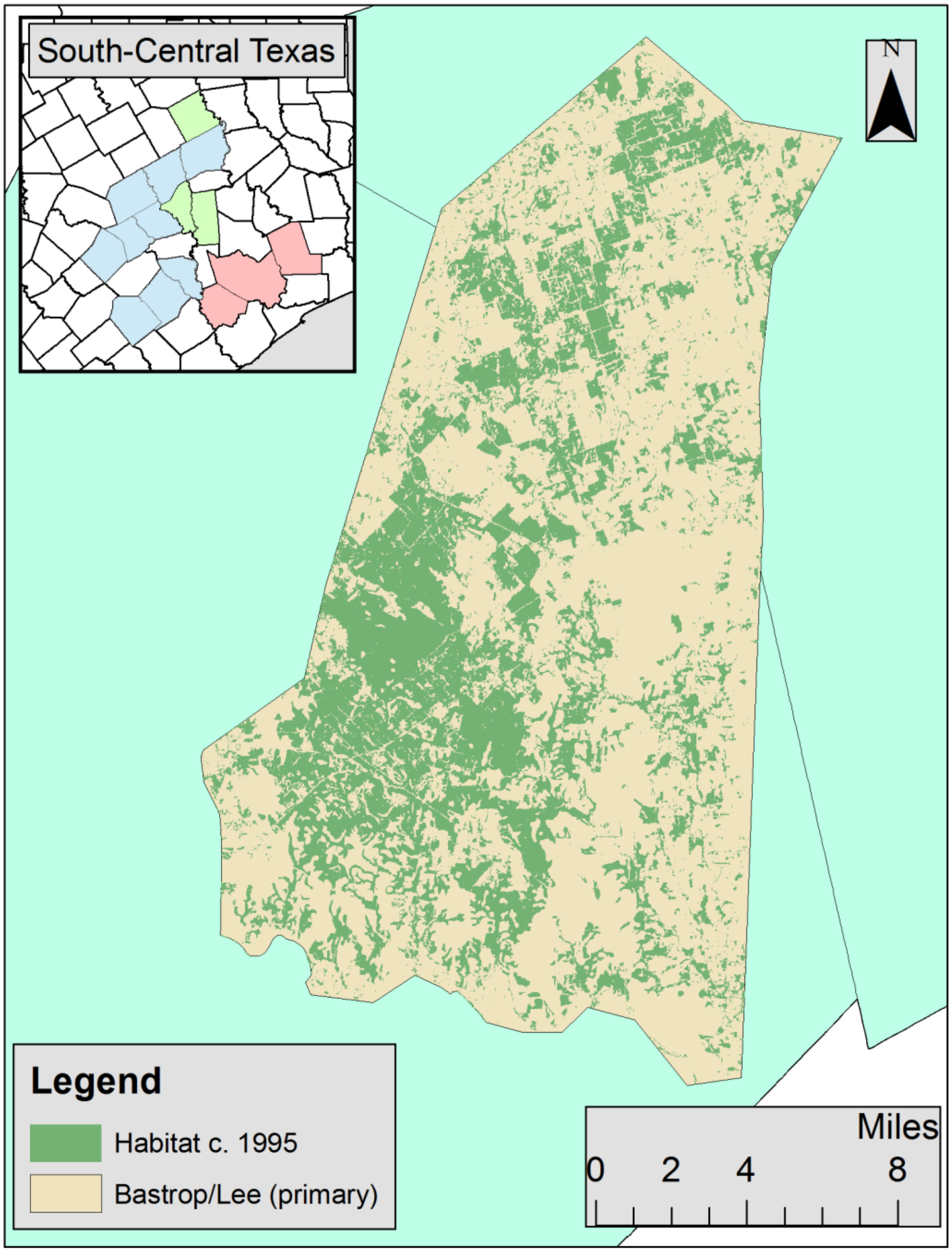

Figure 10. Bastrop/Lee (primary) USFWS-Focus Area for the Houston toad (*Bufo houstonensis*) with habitat (c. 1995). The areas in green represent habitat derived in part from satellite imagery captured on May 19, 1995. This Focus Area spans Bastrop and Lee counties.

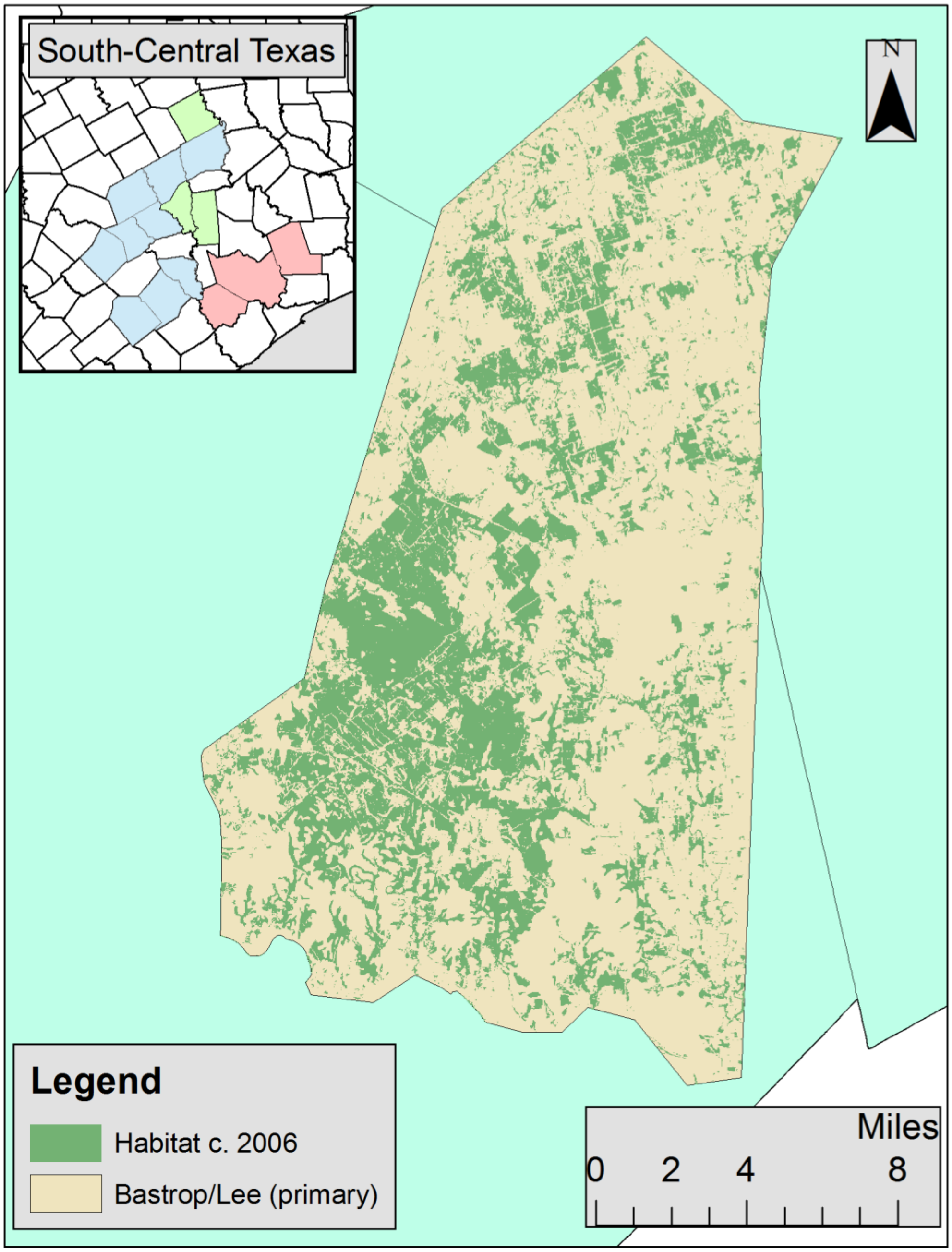

Figure 11. Bastrop/Lee (primary) USFWS-Focus Area for the Houston toad (*Bufo houstonensis*) with habitat (c. 2006). The areas in green represent habitat derived in part from satellite imagery captured on May 1, 2006. This Focus Area spans Bastrop and Lee counties.

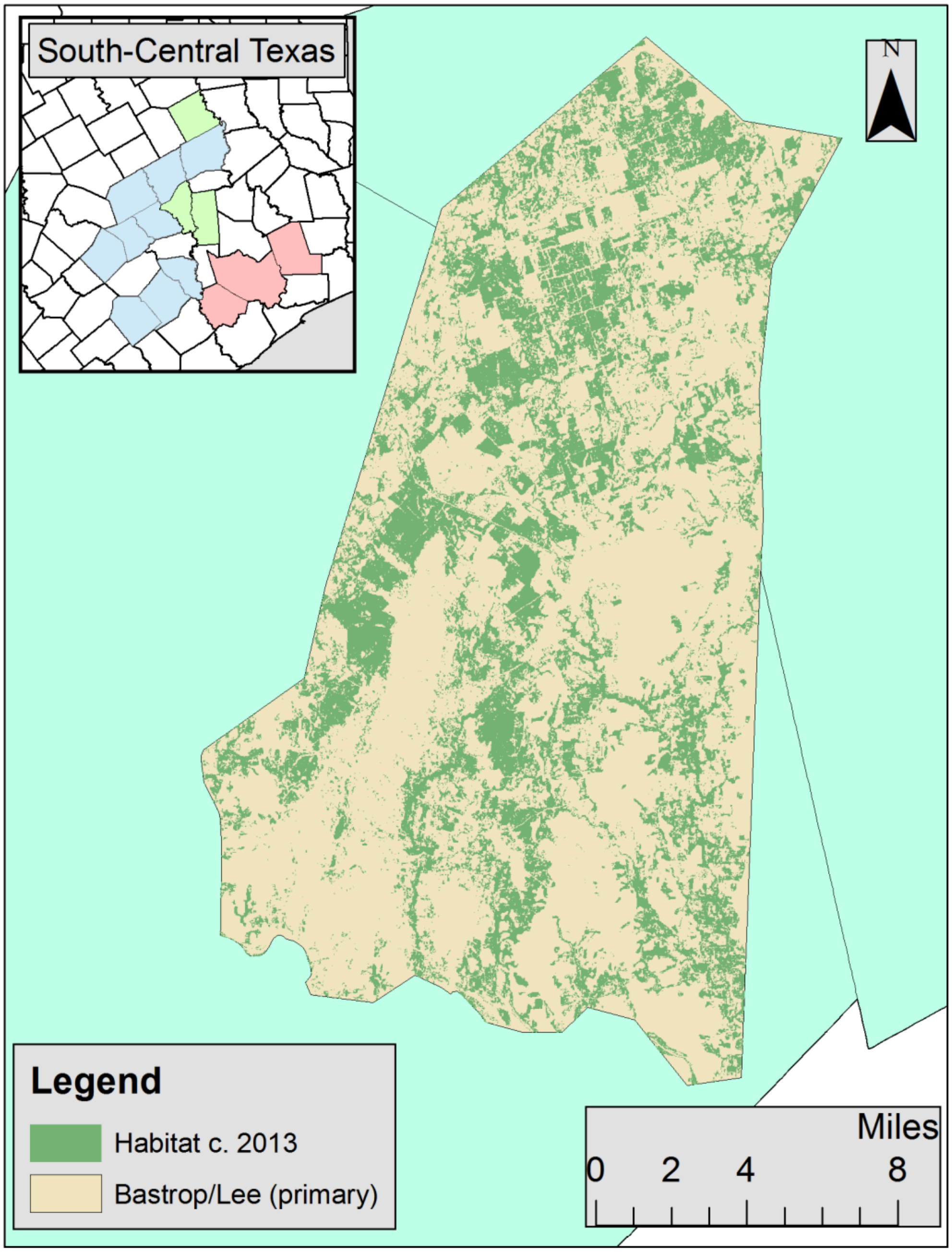

Figure 12. Bastrop/Lee (primary) USFWS-Focus Area for the Houston toad (*Bufo houstonensis*) with habitat (c. 2013). The areas in green represent habitat derived in part from satellite imagery captured on May 4, 2013. This Focus Area spans Bastrop and Lee counties.

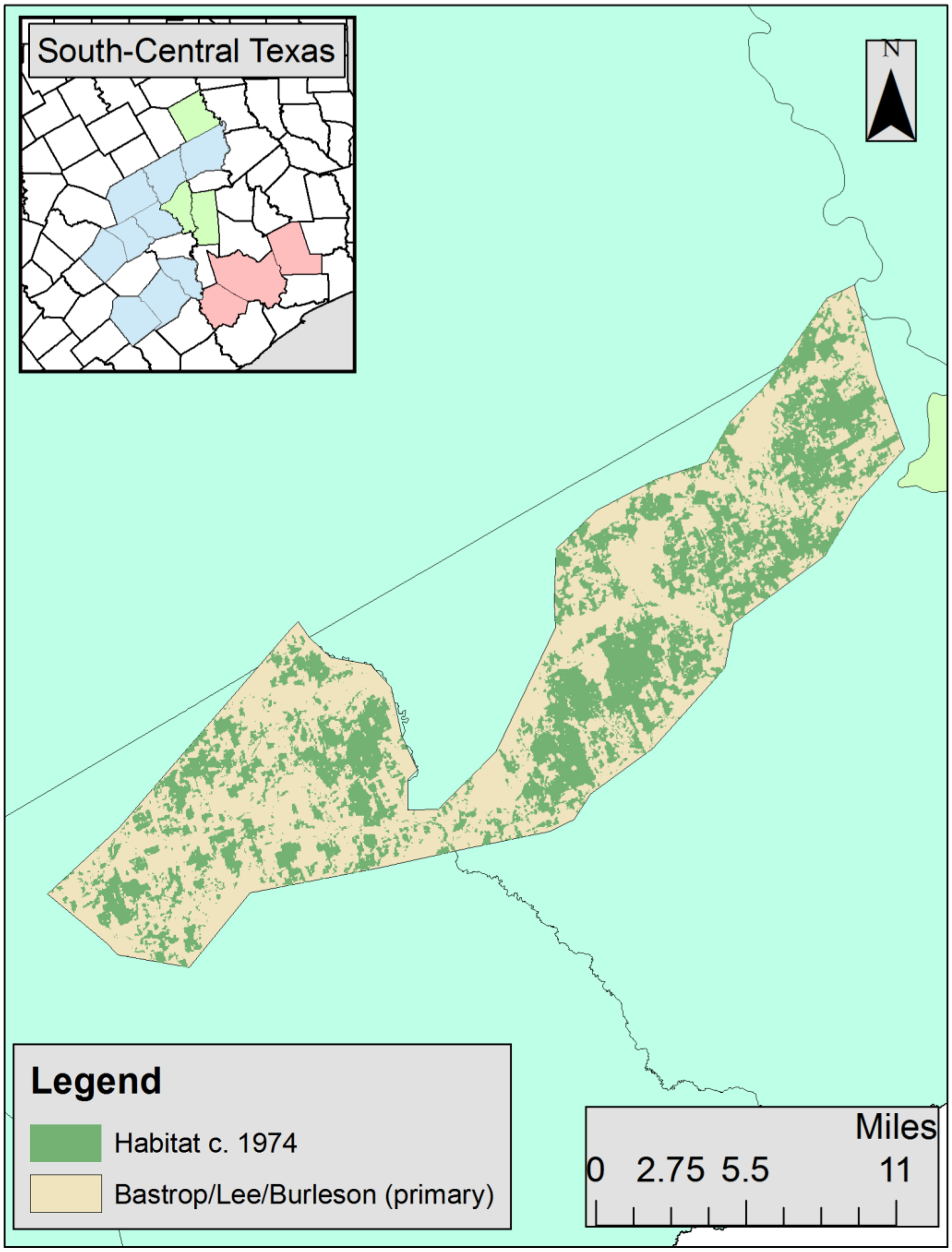

Figure 13. Bastrop/Lee/Burleson (primary) USFWS-Focus Area for the Houston toad (*Bufo houstonensis*) with habitat (c. 1974). The areas in green represent habitat derived in part from satellite imagery captured on March 19, 1974. This Focus Area spans Lee, Burleson, and Milam counties.

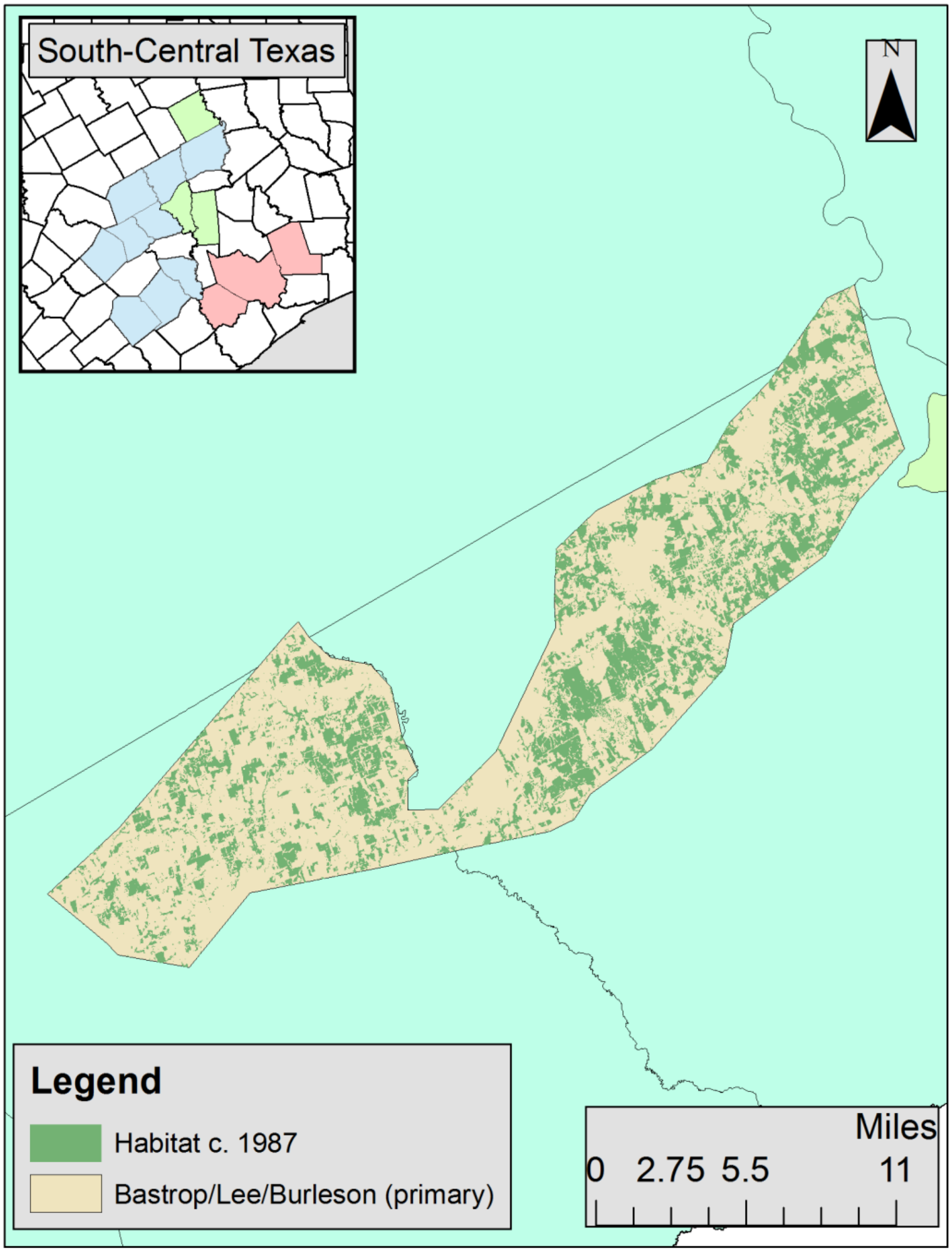

Figure 14. Bastrop/Lee/Burleson (primary) USFWS-Focus Area for the Houston toad (*Bufo houstonensis*) with habitat (c. 1987). The areas in green represent habitat derived in part from satellite imagery captured on April 27, 1987. This Focus Area spans Lee, Burleson, and Milam counties.

