Assessing Occurrence and Habitat Characteristics of the Southeastern Pocket Gopher (*Geomys pinetis*)

by

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accuracy, detection, habitat structure, *Geomys pinetis*, Google Earth, southeastern pocket gopher

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Abstract

The southeastern pocket gopher (*Geomys pinetis*), a species of conservation concern in Florida, Georgia, and Alabama, is of increasing conservation concern due to a range wide decline believed to be due to habitat loss and fragmentation. There is a strong need to better understand the southeastern pocket gopher's occurrence in relation to vegetation attributes and habitat management. To gain better insight to the species it is important to develop new and creative ways to survey and assess occurrence efficiently. I used imagery in the Google Earth platform to assess presence of southeastern pocket gophers based on their soil mounds at 77 sites in Alabama, Florida, and Georgia, and compared imagery survey results to those of independent field surveys of these sites. I recorded imagery detections of mounds at 22 of 23 sites where presence of pocket gophers was observed in the field for a true positive rate of 96%. Additionally, I examined habitat factors associated with the presence of southeastern pocket gophers at a study site in southeast Alabama by using a case-control design. I measured vegetation structure and soil texture in 62, 0.1 ha sites occupied by southeastern pocket gophers and 62 unoccupied sites. All occupied sites at the study site in Alabama had a clay content below 8.05% within the 0-20 cm of soil; this attribute had overwhelming support as the most important single variable separating occupied and unoccupied sites. Logistic regression modeling to compare vegetation of occupied and unoccupied sites identified the quadratic effect of canopy cover as the model with highest support. The data obtained from this project, as well as the methodology, provides vital information that will aid in future pocket gopher conservation efforts.

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Chapter 1:

Detecting Presence of Southeastern Pocket Gophers Using Google Earth Imagery

ABSTRACT For many wildlife species, field surveys are a prohibitively expensive and time consuming approach for obtaining data on occurrence across large areas. Such issues arise in the case of southeastern pocket gophers (*Geomys pinetis*), a species of conservation concern ranging throughout most of Florida and in the Coastal Plain of Georgia and Alabama. I examined the utility and accuracy of using satellite images available in Google Earth to detect presence of southeastern pocket gophers in 1-km^2 survey sites. Independent field and Google Earth imagery surveys were conducted at 77 sites in Alabama, Florida, and Georgia to assess presence of soil mounds produced by southeastern pocket gophers, with imagery survey results taking into account observer uncertainty (high confidence vs low confidence) in imagery mound detections. I recorded imagery detections of mounds at 22 of 23 sites where presence of pocket gophers was observed in the field for a true positive rate of 96%. At most of the 54 sites where pocket gophers were not detected during field surveys, I recorded either no imagery detection (36 sites) or low-confidence imagery detections (17 sites). At one site – with no field detections and where field surveyors were relatively certain that pocket gophers were absent, a high-confidence imagery detection was determined to be a false-positive detection. My results demonstrate that Google Earth imagery is a useful tool for detecting the presence of southeastern pocket gophers and could potentially be used for systematic assessment of occupancy across large scales.

KEY WORDS accuracy, detection, error rates, *Geomys pinetis*, mound, Google Earth, southeastern pocket gopher, southeast.

INTRODUCTION

Designing cost-effective wildlife population surveys is particularly challenging when information is needed across large areas and for secretive, patchily distributed species (Lewis 1970, MacKenzie et al. 2002, Pollock et al. 2002, Thompson 2004). This challenge is directly relevant for the southeastern pocket gopher (*Geomys pinetis*), a fossorial rodent of conservation concern (Georgia Department of Natural Resources 2005, Florida Fish and Wildlife Commission 2011, Wood 2015) associated with sandy soils of the Coastal Plain in Alabama, Florida, and Georgia (Fig. 1.1; Bailey et al. 1895, Harper 1912, Golley 1962, Pembleton and Williams 1978). As with other pocket gopher species (e.g., Mohr 1935, Davis et al. 1938, Reid et al. 1966, , Connior et al. 2010, Wagner et al. 2017), field surveys detect presence of southeastern pocket gophers by observing the small soil mounds they push to the surface during tunnel building (e.g., Harper 1912, Warren et al. 2017a,b). However, effective visual surveys to assess occurrence of this species across a landscape may require relatively fine-grained spatial coverage because of the small home range size of this species (average ~0.09 ha; Warren 2017b), relative rarity and clustered distribution of populations in many areas, (e.g. Bennett 2017: Chapter 2), and low visibility of mounds from a distance in the field when there is high visual obstruction from vegetation. Therefore, field surveys of southeastern pocket gophers occurrence are time and labor intensive, and possibly too costly for routine large scale studies.