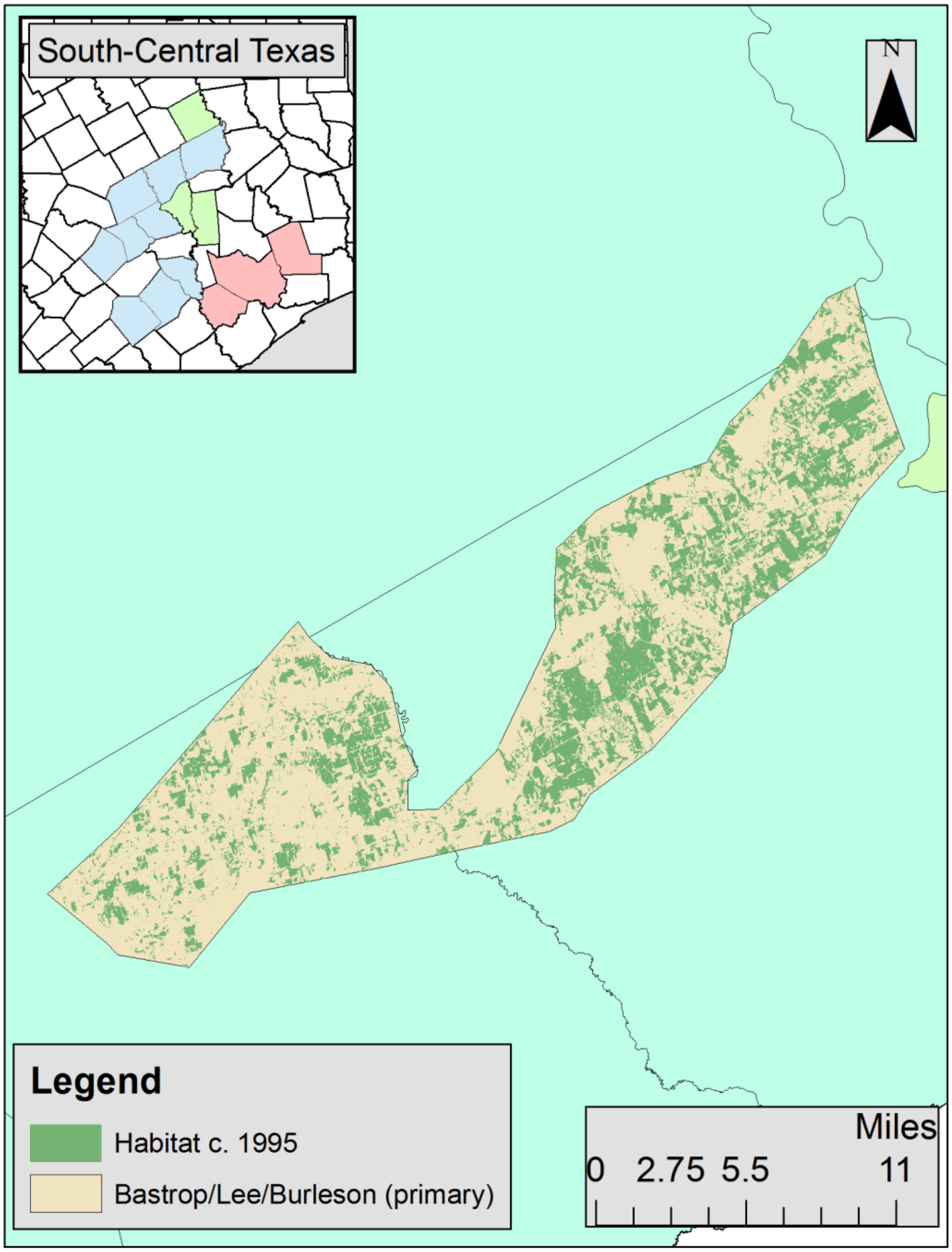

Figure 15. Bastrop/Lee/Burleson (primary) USFWS-Focus Area for the Houston toad (*Bufo houstonensis*) with habitat (c. 1995). The areas in green represent habitat derived in part from satellite imagery captured on April 19, 1995. This Focus Area spans Lee, Burleson, and Milam counties.

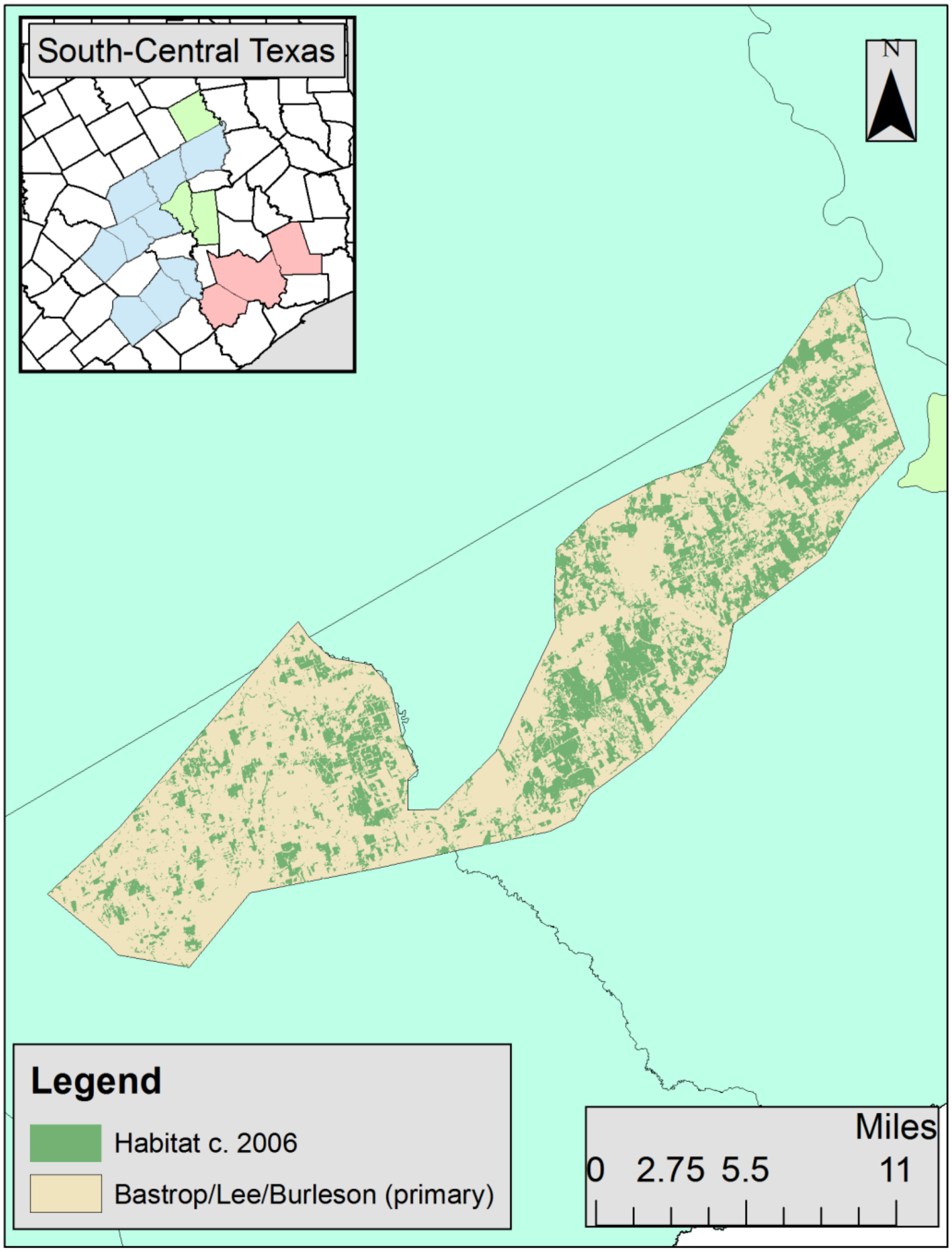

Figure 16. Bastrop/Lee/Burleson (primary) USFWS-Focus Area for the Houston toad (*Bufo houstonensis*) with habitat (c. 2006). The areas in green represent habitat derived in part from satellite imagery captured on May 1, 2006. This Focus Area spans Lee, Burleson, and Milam counties.

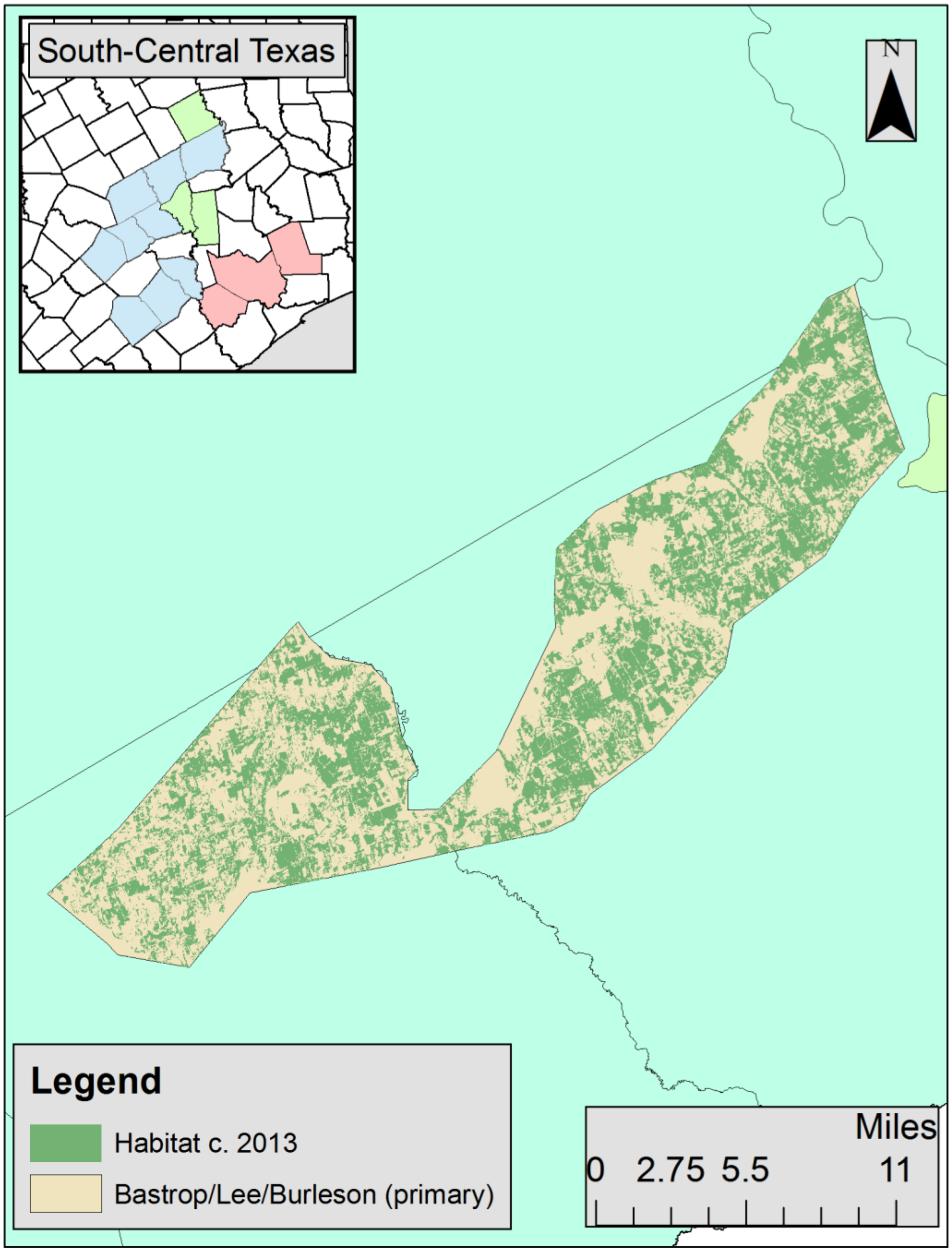

Figure 17. Bastrop/Lee/Burleson (primary) USFWS-Focus Area for the Houston toad (*Bufo houstonensis*) with habitat (c. 2013). The areas in green represent habitat derived in part from satellite imagery captured on May 4, 2013. This Focus Area spans Lee, Burleson, and Milam counties.

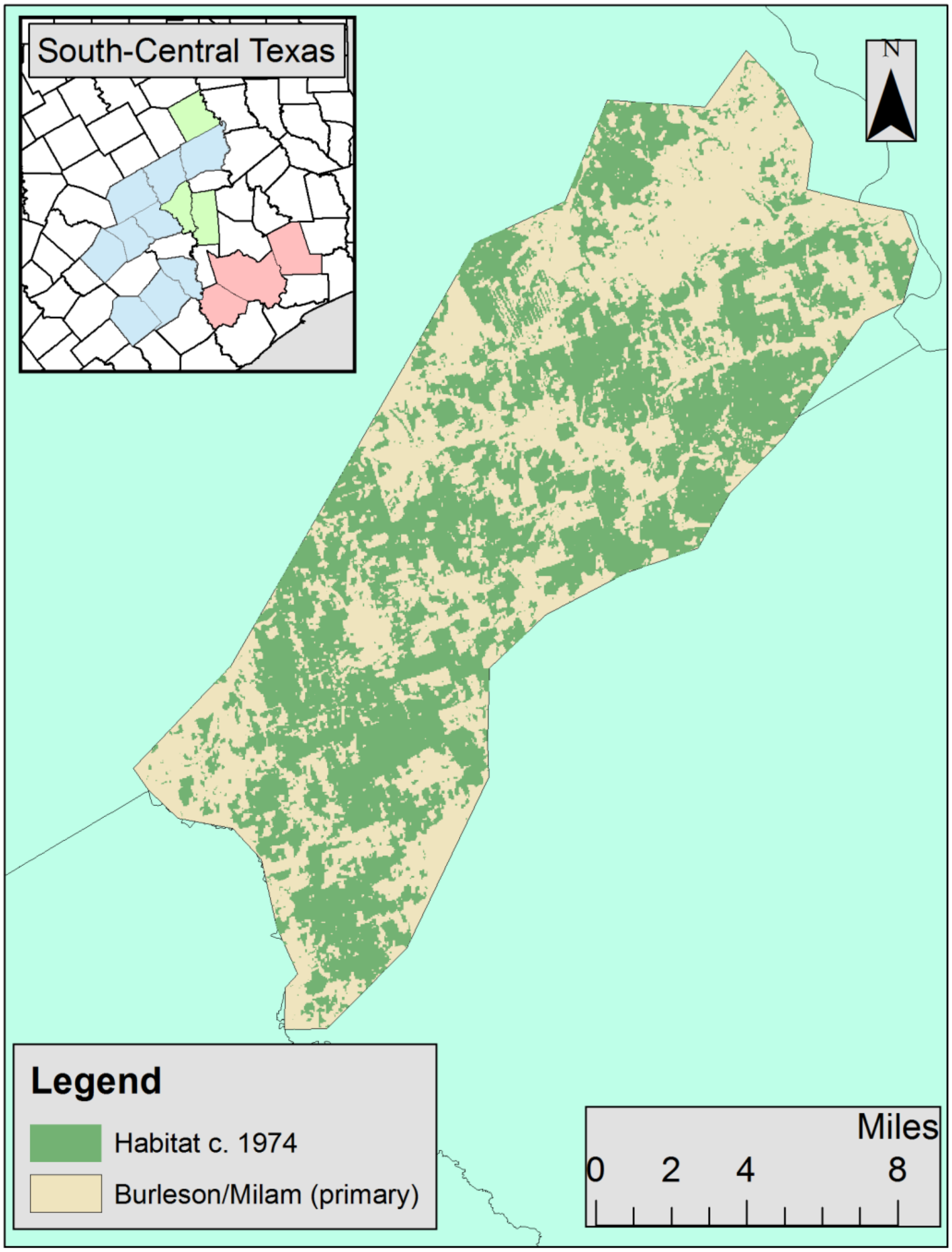

Figure 18. Burleson/Milam (primary) USFWS-Focus Area for the Houston toad (*Bufo houstonensis*) with habitat (c. 1974). The areas in green represent habitat derived in part from satellite imagery captured on March 19, 1974. This Focus Area spans Burleson and Milam counties.