Alternatively, remotely sensed imagery is promising as a cost-effective survey approach for assessing the presence of this species as previous studies have used imagery to detect mounds and other soil disturbances made by invertebrate (Vogt 2004, Vogt and Wallet 2008, Moro et al. 2014) and vertebrate taxa, including other species of pocket gophers (*Geomys personatus* and *Thomomys talpoides*; Driscoll 1971, Driscoll and Watson 1974, Everitt and Nixon 1985, Hugenholtz et al. 2013, Whitehead et al. 2014). Remotely sensed images, including aerial and satellite imagery, can cover large areas, utilize an extended spectral range, provide permanently available spatial data for multiple time periods, and allow examination of otherwise inaccessible places (Fuller et al. 1998; Bastiaanssen et al. 2000, Ozesmi and Bauer 2002, Bolstad 2005, Olea and Mateo-Thomás 2013). Google Earth (Google Inc., Mountain View, CA, 2017), an internet-based imagery viewing platform, may be especially advantageous because it is free, available worldwide, easy to access, user friendly, and utilizes sub-meter resolution imagery in many areas (Thenkabail 2015). The images available in Google Earth (hereafter "Google Earth imagery") have been used to determine termite (e.g. *Macrotermes falciger*) mound density, position, and distribution (Isabelle et al. 2014) and to assess the spatial structure and density of harvester ant (*Pogonomyrmex occidentalis*) populations while distinguishing harvest ant mounds from prairie dog (*Cynomys spp.*) mounds (Dibner et al. 2015). Imagery available in Google Earth for the southeastern U.S. is generally of sufficient spatial and spectral resolution to permit the observation of soil mounds (e.g., white patches, Fig. 1.2), making Google Earth a potentially useful platform for assessing occupancy (patch-level species presence/absence; MacKenzie et al. 2002) of southeastern pocket gophers.

However, the accuracy with which biologists can classify soil patches visible in Google Earth imagery as pocket gopher mounds remains unknown. Only a few previous studies have systematically assessed accuracy of remote imagery-based surveys for any mound-forming species (Driscoll and Watson 1974, Vogt 2004, Vogt and Wallet 2008, Isabelle et al. 2014, Dibner et al. 2015). In southeastern U.S. landscapes, ant [e.g. Florida harvester ants (*Pogonomyrmex badius)* and red imported fire ants (*Solenopsis invicta*)] mounds (Skelly and Kovarik 2001; Fig. 1.2C, 1.2D), gopher tortoise (*Gopherus polyphemus*) burrows (Simkin and

Michener 2005), and soil mounds from agricultural plowing are common features that can look similar to pocket gopher mounds on the ground and in Google Earth imagery. Similarly, tree cover (Houston 1972, Keane et al. 2001, Arroyo et al. 2008), atmospheric conditions (Herwitz et al. 2004, Chang et al. 2009) and image quality (Kamadjeu 2009, Guo et al. 2010) may interfere with viewing mounds in Google Earth imagery. An understanding of feasible accuracy is needed to assess the utility of any new survey method, and estimates of potential detection error rates are needed for designing effective studies (MacKenzie and Royle 2005, Miller et al. 2011, Chambert et al. 2015, Clement 2016). Therefore, my objective was to determine the accuracy of using Google Earth imagery to detect presence of southeastern pocket gophers at study sites across their range.

METHODS

Field and Google Earth Surveys

Field and Google Earth surveys to assess presence of southeastern pocket gophers were conducted on 77 sites in Alabama, Florida, and Georgia (Fig. 1.1). These 1-km^2 sites were selected from public lands within the historical range of the species and with ≥50% of the following land cover categories: evergreen forests, mixed forests, shrub/scrub, grasslands/herbaceous, pasture/hay and/or cultivated crops (NLCD 2011, Homer et al. 2015). Each site was surveyed once in the field during March through August 2016. Two surveyors walked a 2000-m transect, forming a 500 x 500 m square, within the site, and recorded GPS coordinates of all pocket gopher mound clusters visible from the transect line (Fig. 1.1 inset). Mound clusters were defined as a group of 2 or more pocket gopher mounds likely to have been produced by the same individual (i.e. clusters were separated by ≥ 5 m; Ford 1980). Mounds of pocket gophers were easily distinguished from mounds of red imported fire ants based on the presence of ants or ant tunnels (Appendix 1), thus the probability of a false-positive field detection was assumed to be zero.

I created a search grid for evaluating Google Earth imagery using ArcMap v. 10.2 (ArcMap; Environmental Systems Research Institute, Inc., Redlands, CA 2013). Each field site's grid was created by buffering the 500 x 500 m square transect by 50 m on each side of the transect line, subdividing this buffer into an inner 15 m buffer and an outer 35 m buffer on each side, then dividing the buffered transect into 100-m sections (Fig. 1.1, inset), producing grid cells averaging 3345 m^2/cell (average 59 cells per grid). This grid layout was designed to facilitate consistent (i.e. cell by cell) examination of each site's imagery. The inner and outer buffers initially were chosen to allow for potential fine scale examination of cell-level detection locations in relation to the designated field survey transect, but subsequently I focused on patterns at the site level. The actual GPS tracks of field-survey routes between corners of the square transect were not used in designing imagery survey grids, as field tracks could have cued observers to locations of mounds and reduced independence of field and imagery surveys.

Prior to surveying Google Earth imagery for these 77 sites, I examined other areas known to be occupied by southeastern pocket gophers in Alabama to develop a 3-category observation classification for imagery surveys. Presence of clearly visible mounds (i.e. white patches) in lines or clusters was categorized as a “high confidence” detection (Appendix 2a). When mounds were less visible or more sporadic, then the detection was categorized as “low confidence” (Appendix 2b). There may have only been 1 or 2 potential mounds visible for low confidence detections. If no mounds were detected, this was categorized as “no detection.” Although incorporating 2 levels of confidence for when potential mound were observed added complexity to the results, capturing such differential observation uncertainty is increasingly standard practice in occupancy surveys facing potential false-positive detection errors (Miller et al. 2011, Chambert et al. 2015).