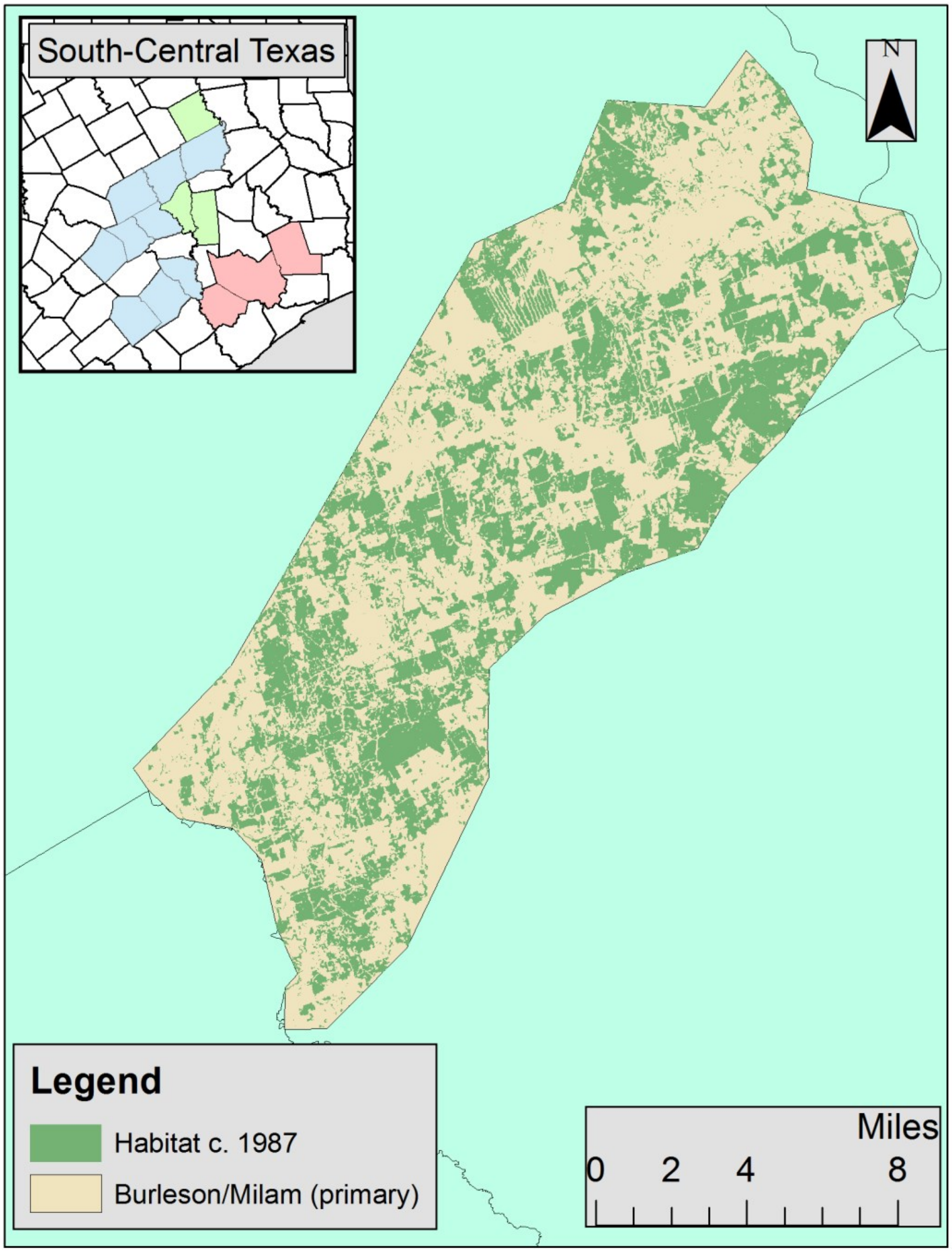

Figure 19. Burleson/Milam (primary) USFWS-Focus Area for the Houston toad (*Bufo houstonensis*) with habitat (c. 1987). The areas in green represent habitat derived in part from satellite imagery captured on April 27, 1987. This Focus Area spans Burleson and Milam counties.

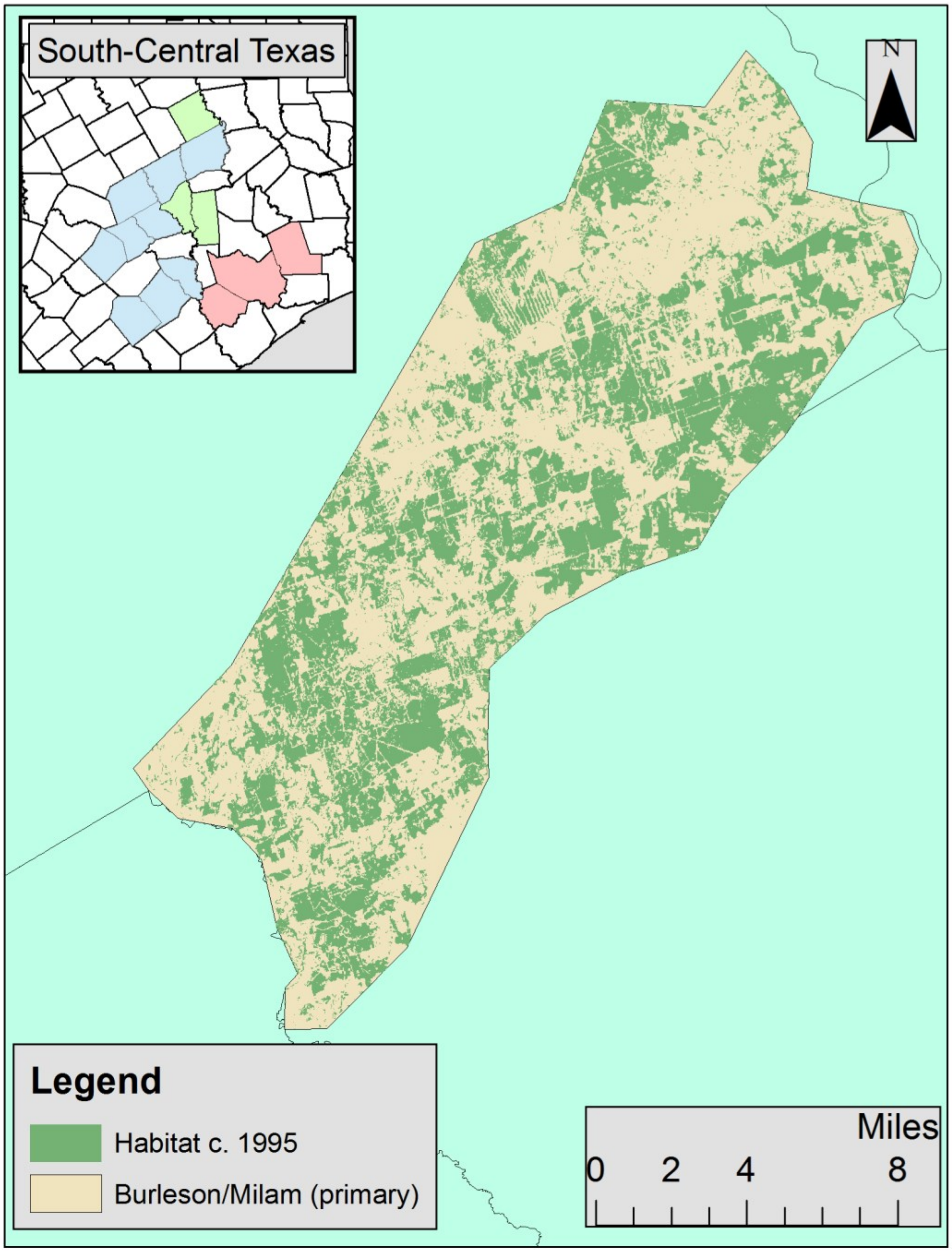

Figure 20. Burleson/Milam (primary) USFWS-Focus Area for the Houston toad (*Bufo houstonensis*) with habitat (c. 1995). The areas in green represent habitat derived in part from satellite imagery captured on April 19, 1995. This Focus Area spans Burleson and Milam counties.

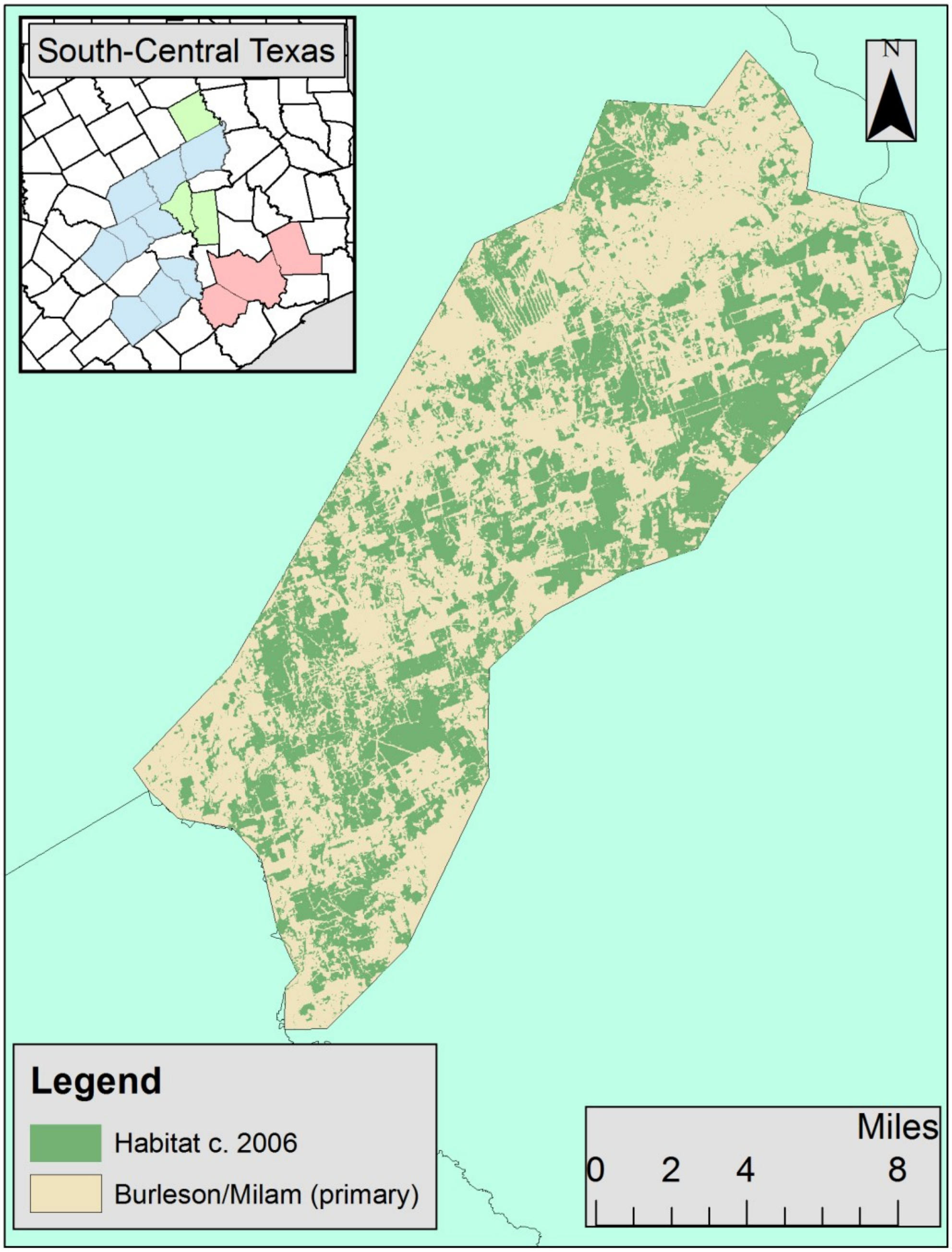

Figure 21. Burleson/Milam (primary) USFWS-Focus Area for the Houston toad (*Bufo houstonensis*) with habitat (c. 2006). The areas in green represent habitat derived in part from satellite imagery captured on April 1, 2006. This Focus Area spans Burleson and Milam counties.

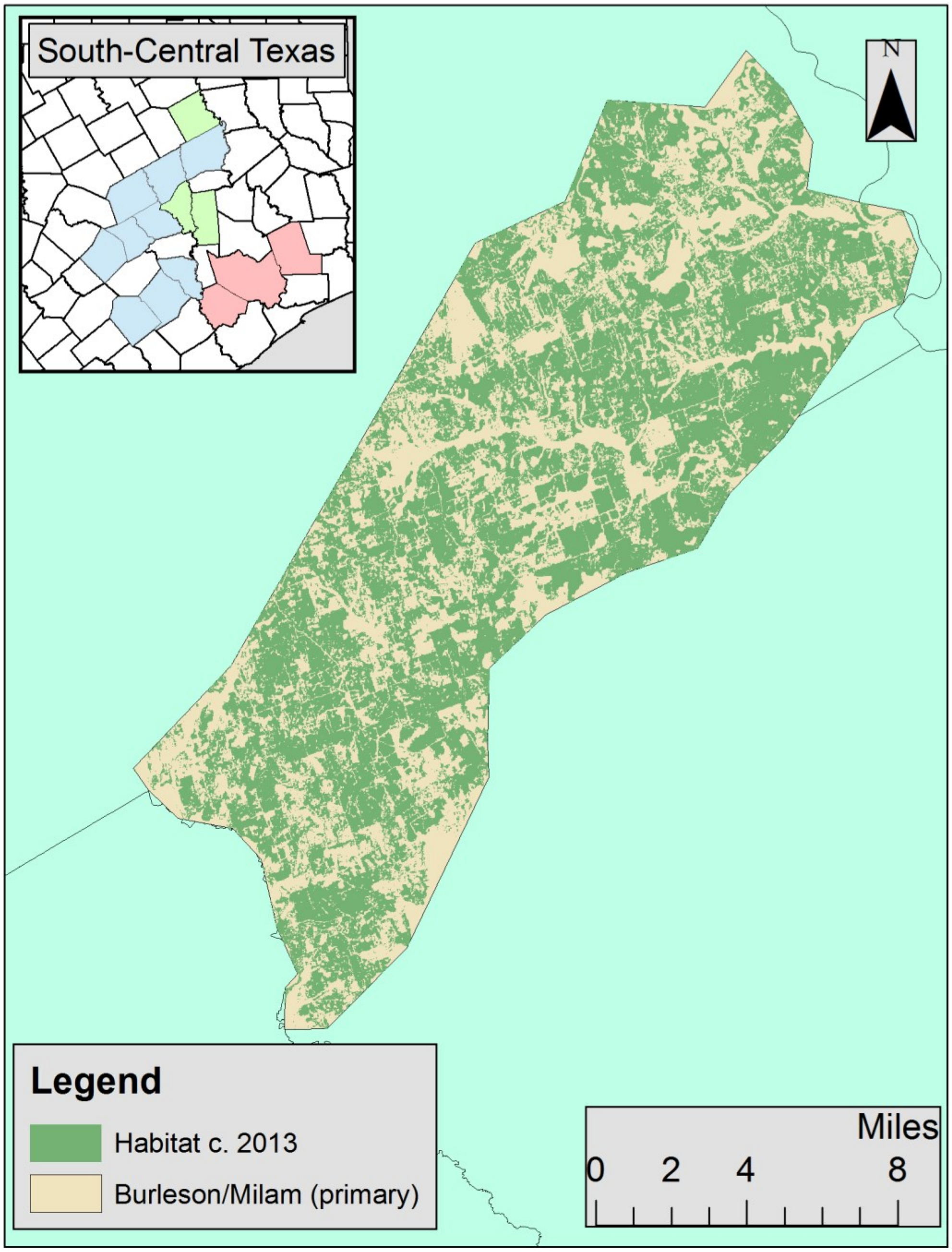

Figure 22. Burleson/Milam (primary) USFWS-Focus Area for the Houston toad (*Bufo houstonensis*) with habitat (c. 2013). The areas in green represent habitat derived in part from satellite imagery captured on May 4, 2013. This Focus Area spans Burleson and Milam counties.

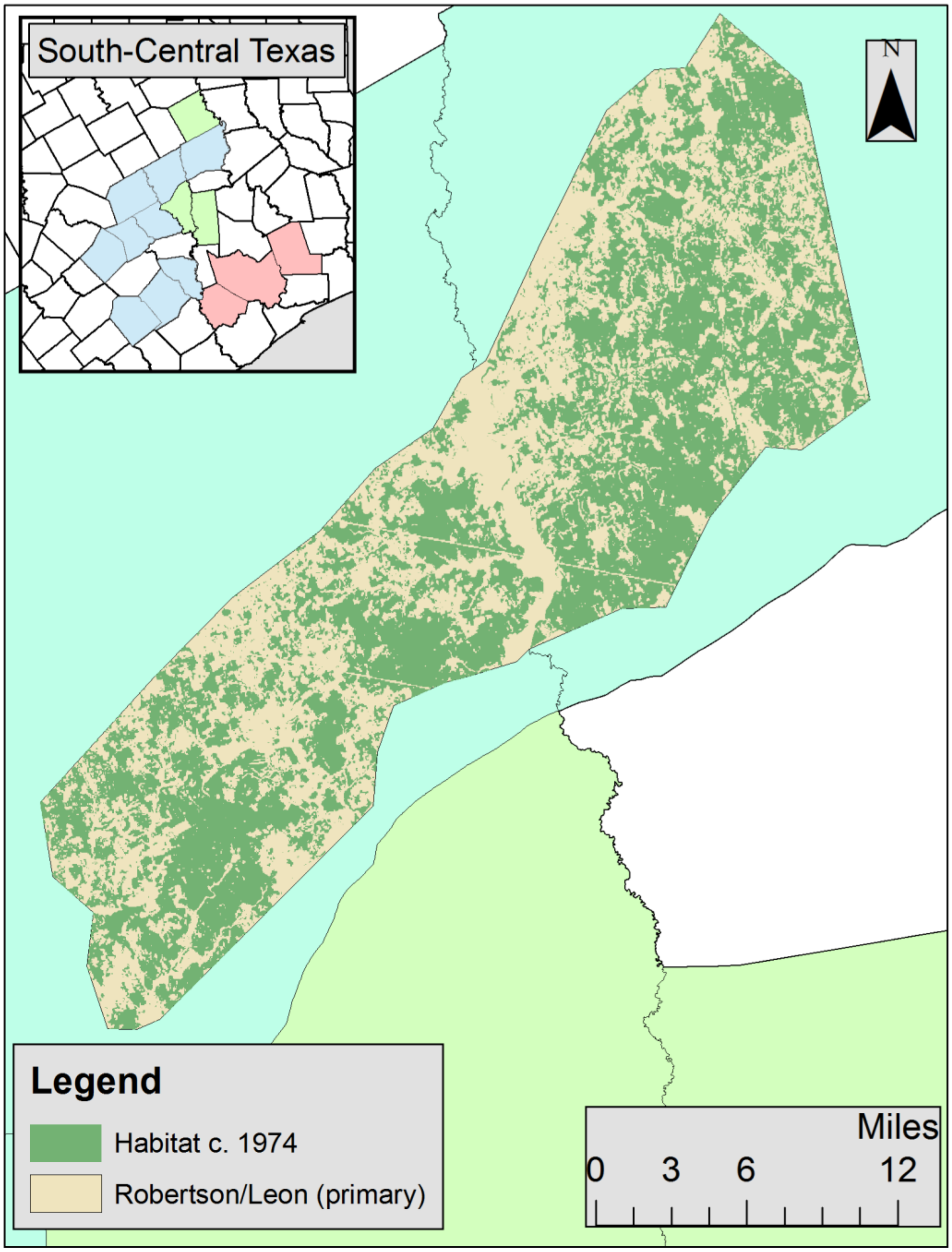

Figure 23. Robertson/Leon (primary) USFWS-Focus Area for the Houston toad (*Bufo houstonensis*) with habitat (c. 1974). The areas in green represent habitat derived in part from satellite imagery captured on March 19, 1974. This Focus Area spans Robertson and Leon counties.

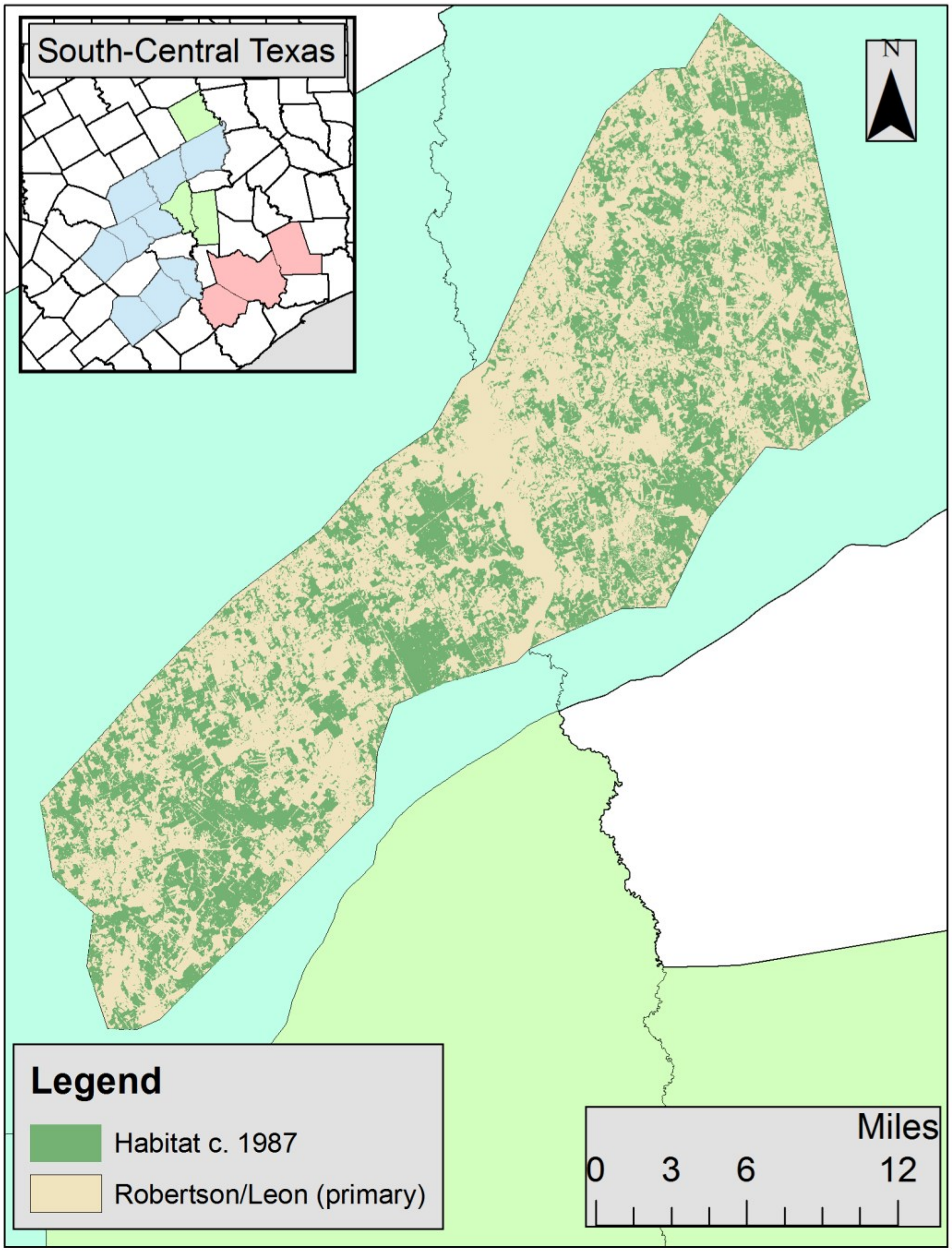

Figure 24. Robertson/Leon (primary) USFWS-Focus Area for the Houston toad (*Bufo houstonensis*) with habitat (c. 1987). The areas in green represent habitat derived in part from satellite imagery captured on April 27, 1987. This Focus Area spans Robertson and Leon counties.

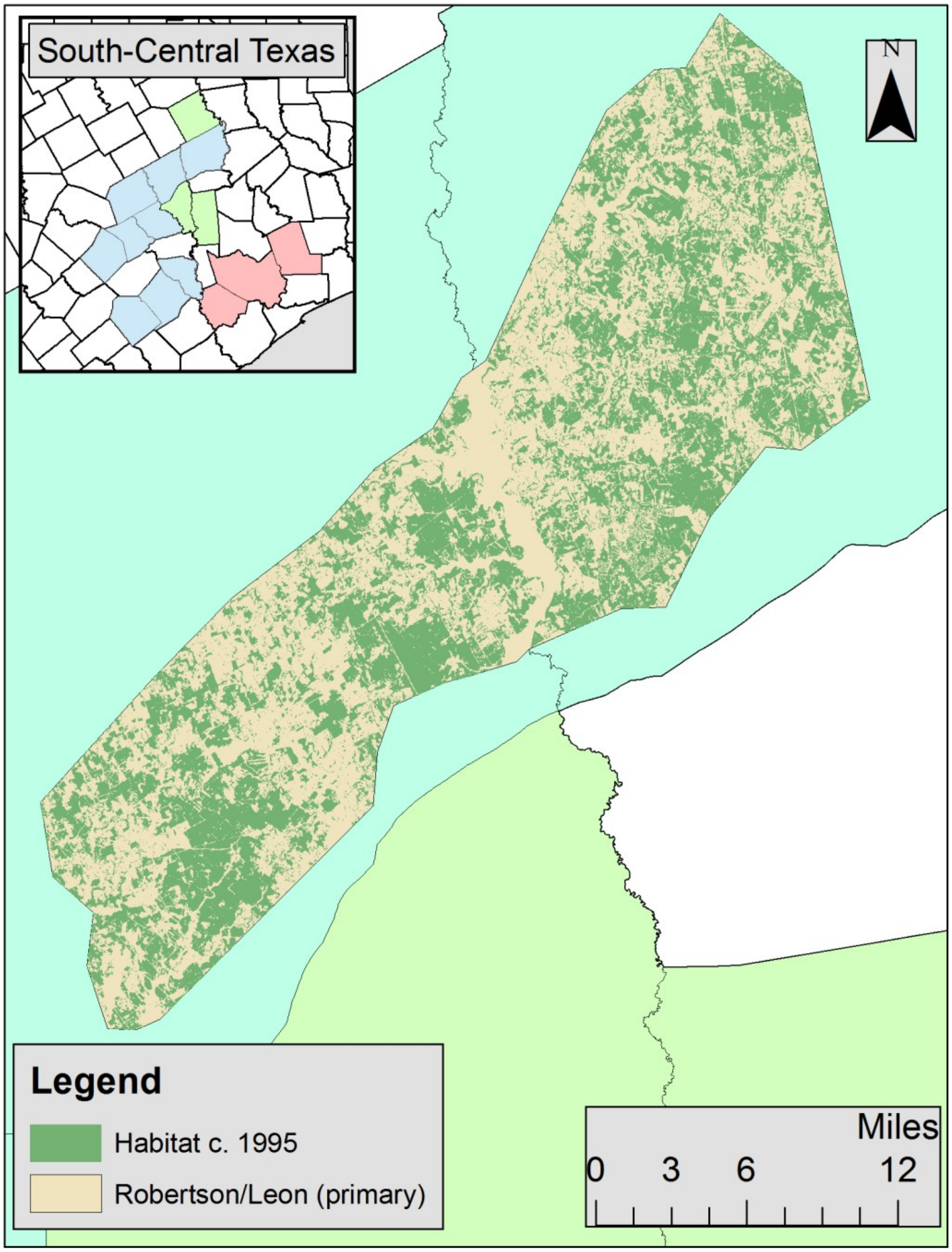

Figure 25. Robertson/Leon (primary) USFWS-Focus Area for the Houston toad (*Bufo houstonensis*) with habitat (c. 1995). The areas in green represent habitat derived in part from satellite imagery captured on May 19, 1995. This Focus Area spans Robertson and Leon counties.

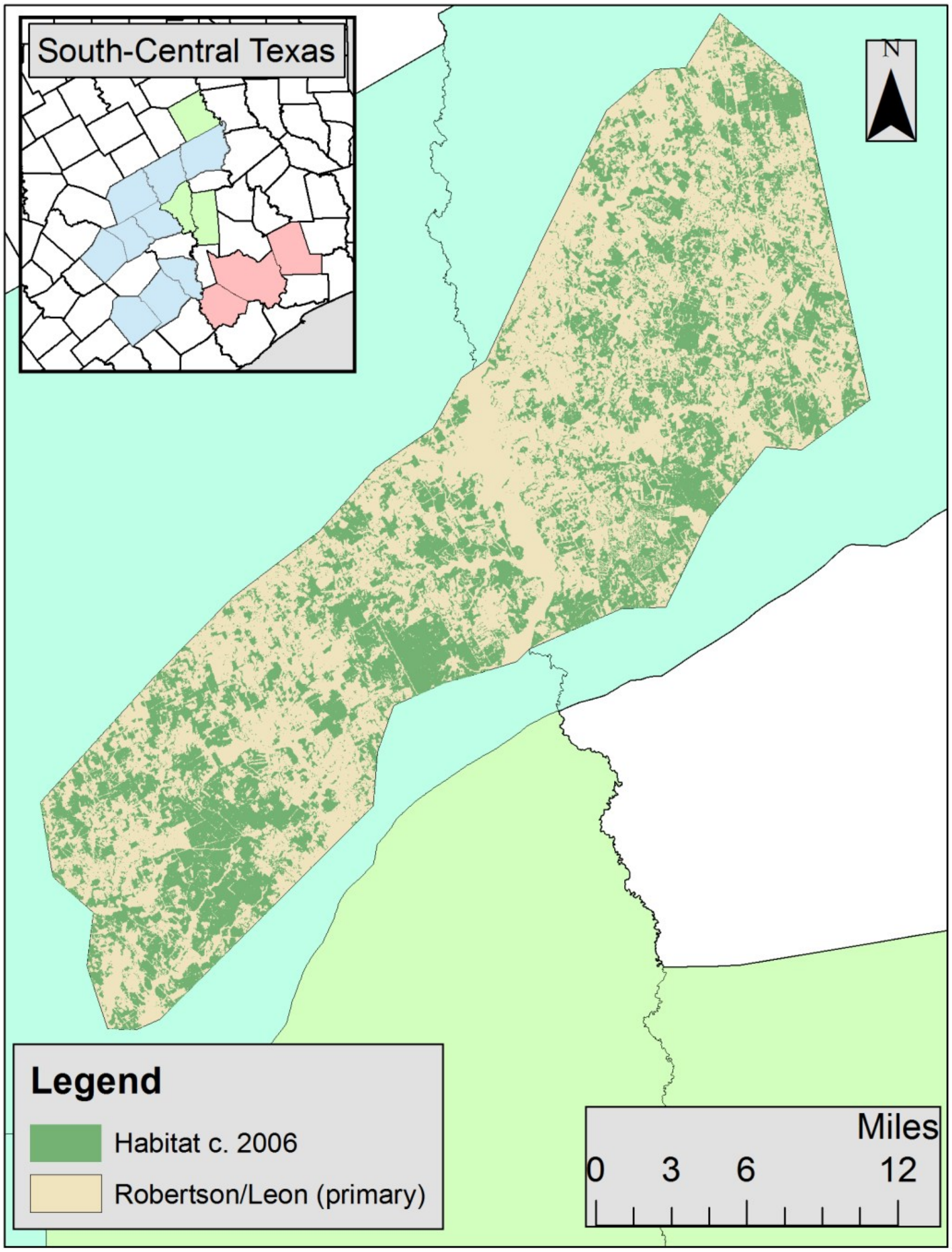

Figure 26. Robertson/Leon (primary) USFWS-Focus Area for the Houston toad (*Bufo houstonensis*) with habitat (c. 2006). The areas in green represent habitat derived in part from satellite imagery captured on May 1, 2006. This Focus Area spans Robertson and Leon counties.

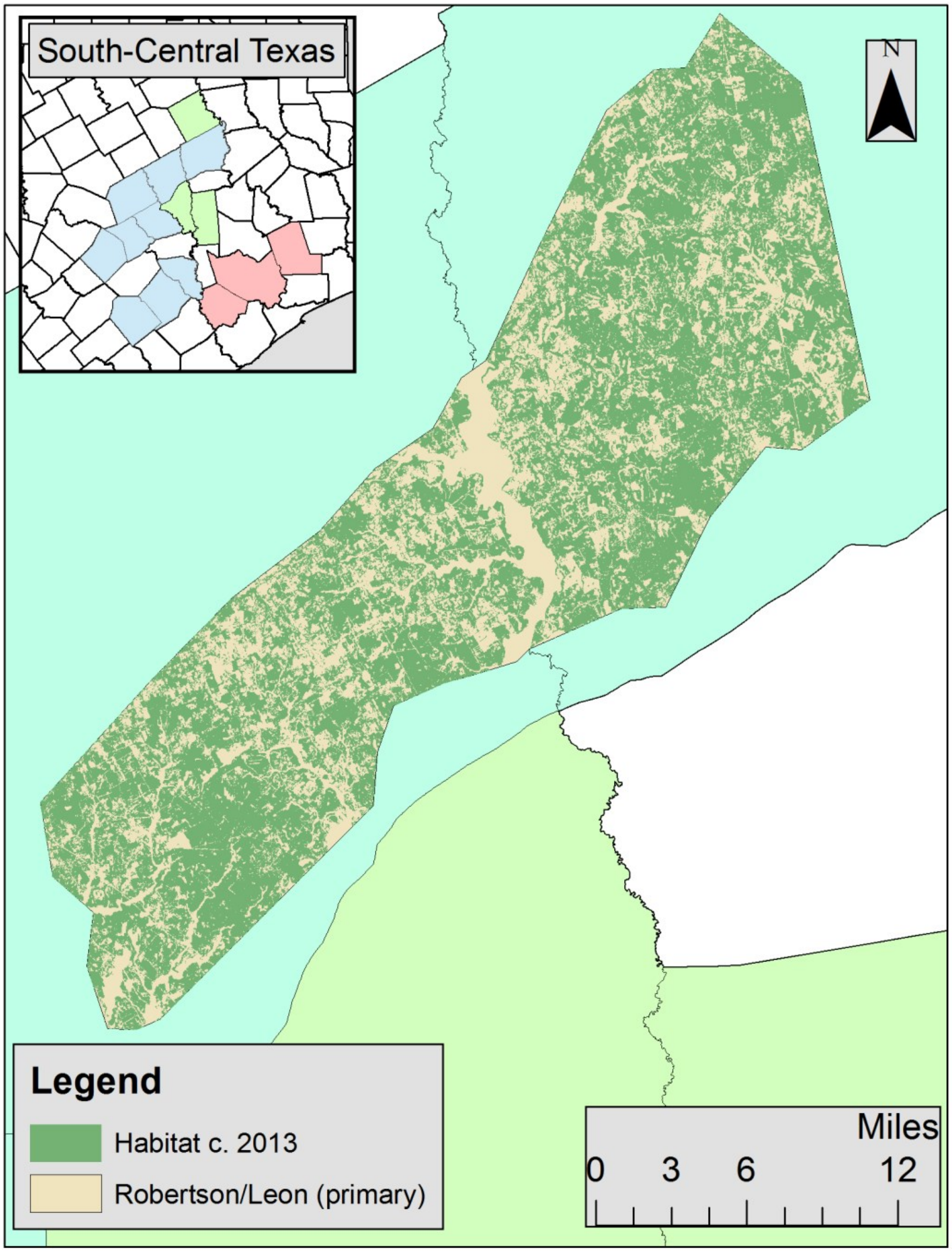

Figure 27. Robertson/Leon (primary) USFWS-Focus Area for the Houston toad (*Bufo houstonensis*) with habitat (c. 2013). The areas in green represent habitat derived in part from satellite imagery captured on May 4, 2013. This Focus Area spans Robertson and Leon counties.

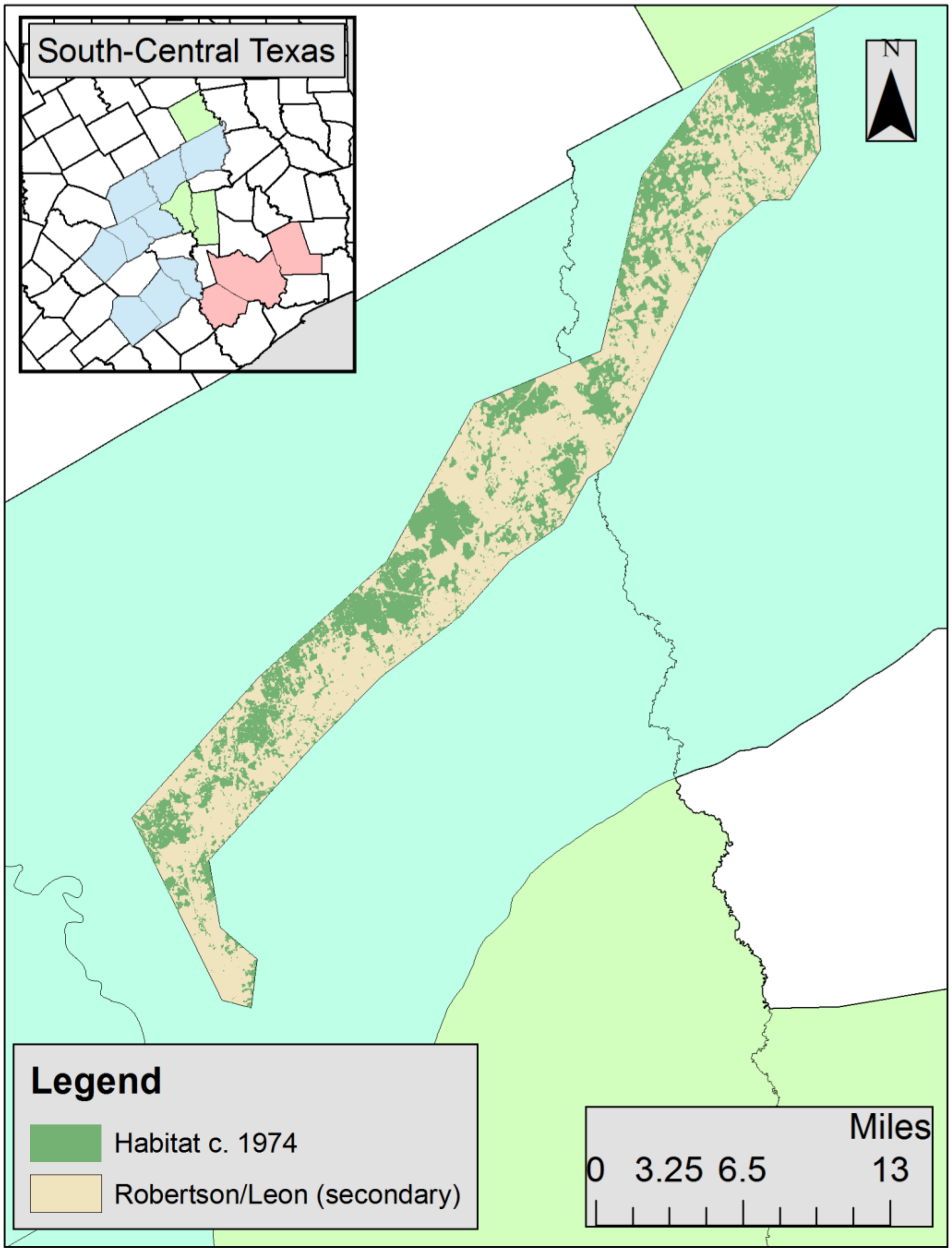

Figure 28. Robertson/Leon (secondary) USFWS-Focus Area for the Houston toad (*Bufo houstonensis*) with habitat (c. 1974). The areas in green represent habitat derived in part from satellite imagery captured on March 19, 1974. This Focus Area spans Robertson and Leon counties.