Google Earth surveys used sub-meter imagery dated from March 2013 to March 2017 depending on image availability at each site. As multiple imagery dates were available for each site, the imagery with the smallest difference in time elapsed between imagery date and the 2016 field survey date was used. Imagery surveys were conducted in a random order and were blind with respect to field-survey results. For each site, each cell in the imagery survey grid was inspected at a Google Earth eye altitude (the elevation of my viewpoint above the surface of the ground) ranging between 100-375 m. Cells that had canopy closure that completely obstructed the view of the ground were surveyed at a higher altitude when compared to cells in which the ground could be observed to maximize search efficiency. Based on examining all grid cells for a site, I recorded the site-level detection status in the following 3 categories: high-confidence detection (≥ 1 cell with high-confidence detection), low-confidence detection (≥ 1 cell with low confidence detection and no cells with high-confidence detections), and no detection.

Analysis

I classified sites into 1 of 2 site-level field detection categories ("field detection" if one more mound clusters were detected on the site's 2000-m transect; "no field detection" otherwise). For sites with field detections, I calculated the proportion of sites in each of the 3 Google Earth imagery survey categories (high confidence, low confidence, no detections), along with corresponding simultaneous 95% confidence intervals using the MultinomialCI package in R (R: The R Project for Statistical Computing, R version 3.2.0). I repeated these calculations for sites without field detections. When there were differences in site-level detection results from field surveys vs. imagery surveys (i.e. detections recorded in the field but not from imagery, or vice versa), I reexamined a subsample of imagery and discussed results with field surveyors to help assess the nature and potential causes of errors. To determine if temporal discrepancy in survey timing was greater for sites with potential imagery detection errors, I summarized time elapsed between imagery dates and field surveys for each category of field vs. imagery survey results. To assess whether false-negative and low-confidence true-positive imagery detections were more likely for sites with relatively small populations (sensu MacKenzie et al. 2006), I summarized site-level relative abundance of pocket gophers (number of clusters recorded during field transect surveys) for occupied sites.

RESULTS

Field surveys recorded southeastern pocket gopher mound clusters on 22 sites. I recorded high-confidence imagery detections for 19 of these sites and low-confidence imagery detections for 2 sites (Table 1). For the single site with field detections but no imagery detections, imagery used was relatively recent (6 months earlier than field survey, Table 2), but field surveys recorded low relative abundance of southeastern pocket gophers on this site [4 clusters on this site vs. an average of 22.18 clusters (SE = 5.65) per site for the 22 sites with clusters recorded during transect surveys]. The 2 sites with field detections but classed as a low-confidence detection from imagery had between 6 and 17 months of elapsed time between image acquisition and field surveys, and low (i.e., 1 cluster) or moderately low (i.e., 12 clusters) numbers of mound clusters detected by field crews.

Of 55 sites with no detections recorded during field transect surveys, 2 sites had high-confidence imagery detections. For one of these sites (Site Florida 8; Appendix 1.C), discussions with field surveyors indicated that the site was occupied, as pocket gopher mounds were observed in the vicinity but not from the sampling transect. For the second site, field surveyors were highly confident that the site was not occupied by pocket gophers, but noted that gopher tortoises were present. In addition, the site was recently burned when the focal imagery was recorded, 27 months prior to the field survey, such that pockets of sand may have been in high contrast with charred ground. In more recent imagery of that site, white patches were no longer visible.

Of the remaining 53 sites with no field-transect detections, 36 had no imagery detections, while 17 had low-confidence imagery detections. Discussions with field surveyors and reexamination of imagery of select sites indicated that many of these sites had other sources of ground disturbance such as fire ant mounds, burrows of gopher tortoises and old-field deer mice (*Peromyscus polionotus*), logging, and plowing.

DISCUSSION

My results demonstrate that Google Earth imagery is a practical tool for detecting the presence of southeastern pocket gophers and potentially for systematic assessment of occupancy across large spatial scales. Including one site where no detections were recorded on field transects but that was subsequently confirmed to be occupied, I successfully detected southeastern pocket gophers on 96% of sites known to be occupied (22 of 23 sites; 20 with high confidence detections; 2 with low confidence detections). This true-positive detection rate is similar to a study detecting western harvester ant mounds in California (96%, Dibner et al. 2015) and exceeded rates of an automated study of detecting fire ant mounds (79%, Vogt and Wallet 2008), the predicted detection of a study detecting large fire ant mounds by photointerpretation (66%, Vogt 2004) and the average mound detection of northern pocket gopher mounds in aerial imagery (41%, Driscoll and Watson 1974). Potential false-positive imagery detections were driven by low-confidence detections (recorded at 17 of 54 potentially unoccupied sites, i.e. sites with no on- or off-transect field observations of mounds). There was only 1 of 54 potentially unoccupied sites where I recorded high-confidence imagery detections.

While imagery surveys had high rates of detecting pocket gopher mounds at sites known to be occupied, these surveys can improperly identify species (false-positives) and can also fail to detect species (false-negatives; Miller et al. 2011). The accuracy of an observer using imagery to detect the presence of pocket gopher mounds will be dependent upon several factors. Features on the landscape that can be misinterpreted as southeastern pocket gopher mounds (i.e. ant mounds, gopher tortoise burrows, and soil mounds from agricultural plowing) can result in greater false-positive error rates. For example, at one site in Georgia, only 1 cluster was detected in the field but multiple cells had low-confidence detections; this site contained soil disturbances associated with roadsides and tractors. Similarly, objects that visually obstruct mounds (i.e. tree cover, shrub cover, midstory cover; Houston 1972, Keane et al. 2001, Arroyo et al. 2008) will increase false-negative rates. Obstructions due to foliage, especially by those caused by understory vegetation (i.e. low growing shrubs on northern pocket gopher mounds; Driscoll and Watson 1974), will likely be minimized if imagery captured during the winter (i.e., leaf off) periods is available.

Shadows, however, are a problematic obstruction that will be difficult to mitigate while using Google Earth imagery, especially if looking to use this tool at a finer scale. Almost 1/3 of the sites that had pocket gopher mounds clusters identified in the field also had clusters that were not identified in Google Earth imagery as a result of being obstructed by shadows. Historical imagery available in Google Earth's may help to overcome the limitation of shadows. Shadows in the imagery are a result of illumination intensity, atmospheric components, land cover type, and viewing angle of the sensor (Guo et al. 2010) and imagery taking from different dates will offer different perspective of the landscape, but this may only be helpful when low confidence detections are observed in images. In Florida for example, a site with high shadows and dark imagery had mounds detected in the field but had only low confidence Google Earth detections. However, upon examining imagery post field survey, there were many pocket gopher mounds visible in older, brighter (i.e. saturated) imagery. In addition, historical imagery available in Google Earth indicated visible pocket gopher mounds at the site since at least 2011.

As with the problem of shadows, incorporating other imagery dates would help reduce false-negative errors due to temporal variation in mounding activity. While mounding activity can occur year round, seasonal influences which can be associated with soil moisture and/ or plant productivity (Scheffer 1931, Miller 1948, Bandoli 1981, Cox and Hunt 1992, Romañach et al. 2005) and daily variations (Vauhn and Hansen 1961) in mound production have been documented in pocket gophers. For the southeastern pocket gopher, mound production seasonally peaks in the winter (November to January; Simkin and Michener 2005), although the per-individual rate of mound formation may also vary (Gates and Tanner 1988). Therefore, it is possible that Google Earth images of occupied pocket locations may have drastically different amounts of mounds, both in sum and extent, depending on when the image was recorded. Moreover, areas that have increased mounding activity may be easier to detect in Google Earth. While mounds have been observed to persist for this species for up to 6 months at my Ch2 study sited and between 1-2 years for other species (*Thomomys talpoides*; Whitehead et al. 2014), it may be easier for an observer to detect changes on the landscape (i.e. new or old mounds formations) when time sequenced images are used.

Understanding factors affecting probability of detection errors is important for addressing constraints on accuracy. A next step for Google Earth surveys of southeastern pocket gopher occurrence is assessing potential design and analysis options that may provide reliable information about occurrence despite detection errors. False-positive occupancy models (Miller et al. 2011, etc.) are the logical focus of this assessment, as suitably designed occupancy studies can adjust for potential biases due to false-positive and false-negative detection errors and differential confidence in accuracy of detections. Such models routinely incorporate factors that affect probability of detection errors, such as cover type and canopy cover, land use (e.g. recent plowing), date of imagery, and presence of shadows. While observer training will be a critical component for identifying mounds, repeated examinations of the same survey units in one set of imagery could help assess within- and among-observer consistency

To adequately conserve a species, there is a need to have a thorough understanding of the resources utilized. This tool will allow for the exploration of previously unexplored sites on both public and private lands and may lead to a broader understanding of the habitat requirements associated with this species. This method was also time-efficient, as it typically took less than 10 minutes to survey a site through photointerpretation, compared to field surveys which required at least several hours per site without accounting for travel time. Surveys of Google Earth imagery are practical across large spatial scales and have the potential to be incorporated into statistically defensible designs for monitoring occupancy status and dynamics across large areas. By utilizing Google Earth imagery, future studies, including occupancy modeling, may be able to gain more knowledge about the distribution of southeastern pocket gophers across their range while saving time and money.

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Table 1.1. Categorization of 77 sites surveyed for southeastern pocket gophers during 2016-2017 in Alabama, Florida, and Georgia by Google Earth imagery survey result (high confidence detection of pocket gopher mounds, low confidence detection, or not detected) and field-transect survey result (detected, not detected). The proportion of sites (p-hat) in each Google Earth detection category are calculated separately for the 22 sites where pocket gopher mounds were detected in the field and for the 55 sites where mounds were not detected in the field.

	Field Detected (n = 22)		Field Not Detected (n = 55)	
Google Earth	Sites	$\hat{p}$ (95% C.I.)	Sites	$\hat{p}$ (95% C.I.)
High confidence	19	0.86 (0.77-1.00)	2[a]	0.036 (0.00-0.17)
Low confidence	2	0.091 (0.00-0.24)	17	0.31 (0.20-0.44)
Not detected	1	0.045 (0.00-0.19)	36	0.65 (0.54-0.79)

[a] Includes 1 site where mounds were not detected from the field transect but were observed off-transect.

Table 1.2. Average (SE) time elapsed in months between field surveys and date of imagery used in Google Earth surveys for 77 sites in Alabama, Florida, and Georgia by imagery survey result (high confidence detection of southeastern pocket gopher mounds, low confidence detection, no detection) and field-transect survey result.

	Field Detected (n = 22)		Field Not Detected (n = 55)	
Google Earth	Sites	Months $\bar{x}$ (SE)	Sites	Months $\bar{x}$ (SE)
High confidence	19	6.37 (1.0)	2[a]	14.5 (12.5)
Low confidence	2	11.5 (5.5)	17	17.7 (3.1)
Not Detected	1	6 (-)	36	11.8 (1.3)

[a] Includes 1 site where mounds were not detected from the field transect but were observed off-transect.