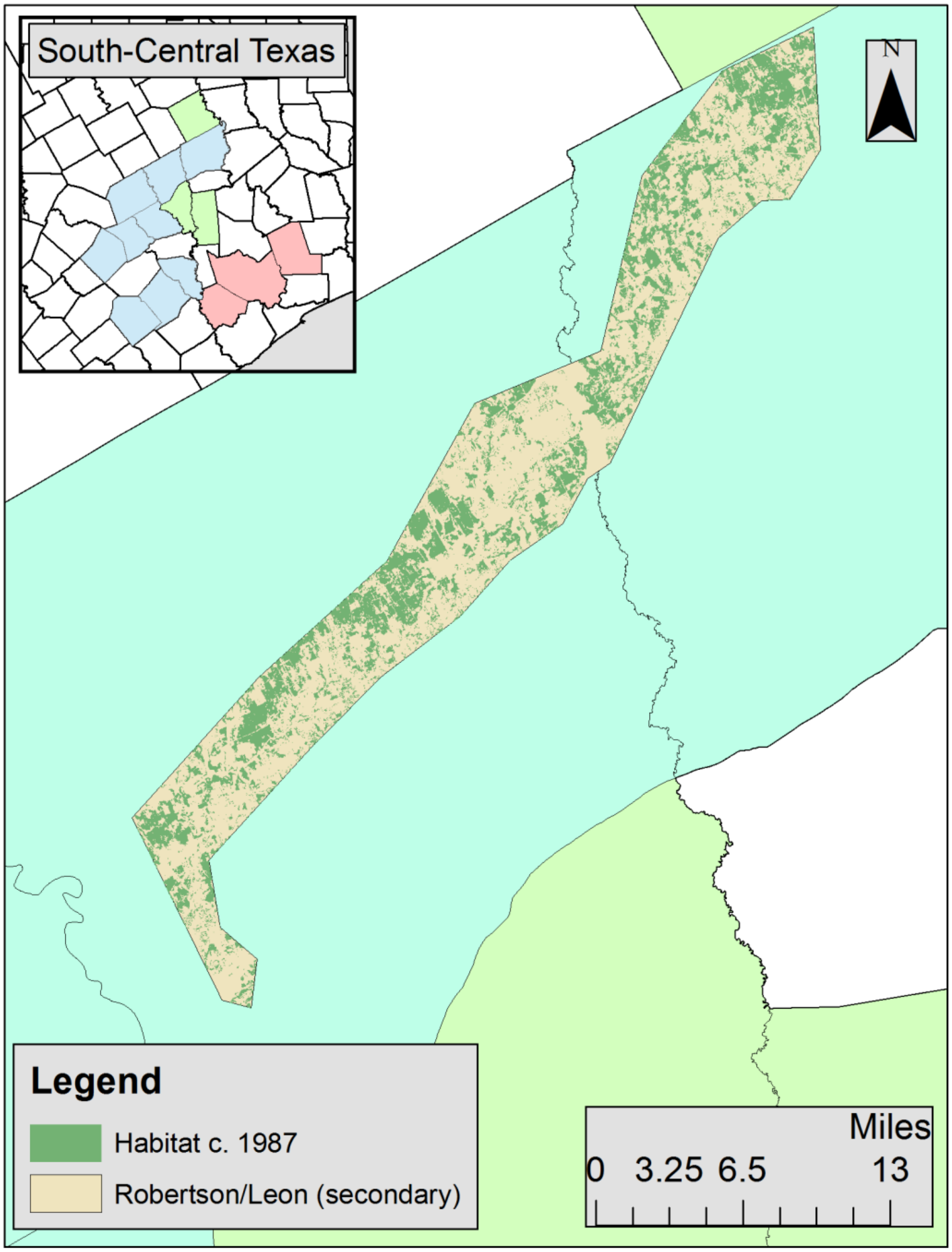

Figure 29. Robertson/Leon (secondary) USFWS-Focus Area for the Houston toad (*Bufo houstonensis*) with habitat (c. 1987). The areas in green represent habitat derived in part from satellite imagery captured on April 27, 1987. This Focus Area spans Robertson and Leon counties.

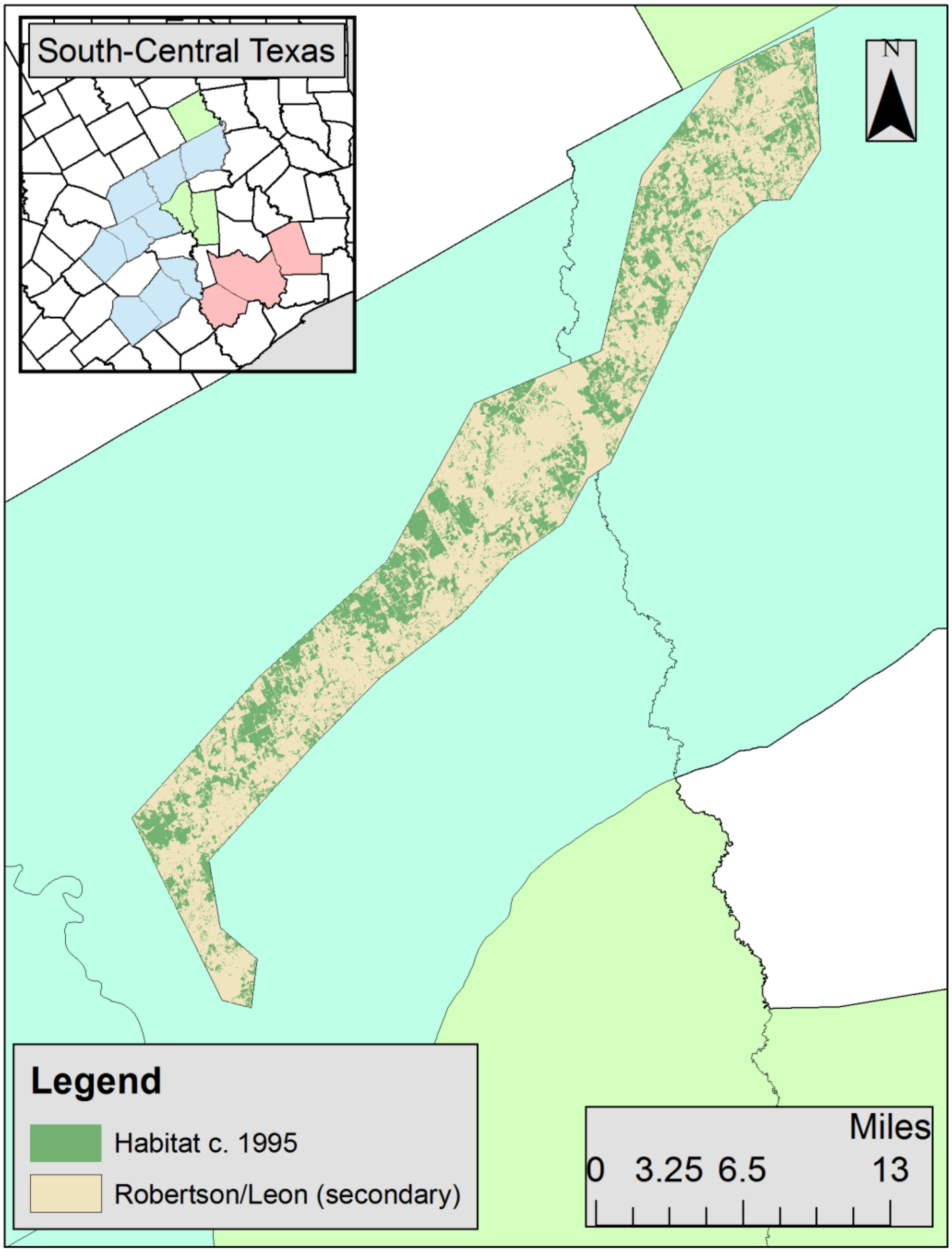

Figure 30. Robertson/Leon (secondary) USFWS-Focus Area for the Houston toad (*Bufo houstonensis*) with habitat (c. 1995). The areas in green represent habitat derived in part from satellite imagery captured on May 19, 1995. This Focus Area spans Robertson and Leon counties.

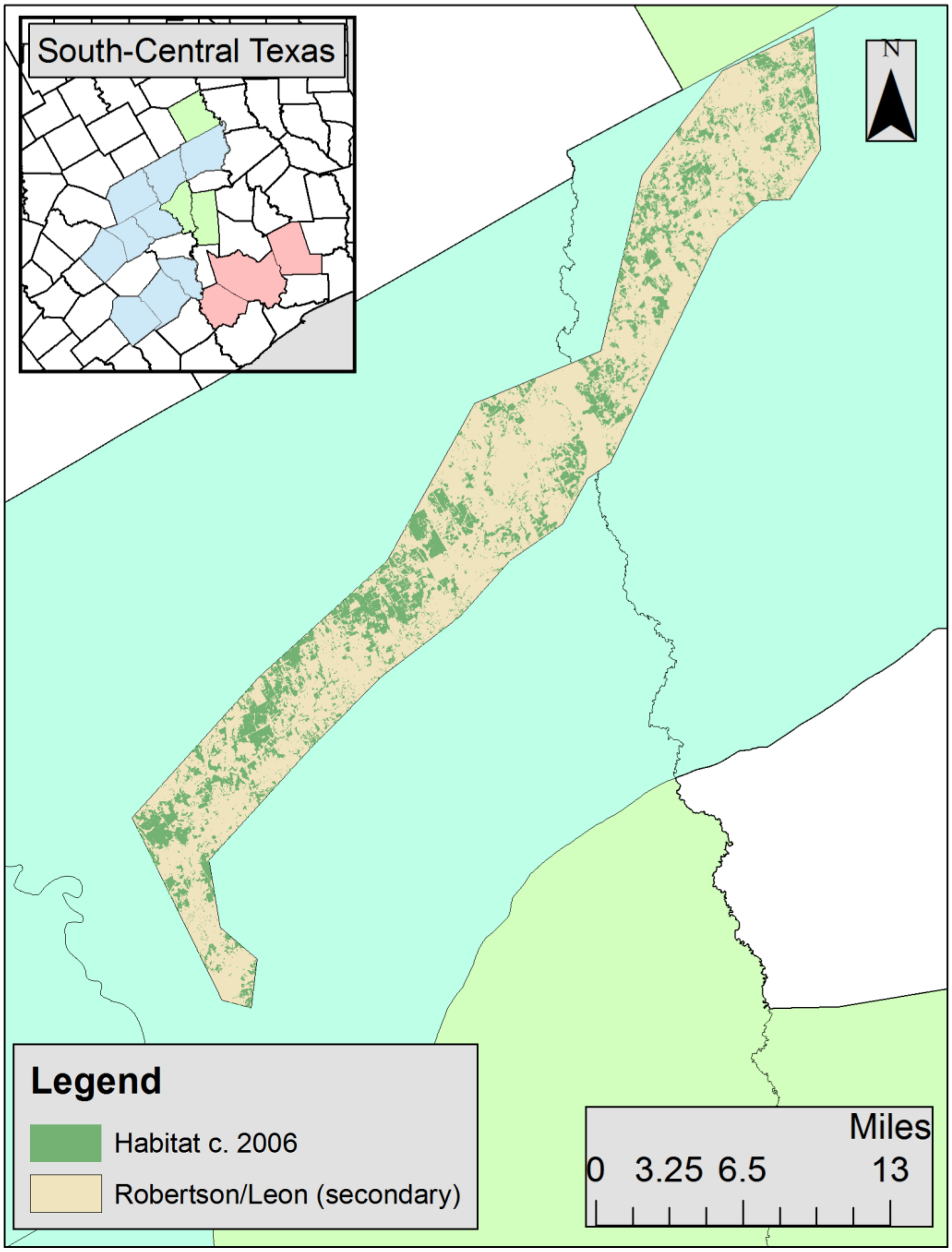

Figure 31. Robertson/Leon (secondary) USFWS-Focus Area for the Houston toad (*Bufo houstonensis*) with habitat (c. 2006). The areas in green represent habitat derived in part from satellite imagery captured on May 1, 2006. This Focus Area spans Robertson and Leon counties.

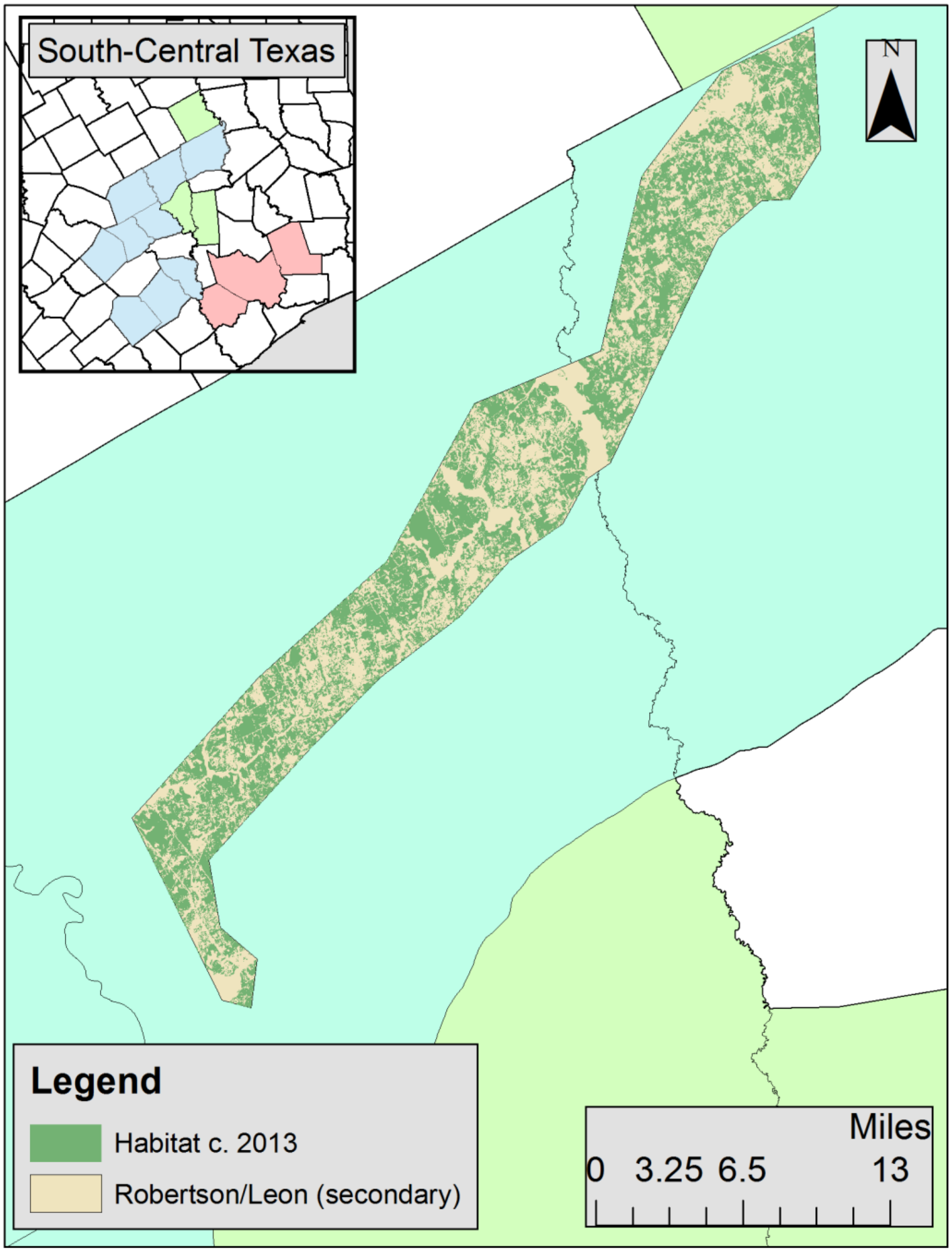

Figure 32. Robertson/Leon (secondary) USFWS-Focus Area for the Houston toad (*Bufo houstonensis*) with habitat (c. 2013). The areas in green represent habitat derived in part from satellite imagery captured on May 4, 2013. This Focus Area spans Robertson and Leon counties.

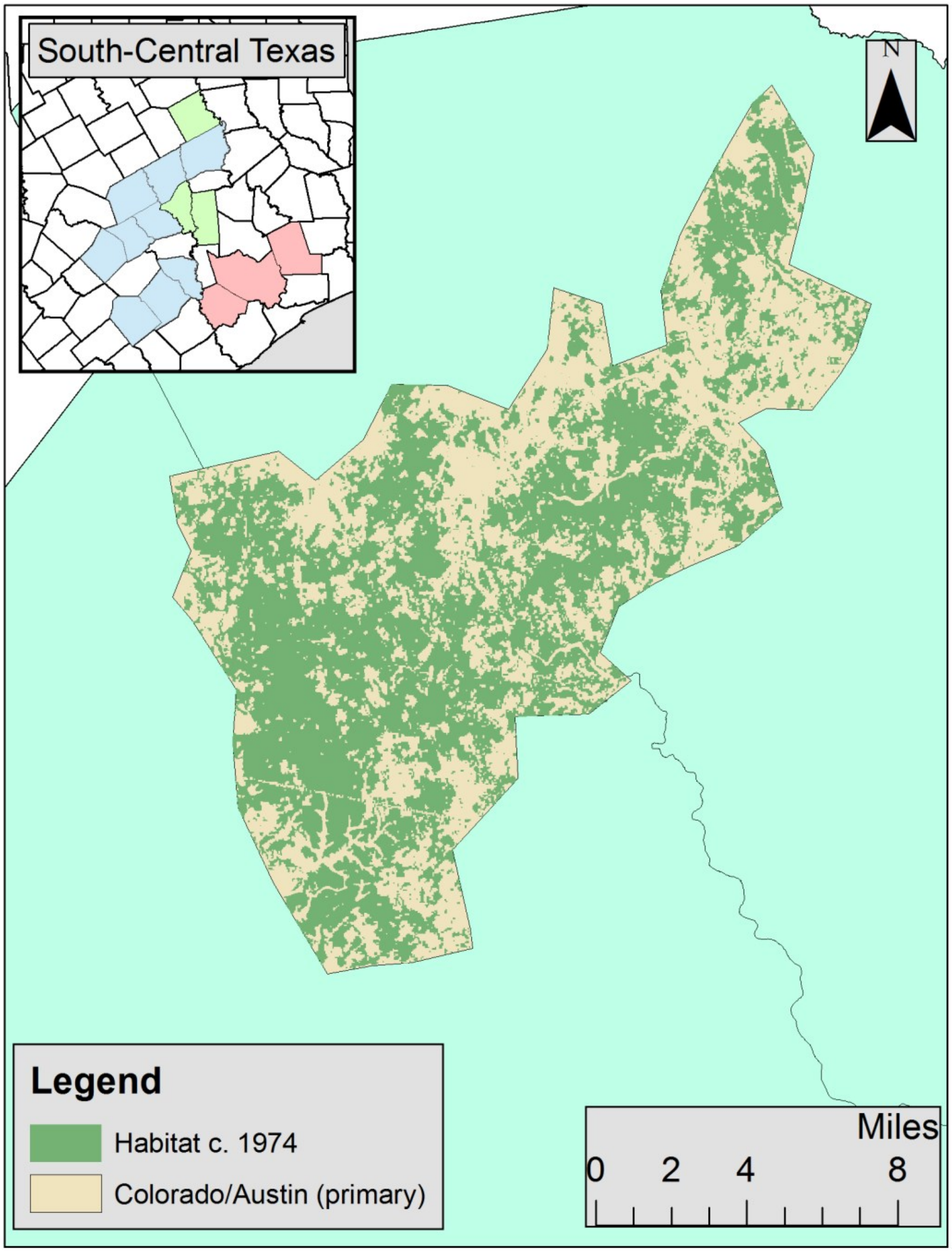

Figure 33. Colorado/Austin (primary) USFWS-Focus Area for the Houston toad (*Bufo houstonensis*) with habitat (c. 1974). The areas in green represent habitat derived in part from satellite imagery captured on March 19, 1974. This Focus Area spans Colorado and Austin counties.

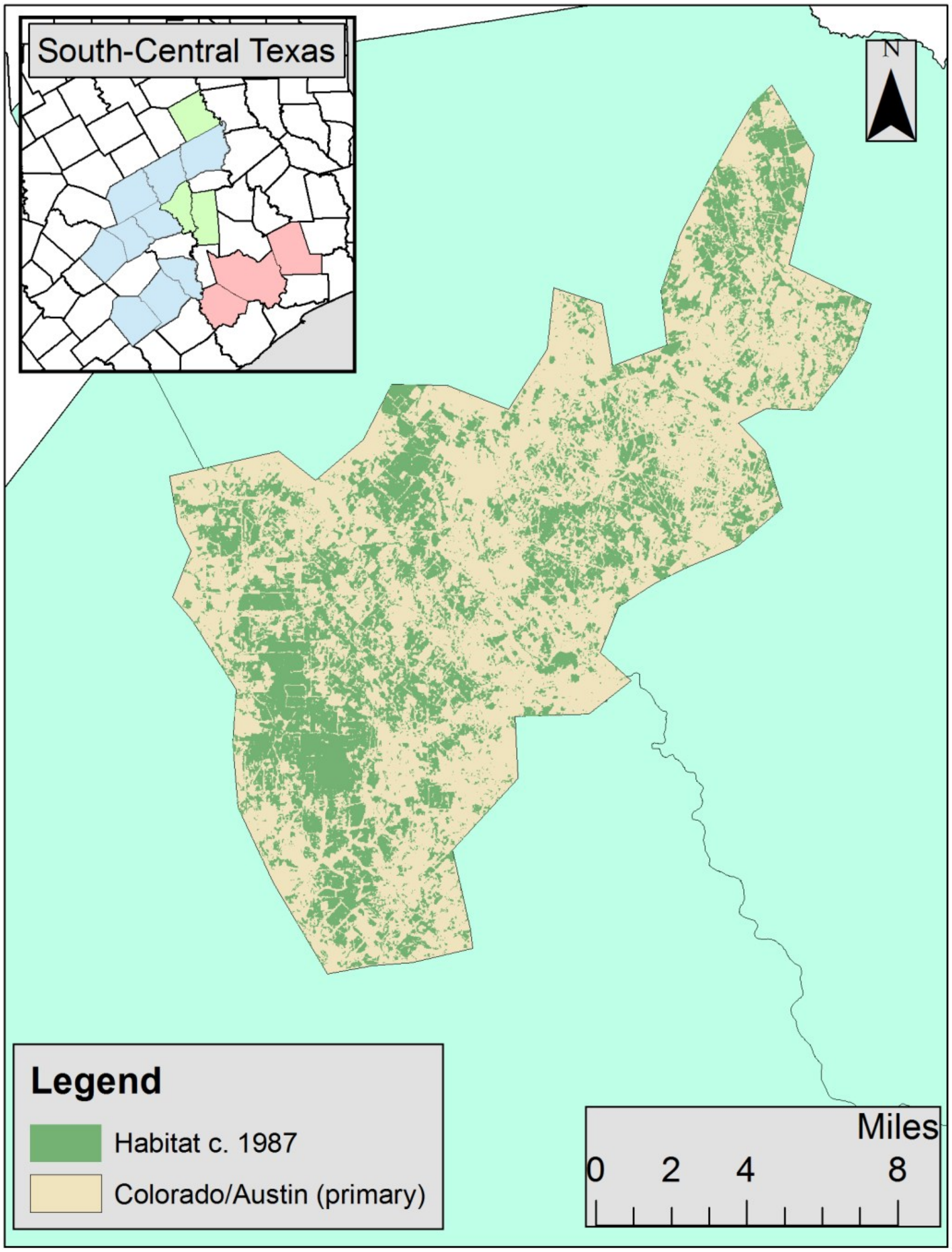

Figure 34. Colorado/Austin (primary) USFWS-Focus Area for the Houston toad (*Bufo houstonensis*) with habitat (c. 1987). The areas in green represent habitat derived in part from satellite imagery captured on April 27, 1987. This Focus Area spans Colorado and Austin counties.

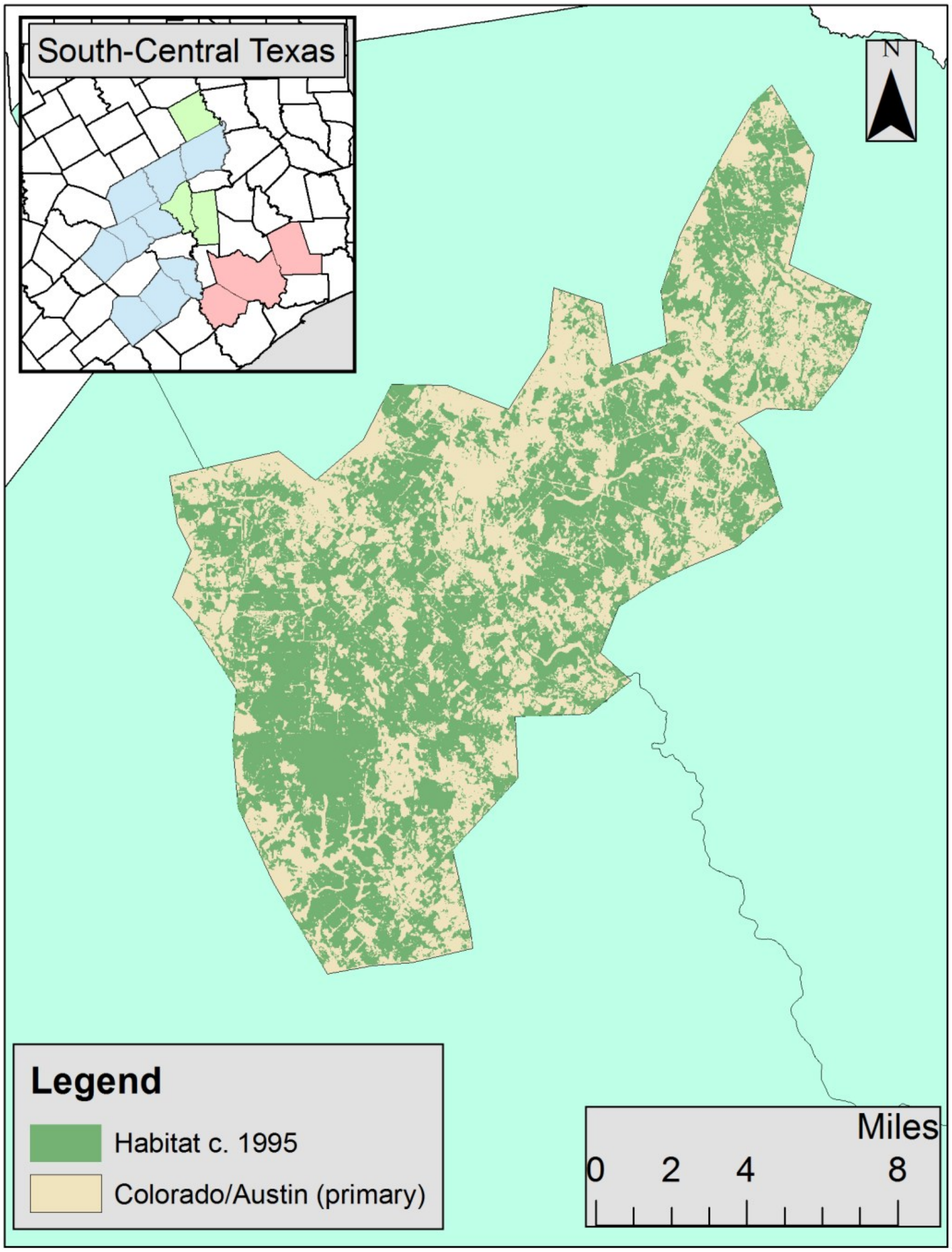

Figure 35. Colorado/Austin (primary) USFWS-Focus Area for the Houston toad (*Bufo houstonensis*) with habitat (c. 1995). The areas in green represent habitat derived in part from satellite imagery captured on May 19, 1995. This Focus Area spans Colorado and Austin counties.

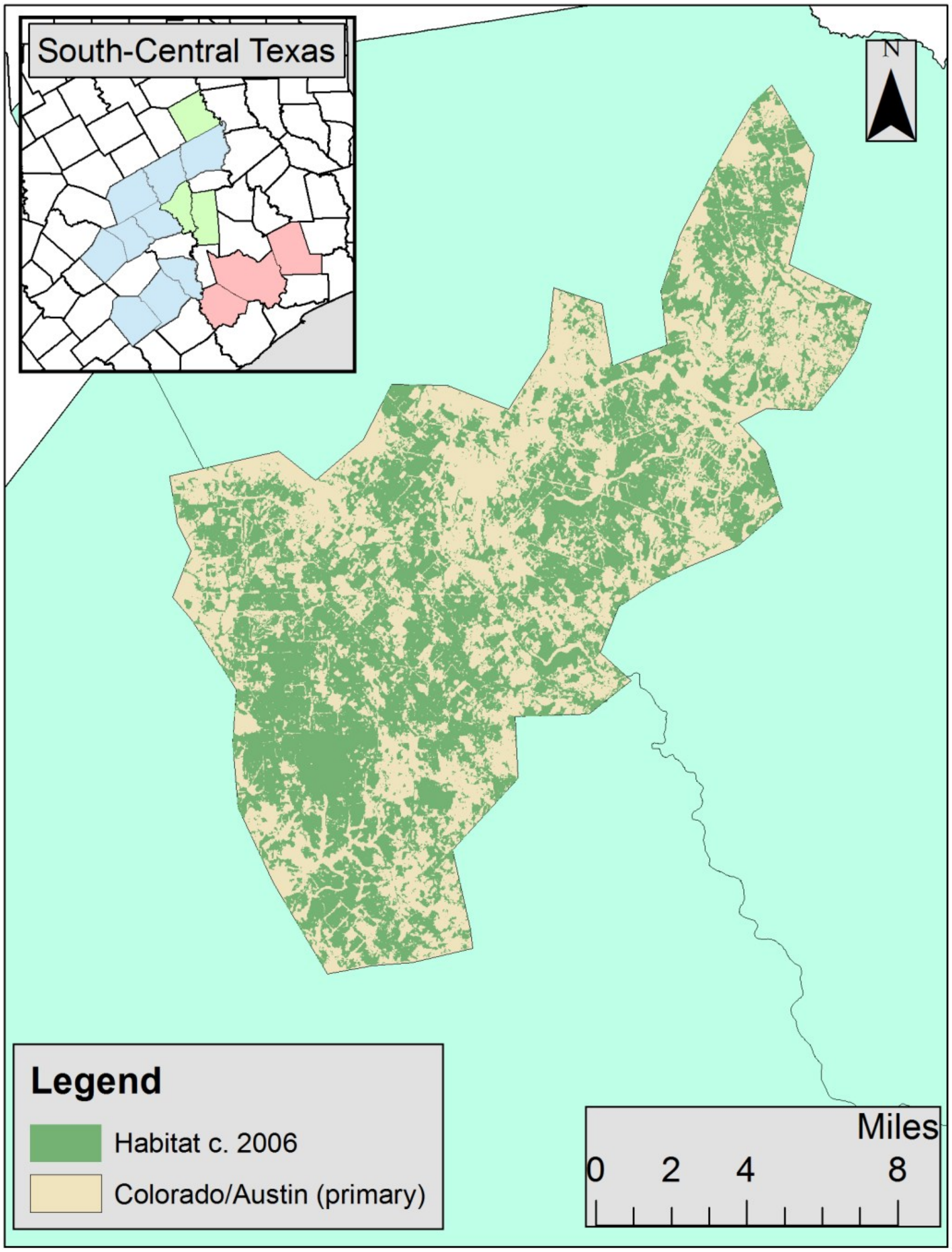

Figure 36. Colorado/Austin (primary) USFWS-Focus Area for the Houston toad (*Bufo houstonensis*) with habitat (c. 2006). The areas in green represent habitat derived in part from satellite imagery captured on May 1, 2006. This Focus Area spans Colorado and Austin counties.

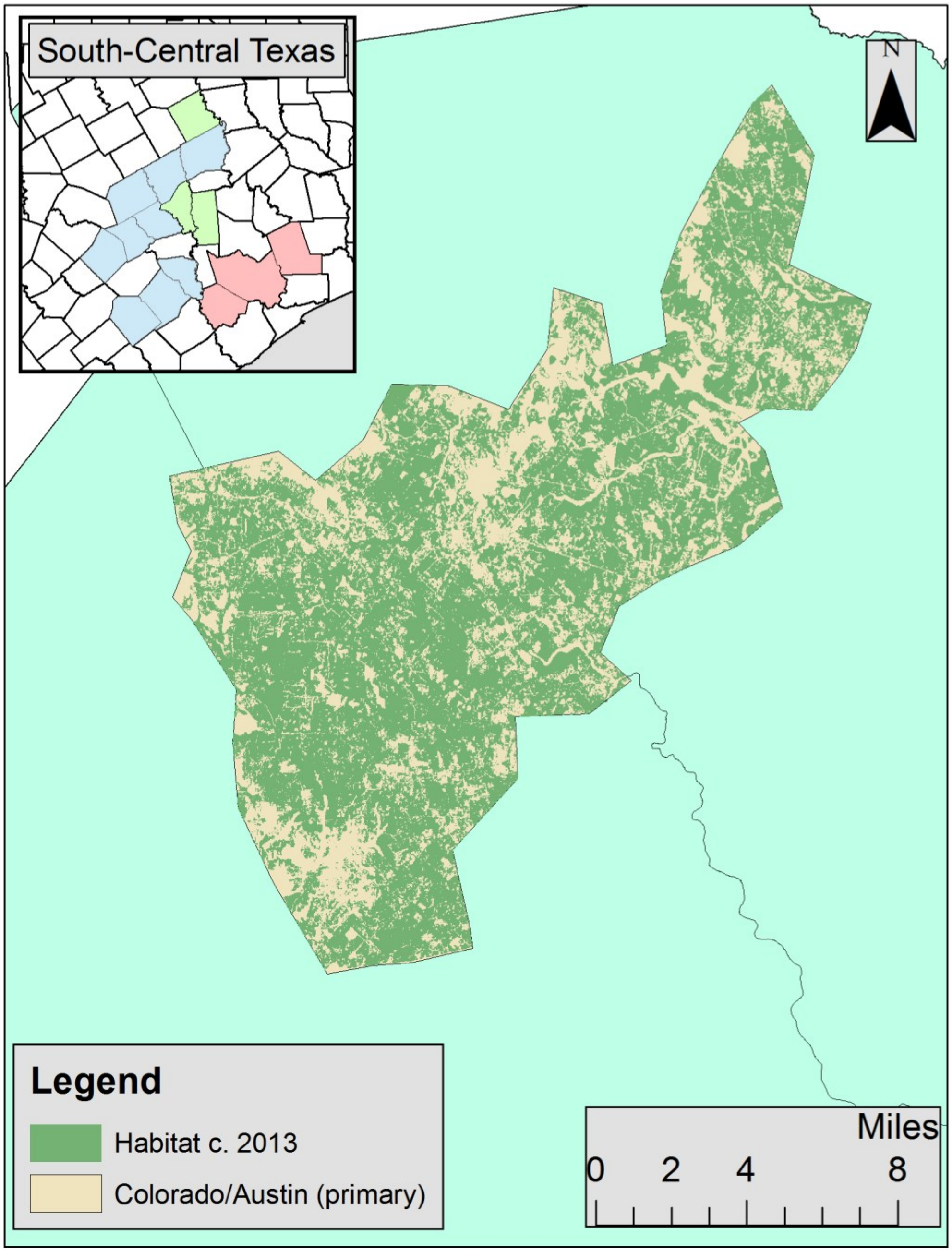

Figure 37. Colorado/Austin (primary) USFWS-Focus Area for the Houston toad (*Bufo houstonensis*) with habitat (c. 2013). The areas in green represent habitat derived in part from satellite imagery captured on May 4, 2013. This Focus Area spans Colorado and Austin counties.