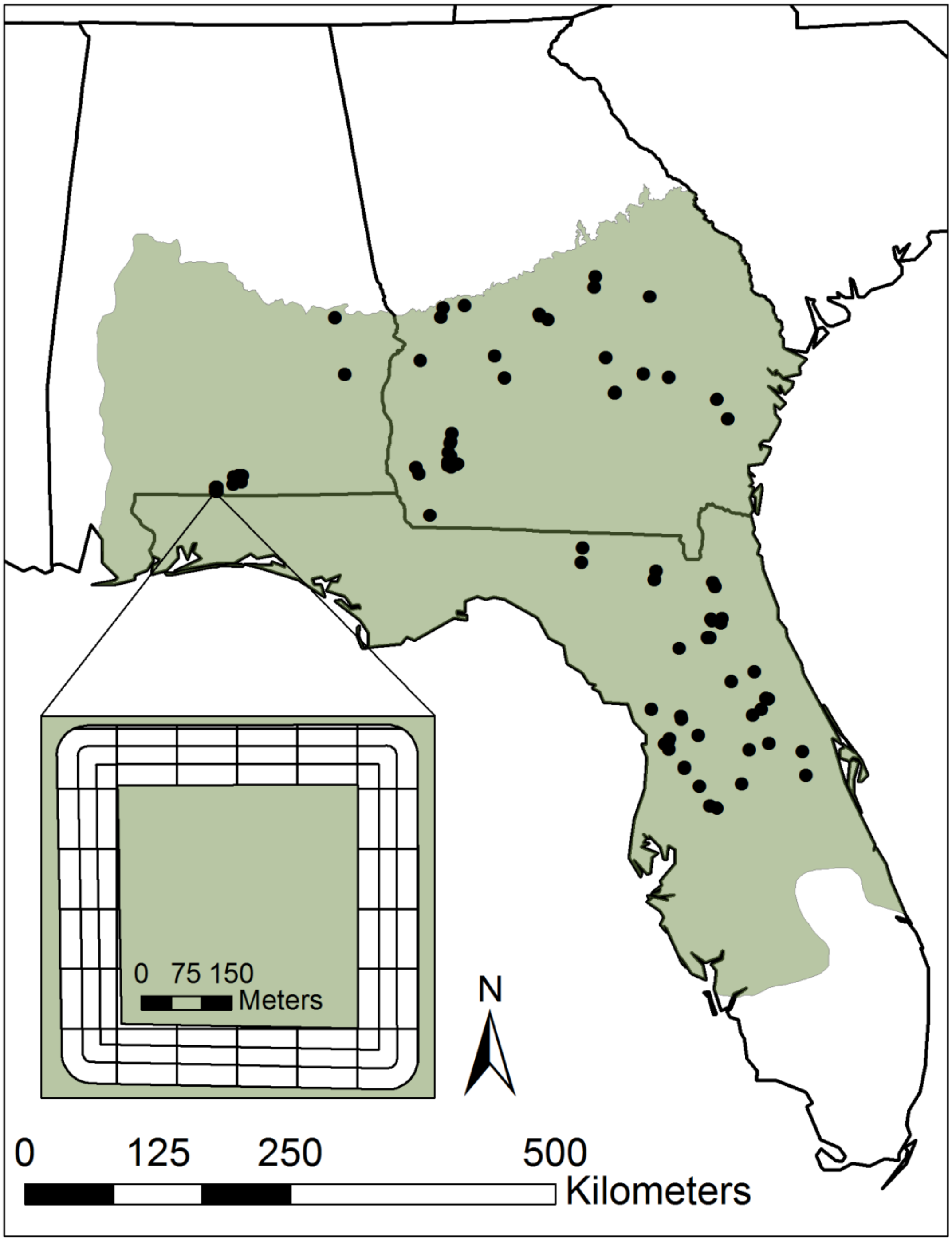

Figure 1.1. The 77 sites (black dots) surveyed in the field and in Google Earth for southeastern pocket gopher occupancy throughout the range (green shading) with an example of the Google Earth survey grid (inset).