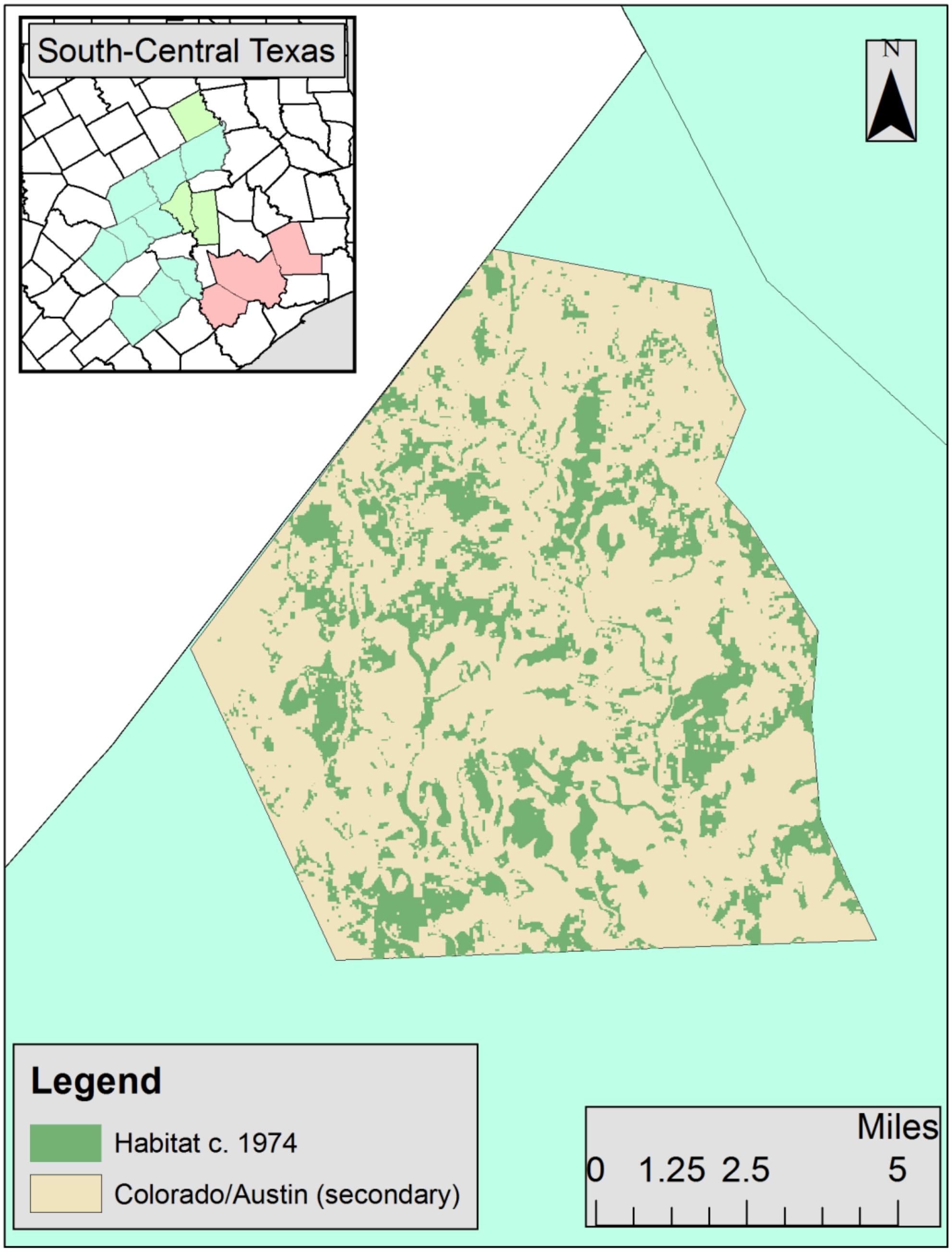

Figure 38. Colorado/Austin (secondary) USFWS-Focus Area for the Houston toad (*Bufo houstonensis*) with habitat (c. 1974). The areas in green represent habitat derived in part from satellite imagery captured on March 19, 1974. This Focus Area is located in Colorado County.

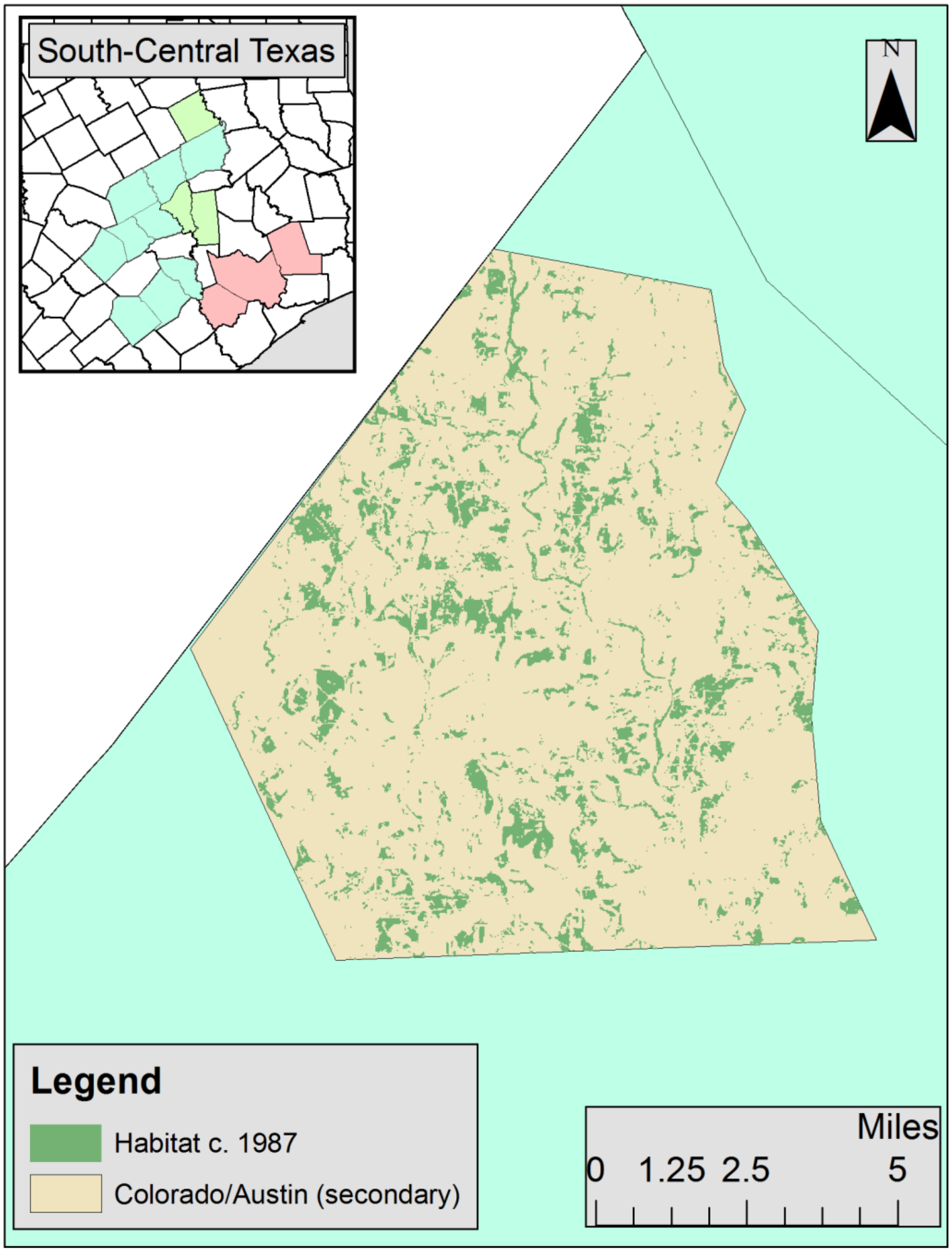

Figure 39. Colorado/Austin (secondary) USFWS-Focus Area for the Houston toad (*Bufo houstonensis*) with habitat (c. 1987). The areas in green represent habitat derived in part from satellite imagery captured on April 27, 1987. This Focus Area is located in Colorado County.

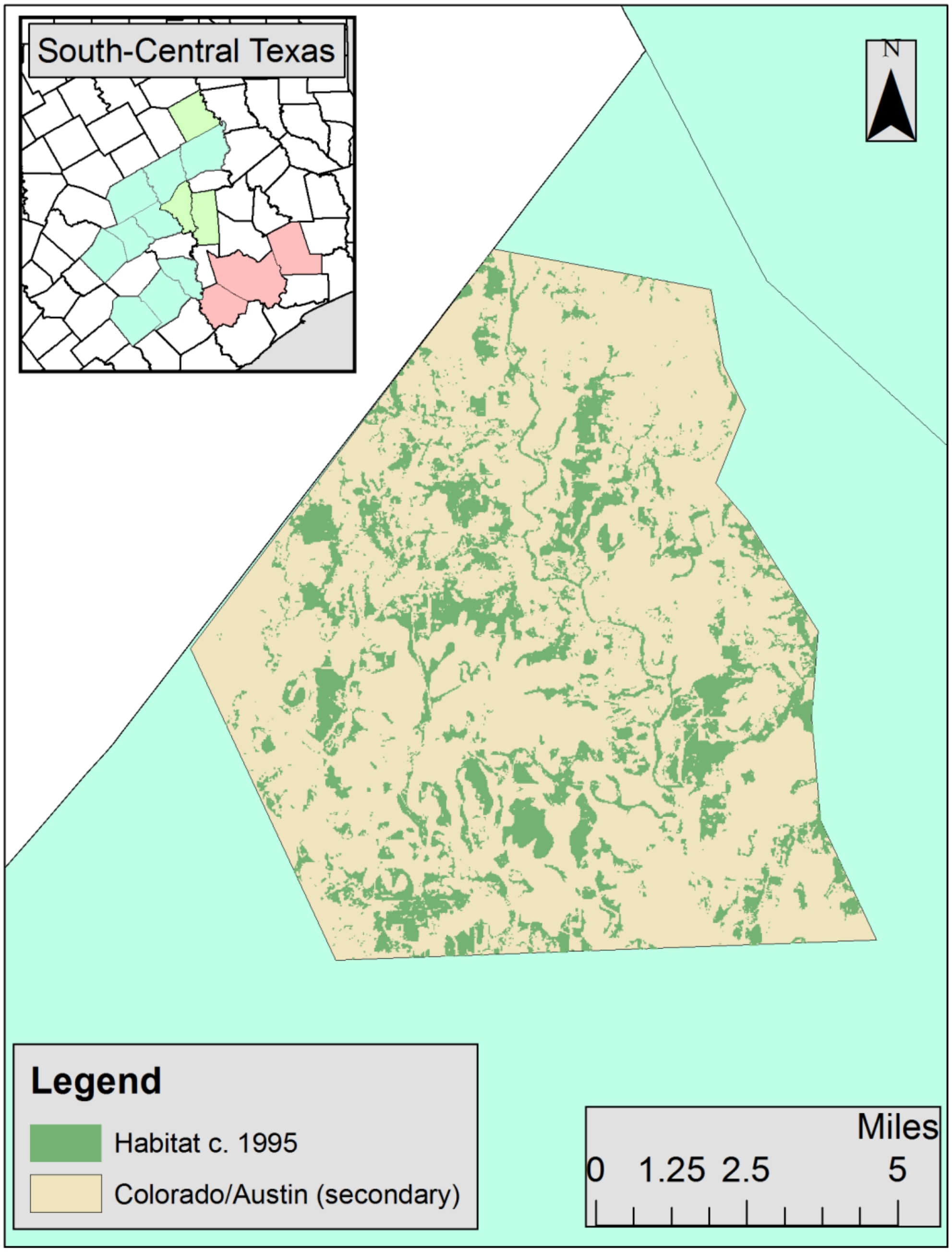

Figure 40. Colorado/Austin (secondary) USFWS-Focus Area for the Houston toad (*Bufo houstonensis*) with habitat (c. 1995). The areas in green represent habitat derived in part from satellite imagery captured on May 19, 1995. This Focus Area is located in Colorado County.

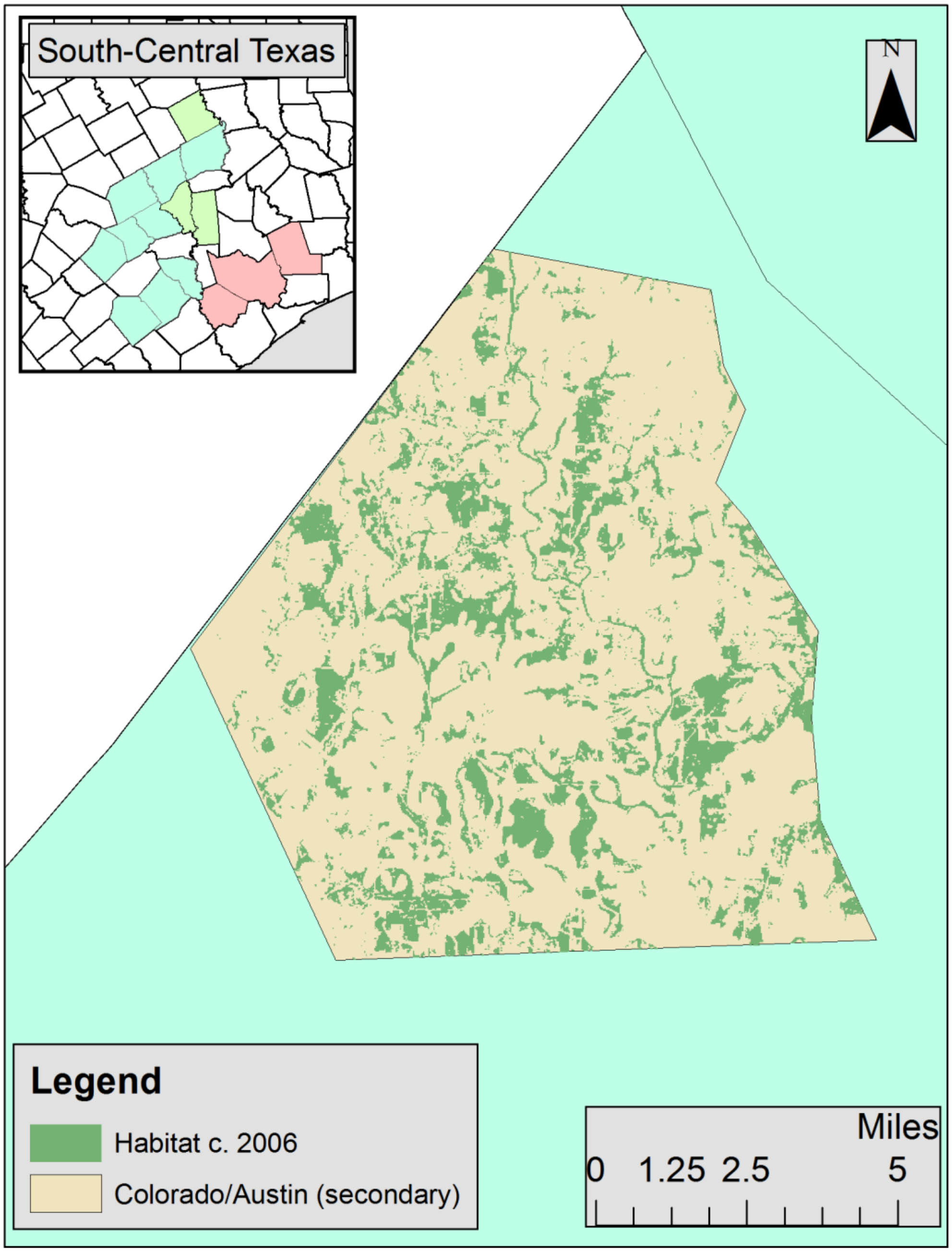

Figure 41. Colorado/Austin (secondary) USFWS-Focus Area for the Houston toad (*Bufo houstonensis*) with habitat (c. 2006). The areas in green represent habitat derived in part from satellite imagery captured on May 1, 2006. This Focus Area is located in Colorado County.

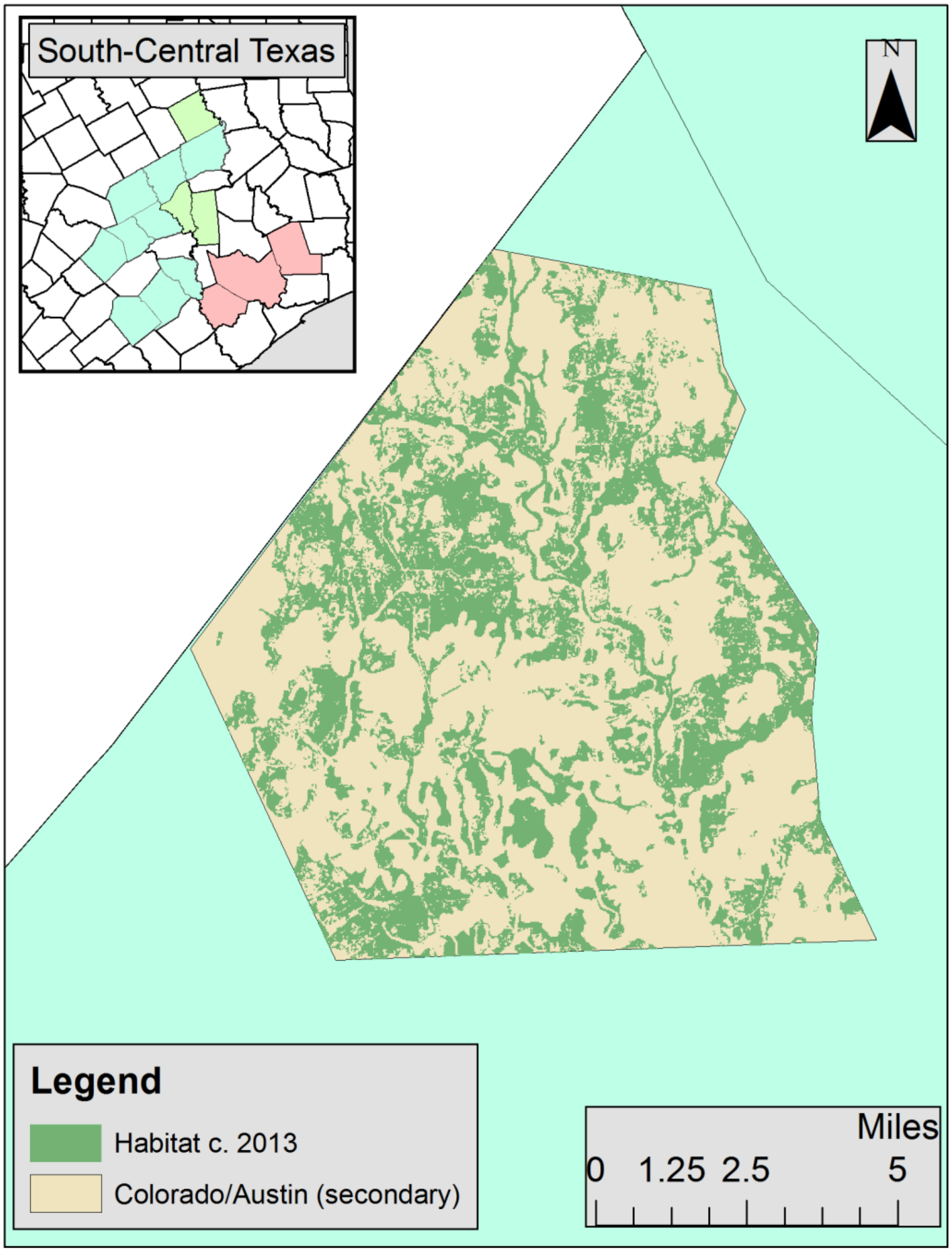

Figure 42. Colorado/Austin (secondary) USFWS-Focus Area for the Houston toad (*Bufo houstonensis*) with habitat (c. 2013). The areas in green represent habitat derived in part from satellite imagery captured on May 4, 2013. This Focus Area is located in Colorado County.