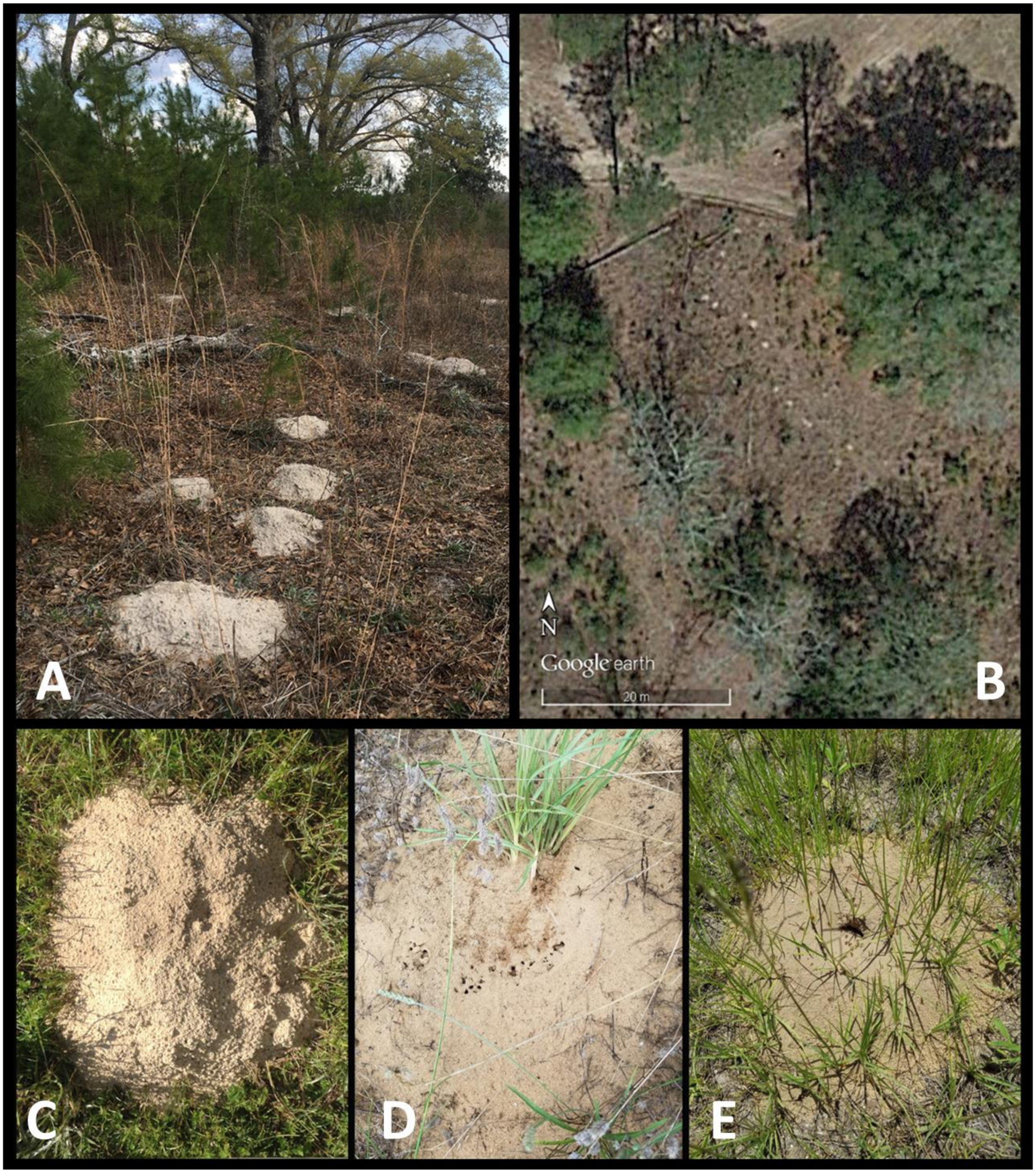

Figure 1.2. A cluster of southeastern pocket gopher mounds located on the Barbour Wildlife Management Area, Barbour County, AL (A) with the corresponding Google Earth imagery for that location (B). View from above of southeastern pocket gopher mound (C) vs. red imported fire ant mound (D) vs. harvester ant mound (E). The southeastern pocket gopher mound is easily identified by its fan like shape and loose soil when freshly excavated. The red imported fire ant and harvester ant mounds are easily identified by the presence of ants or ant tunnels.

Chapter 2:

Habitat attributes of the southeastern pocket gopher: a focus on soil texture and vegetation structure

ABSTRACT

Habitat quality for southeastern pocket gophers (*Geomys pinetis*), a species of conservation concern in Florida, Georgia, and Alabama, is closely linked to specialized soil and vegetation characteristics. Soil type plays an important role in determining where pocket gophers can reside due to the energetic demands associated with burrowing, while, the absence of suitable vegetation may further limit site occupancy. I examined habitat factors associated with the presence of southeastern pocket gophers in the following two adjacent public lands in southeastern Alabama: the Wehle Forever Wild Tract and Barbour Wildlife Management Area. Using a case-control design, I measured vegetation structure and soil texture in 62- 0.1 ha sites occupied by southeastern pocket gophers and 62 unoccupied sites. All occupied sites had a clay content below 8.05% within the 0-20 cm of soil, and had overwhelming support as the most important single variable separating occupied and unoccupied sites. I used logistic regression modeling to compare vegetation of occupied and unoccupied sites with <10% clay threshold. The model with a quadratic effect of canopy cover had highest support, but this was most likely due to a lack of unoccupied sites in the 20-74% canopy cover range as occupied sites spanned across the entire range. Other competing models indicated that occupancy was positively associated with higher cover of grass and woody vegetation. This study provides more detail into vegetation and soils requirements of the southeastern pocket gopher and can be used to help identify future sites for cost-effective habitat restoration and reintroduction.

KEY WORDS *Geomys pinetis*, soil texture, southeastern pocket gopher, vegetation structure.

INTRODUCTION

For fossorial herbivores such as pocket gophers (i.e. *Cratogeomys* spp., *Geomys* spp., *Heterogeomys* spp., *Orthogeomys* spp., *Pappogeomys* spp., and *Thomomys* spp.), site suitability and habitat quality are partly determined by soil and vegetation characteristics, particularly soil type (Davis et al. 1938, Best 1973, Vleck 1979, Andersen and MacMahon 1981, Reichman and Smith 1990, Marcy et al. 2013,) and vegetation composition and structure (Powers et al. 2011, Cortez et al. 2015, Wagner et al. 2017). The energetic constraints of burrowing (Vleck 1979, Andersen and MacMahon 1981, Reichman and Smith 1990) and need for gaseous diffusion (Kennerly 1964, McNab 1966, Darden 1972) may limit pocket gophers to loose-textured, well-drained soils (Maclean 1980, Case and Jasch 1994, Connior et al. 2010, Warren et al. 2017a), although there are interspecific and intraspecific variations to exact soil type (Miller 1964, Best 1973, Marcy et al. 2013). Given that diets of pocket gophers are composed of above and below ground parts of forbs and grasses (Scheffer 1931, Miller 1964, Myers and Vaughan 1964), their habitat typically includes a well-developed herbaceous component, as found in grasslands, croplands, and open-canopy forests and woodlands (Ellison 1946, Huntly and Inouye 1988; e.g. Scrivner and Smith 1981, Connior et al. 2010, Kalies et al. 2012).