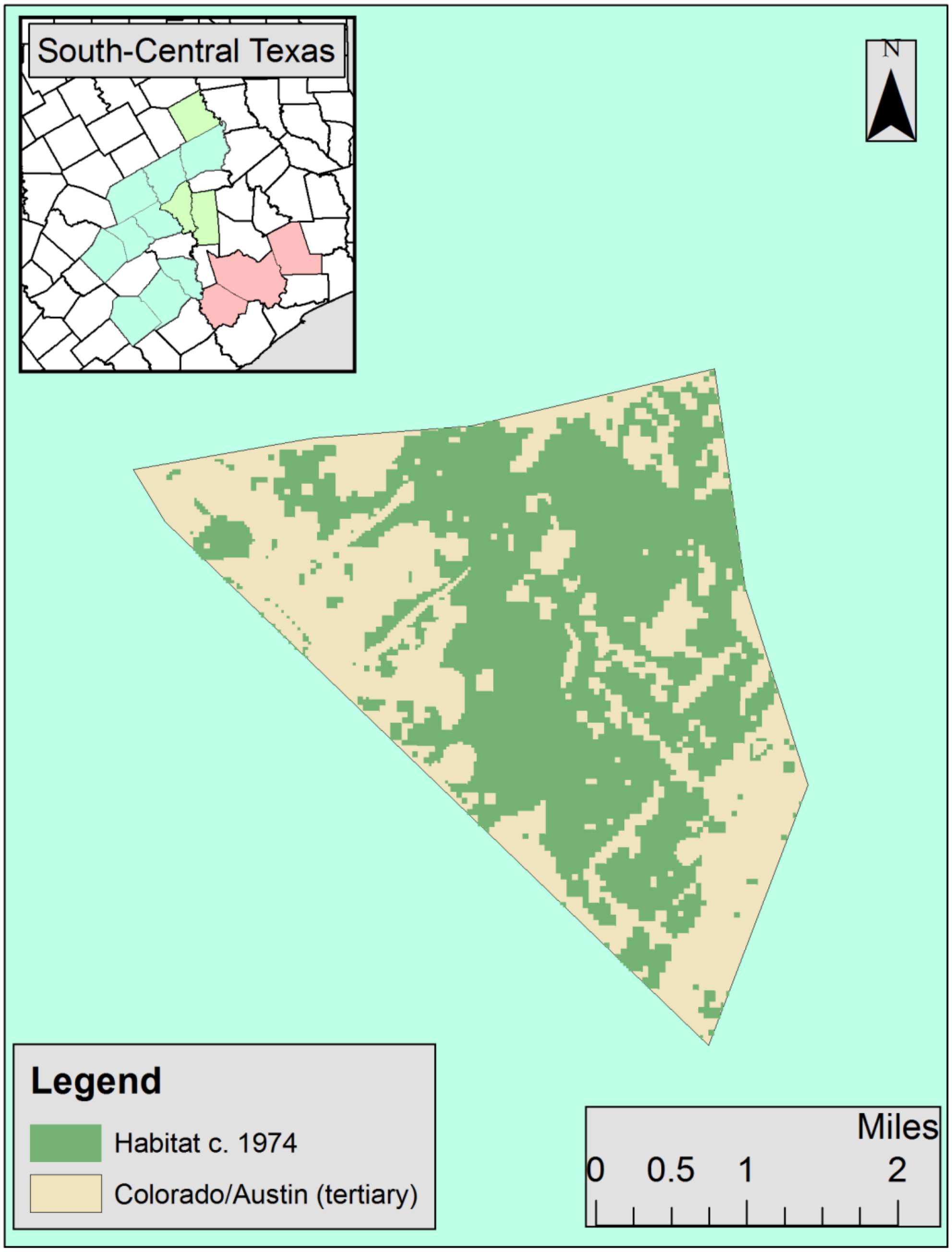

Figure 43. Colorado/Austin (tertiary) USFWS-Focus Area for the Houston toad (*Bufo houstonensis*) with habitat (c. 1974). The areas in green represent habitat derived in part from satellite imagery captured on March 19, 1974. This Focus Area is located in Colorado County.

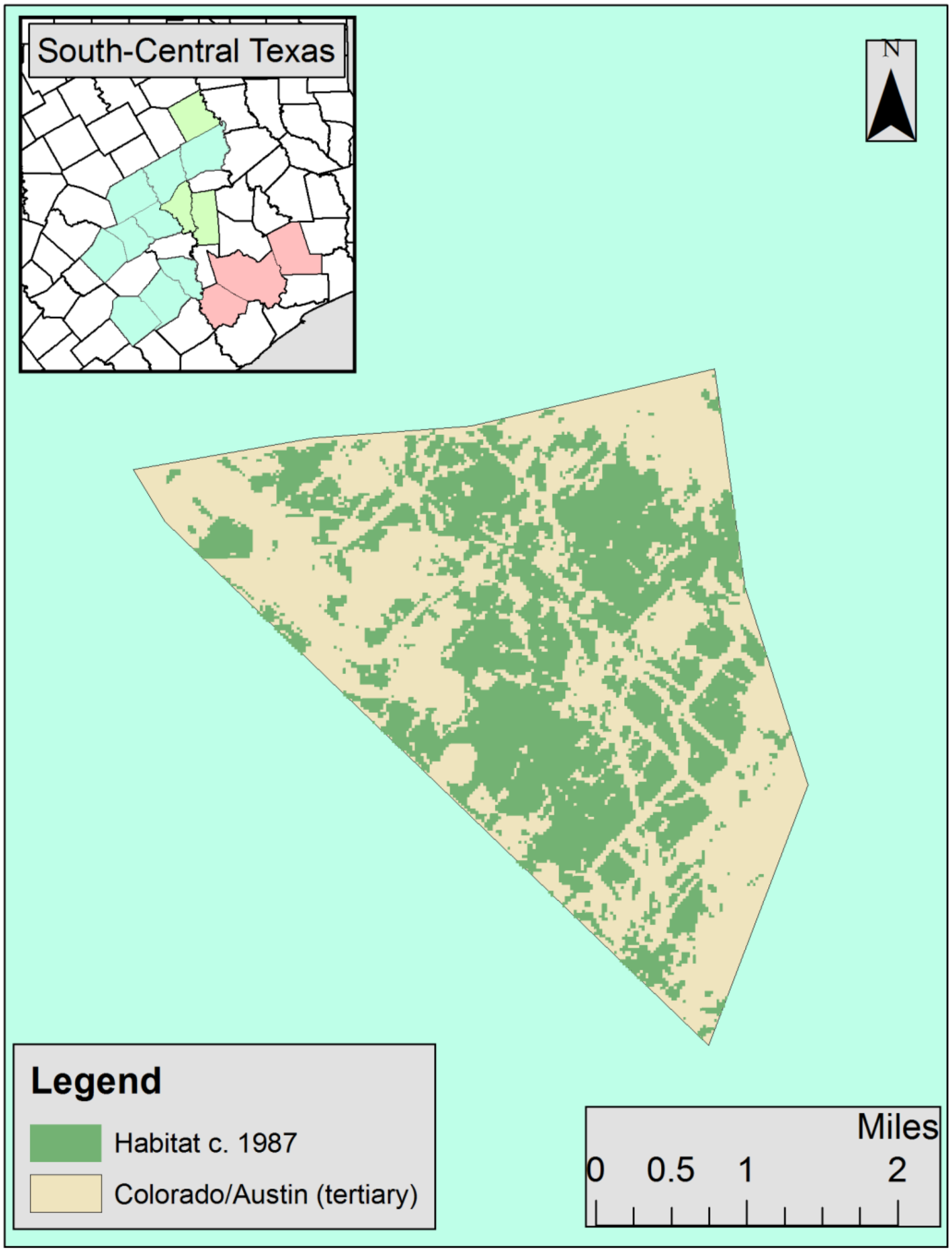

Figure 44. Colorado/Austin (tertiary) USFWS-Focus Area for the Houston toad (*Bufo houstonensis*) with habitat (c. 1987). The areas in green represent habitat derived in part from satellite imagery captured on April 27, 1987. This Focus Area is located in Colorado County.

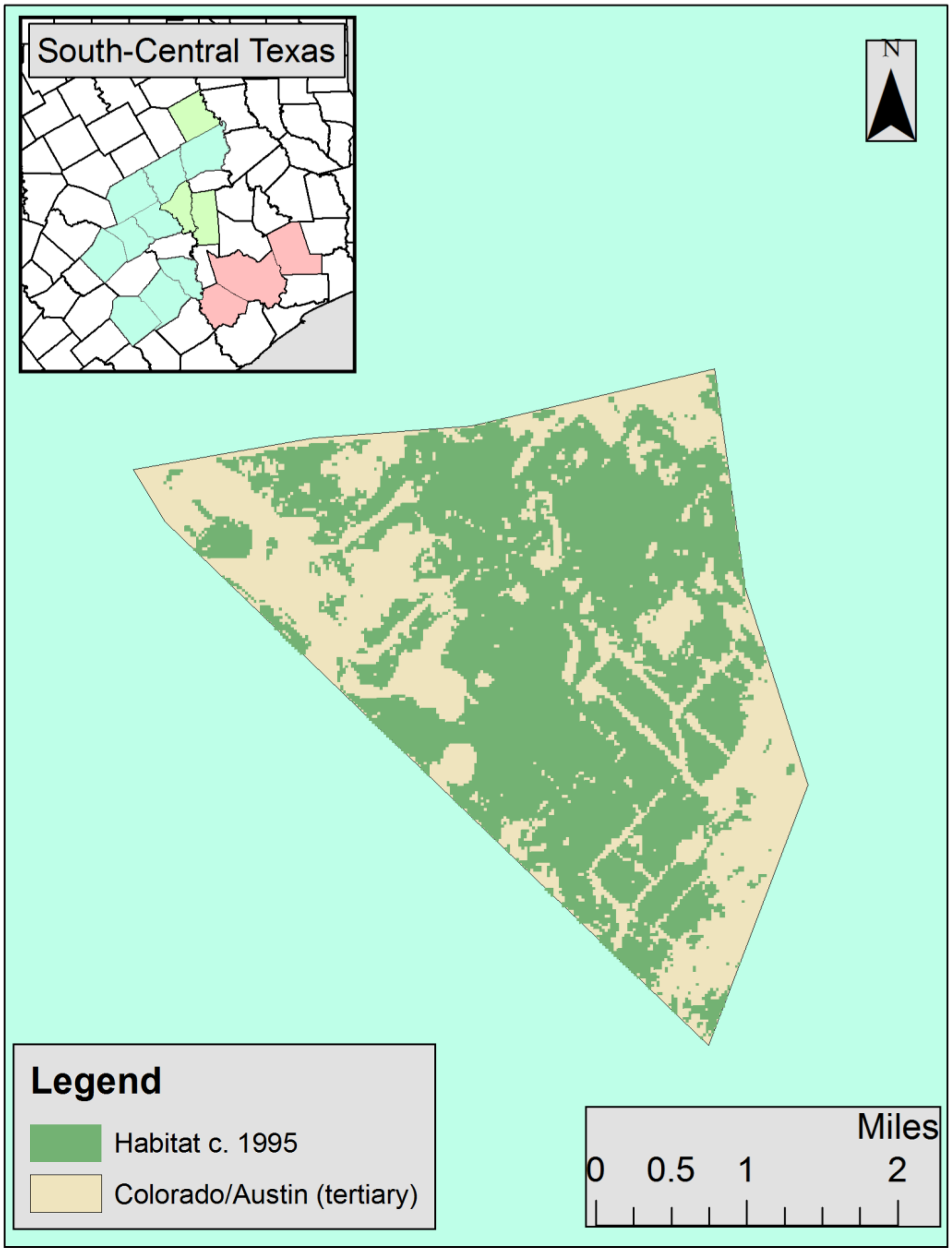

Figure 45. Colorado/Austin (tertiary) USFWS-Focus Area for the Houston toad (*Bufo houstonensis*) with habitat (c. 1995). The areas in green represent habitat derived in part from satellite imagery captured on May 19, 1995. This Focus Area is located in Colorado County.

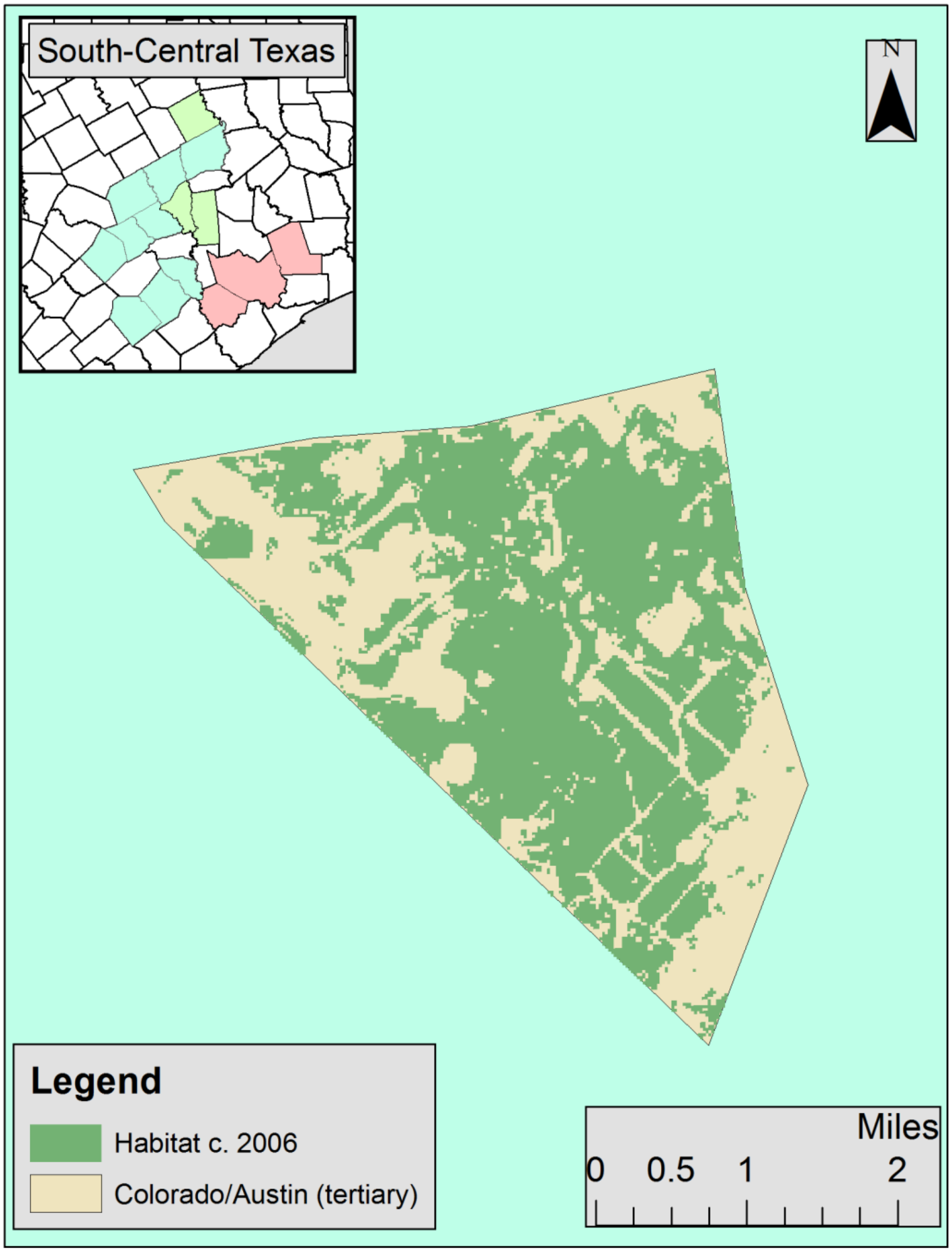

Figure 46. Colorado/Austin (tertiary) USFWS-Focus Area for the Houston toad (*Bufo houstonensis*) with habitat (c. 2006). The areas in green represent habitat derived in part from satellite imagery captured on May 1, 2006. This Focus Area is located in Colorado County.

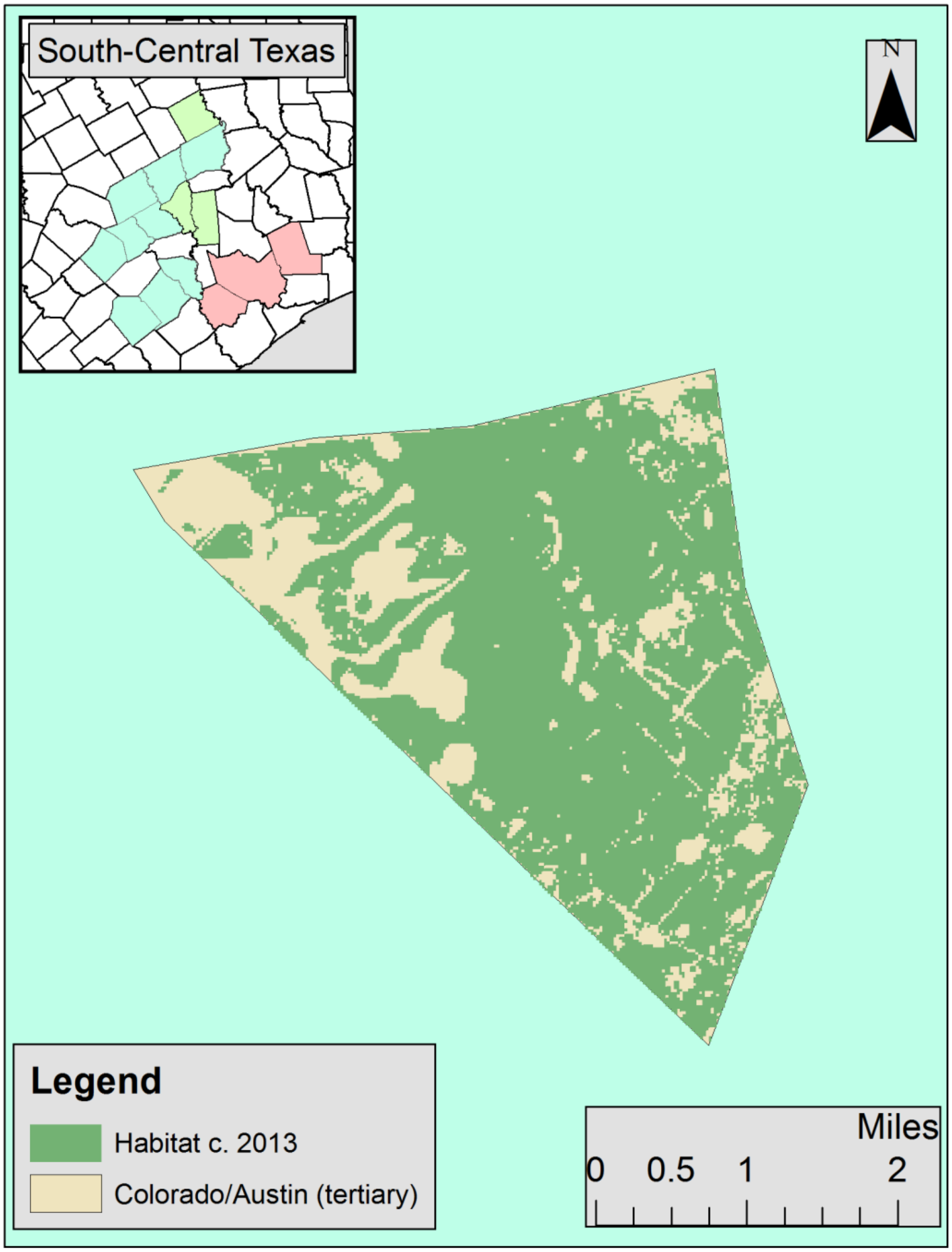

Figure 47. Colorado/Austin (tertiary) USFWS-Focus Area for the Houston toad (*Bufo houstonensis*) with habitat (c. 2013). The areas in green represent habitat derived in part from satellite imagery captured on May 4, 2013. This Focus Area is located in Colorado County.

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