Southeastern pocket gophers (*Geomys pinetis*) are a model Geomyid species for considering the relative importance of soil and vegetation attributes in determining site suitability and habitat management options. Southeastern pocket gophers are associated with open pine forests and xeric, sandy soils in Alabama, Florida, and Georgia, primarily in the Coastal Plain (Bailey 1895, Harper1912, Golley 1962, Pembleton and Williams 1978, Warren et al. 2017a), and are of increasing conservation concern due to an apparent range wide distributional decline likely driven by habitat degradation, loss, and fragmentation (Jordan 2004). Developing effective conservation strategies for this species thus depends on understanding the specific soil and vegetation conditions that define its habitat. Land managers in the Southeast can use practices such as prescribed fire (Lewis and Harshbarger 1976, Van Lear and Harlow 2000), herbicide treatments (Brockway et al. 1998, Miller and Miller 2004, Freeman and Jose 2009), and tree removal (Peits et al. 2001, Green et al. 2015) to develop and maintain well-developed herbaceous understories. However, little can be done about the distribution of suitable upland soil types as soil genesis can take place on the scale of tens of thousands of years (Shaw 1930). Therefore it will be important to focus conservation efforts in areas that are or can be managed to become suitable habitat (i.e. on suitable soils).

I compared vegetation and soil characteristics of sites occupied by southeastern pocket gophers vs. nearby unoccupied sites in a southeast Alabama study area (Fig 1). In the only previous extensive quantification of southeastern pocket gopher habitat, occupancy in a southwestern Georgia study area was tied more strongly to soil characteristics than vegetation structure (Warren et al. 2017a). Although I expected southeastern pocket gophers to be tied to sandy soils in my study area, I also expected to find strong differences in vegetation structure between occupied and unoccupied sites due to the heterogeneous mix of forest structural states and management histories in this landscape. In particular, I expected occupancy to be positively related to cover of grasses and forbs as the roots and tubers of this type of vegetation are associated with pocket gopher foraging, negatively related to cover and density of ground-level and midstory woody vegetation as this type of structure normally shades out herbaceous ground cover, and highest in either low or intermediate levels of overstory cover due to structural effects on understory and thermal effects on soil. I expected a strong association with sandy soils, but the soil survey geographic (SSURGO) database (Soil Survey Staff 2017) categorized most upland portions of my study area as soils with a significant sand component (Appendix A). Therefore, I thought that soil texture might not be a limiting factor within this landscape and would be of lower importance than vegetation in discriminating occupied from unoccupied sites.

METHODS

Study Area

The study area (Fig. 2.1) included 3 properties managed by the Alabama Department of Conservation and Natural Resources in Bullock and Barbour Counties, Alabama, with a combined area of 12,155 ha, Wehle Forever Wild Tract (622 ha), Wehle Nature Center (9 ha) and Barbour Wildlife Management Area (WMA; 11,524 ha).The study area was located within the Southern Hilly Gulf Coastal Plain ecoregion of Alabama (Griffith et al. 2001), and consists predominantly of rolling hills and lowland drainage areas. Natural Resource Conservation Service (NRCS) Web Soil Survey (Soil 2017) indicated that the landscape is dominated by sandy loams and loamy sands, with Luverne series soils making up over half of the study area (52%, Soil Survey Staff; Appendix Soil). Barbour County, where the majority of the study site was located, historically had long hot summers (average summer temperature= 26 °C) and cool short winters (average winter temp = 9 °C) (NCDC 2017, Trayvick 2005, Stubbs 1997). The average annual precipitation was about 137 cm, with 48% occurring within the growing season (April-September; Trayvick 2005, Stubbs 1997). During my two study years, above average annual rainfall occurred in 2015 (187 cm) and below average rainfall occurred in 2016 (119 cm; NCEI 2017).

Upland areas were predominantly in even-aged structural states, including mixed pine – hardwood stands (26% of study area) and pine-dominated stands (seedling – sapling pines: <10 cm dbh, 20% of study area; poles – small pine trees: 2.54 - 30 cm dbh, 18% of study area; and mature pine trees >30cm dbh, 18% of study area; Silvano 2013). Mature upland stands on Wehle FWT generally had relatively open canopies, supporting well-developed herbaceous components, while Barbour WMA had a broad range of canopy densities. Both Wehle FWT and Barbour WMA have undergone recent longleaf pine restoration efforts and Barbour WMA includes tracts of active timber harvest. Prescribed fire is used as a management tool on both properties, with return intervals ranging from 2-5 years. Pine stands throughout the study area included one or more of the following: loblolly pine (*Pinus taeda*), shortleaf pine (*P. echinata*), slash pine (*P. elliottii*) or longleaf pine (*P. palustris*); mixed pine-hardwood forests included pine intermixed with stands of oaks (*Quercus spp*.), maples (*Acer spp*.), sweetgum (*Liquidambar styraciflua*), and yellow poplar (*Liriodendron tulipifera*), and other hardwood species. Bottomland hardwood stands included these taxa, as well as, magnolia (*Magnolia spp*.), mussel wood (*Carpinus caroliniana*), and dogwood (*Cornus spp.*). Common shrub species in uplands were blackberry (*Rubus spp.*), beauty berry (*Callicarpa americana*), *Vaccinium spp.*, winged sumac (*Rhus copallinum*), and wax myrtle (*Morella cerifera*). Broom sedge (*Andropogon spp.*) was the predominant grass.

Site Selection

In summer (May-September) 2015, I used a case-control stratified sampling design (Thomas and Taylor 1990, Manly et al. 2002, Johnson et al. 2006) to select 62 sites occupied by southeastern pocket gophers and 62 unoccupied sites. Site size was 0.10 ha, corresponding to the approximate average home range size for the species (Warren et al. 2017b); thus my design focused on 2nd order habitat selection (Johnson 1980). I used the presence of soil mounds pushed to the surface during tunneling to determine site occupancy of southeastern pocket gophers (e.g., Connior et al. 2010, Olsen 2011, Wagner et al. 2017).

Examination of imagery available in Google Earth (Bennett 2017: Chapter 1), personal communications from land managers, and my field reconnaissance indicated that there were two general portions of my study area occupied by pocket gophers: the northern portion of the study area in Wehle FWT and adjacent Barbour WMA, and the central portion of the study area in Barbour WMA (located off of Mt Andrews road concentrated between Wilson road and Creek road in Barbour WMA). To select a sample of occupied sites I first selected an initial occupied site within each area of known occupancy, and then systematically searched for additional occupied sites by walking in a circular transect until another cluster of pocket gopher mounds were located, maintaining a minimum distance of 50 m between outer edges of each site (Appendix A). If no mounds were found on the transect, I moved to another area believed to be occupied by pocket gophers or systematically searched in nearby potentially suitable habitat.

All occupied sites were examined to ensure that other ground disturbances, such as red imported fire ant (*Solenopsis invicta*) mounds were not misidentified as pocket gopher mounds. I distinguished fire ant mounds by the presence of fire ants and /or ant tunneling structures within mounds (Vinson 1997), and their more grainy soil texture and compact structure compared to pocket gopher mounds. To be included as an occupied sample site, a potential site was required to have three or more pocket gopher mounds. In addition, I limit sampling to areas in a more ‘natural state’ by ignoring sites that had been recently disturbed by timber harvest (time since harvest ≤ 2years) or associated with roads or lawns. Due to an aversion to digging in wet soils (Andersen and MacMahon 1981), unoccupied sites were also restricted to having less than 50% saturated soils within a 3-m radius of the center point.

During pilot sampling in the northern stratum, initially I attempted to pair unoccupied sites with occupied sites by traveling a random distance (86-100 m) and direction from each occupied site. However, due to the spatial pattern of occupancy this was a prohibitively inefficient approach for selecting unoccupied sites, as randomly selected sites in the neighborhood of an occupied site had a high probability of either also being occupied or of being in non-target areas (e.g. bottomlands or adjacent private lands). Therefore, I designated two survey stratum encompassing the northern and central occupied areas and surrounding unoccupied areas, with stratum boundaries formed by geographical features, property edges, and political boundaries (Fig. 2.1). Using ArcMap (Environmental Systems Research Institute, Inc., Redlands, CA 2013), I created a hexagonal tessellation grid (Whiteaker 2013) of 0.1 ha potential sites for each stratum and conducted stratified simple random sampling to select control (unoccupied) sites. Each sample site was examined in the field and rejected from the sample if it was within 50 m of an occupied site, had any pocket gopher mounds, or met any of the rejection criteria listed above for occupied sites. Rejected sample sites were replaced with additional randomly selected sites; in each stratum the final sample size of unoccupied sites was equal to the number of occupied sites.

Vegetation and Soil Sampling

I established an 18-m radius circular plot in each site for vegetation and soil sampling. I assessed soil texture and understory cover variables because of their hypothesized direct importance to southeastern pocket gophers. I also examined mid-story and over story variables because of their direct relevance to forest managers and their potential importance to pocket gophers through their effects on understory conditions (e.g. decrease in herbaceous layer; Brockway et al. 2005, Jose et al. 2007). To measure low (<1.5 m) vegetation cover, I sampled five 1-m^2 sub-plots w in each plot, one at the plot center and 4 others at fixed distances and directions from the center (7 m west, 12 m south, 15 m east, and 17 m north, with this systematic pattern chosen to ensure coverage of the plot while allowing efficient plot establishment (Appendix B). In each subplot, percentage of bare ground, leaf litter, pine straw, graminoids, forbs, woody vegetation (e.g. shrubs and saplings;), woody weeds (e.g. partridgeberry, *Mitchella repens*), downed debris (e.g. downed branches and logs), and pocket gopher mound cover were visually estimated to the nearest percent (Higgins et al. 2012). I averaged the 5 subplot values for each plot. Canopy cover (dominant tree cover in overstory, for pine and hardwood categories; and midstory, (>2 m but not extending into the dominant canopy) was recorded by taking a GSR densitometer (Geographic Resource Solutions^{TM}, Arcata, CA 2008) measurement at 32 points in a circular grid covering each plot, with 4-m spacing between grid points. Density of woody stems [viney shrubs, such as blackberry (*Rubus spp*.)]; non-viney shrubs (total shrub count – viney shrubs count); saplings (immature trees <10 cm DBH); total shrub (non-viney shrub + viney shrub); and total stem (Sapling + total shrub) was determined by counting stems within a 3-m radius subplot at the center of the sites. Basal area was estimated at each plot center via the variable radius method (Higgins et al. 2012), using a 10-factor prism at the center of the site for all live trees and grouped into the following categories: pine, hardwood, and pine + hardwood.

To measure soil texture, soil samples were collected at depths of 0-20 cm, 40-60 cm, and 80-100 cm at the center of each site in summer 2016 using 5-cm diameter soil auger with a 1-m extension rod. Samples were stored in sealed plastic bags until they could be transported and processed at Auburn University. Soil was then dried in a dryer at 105°C for a minimum of three days and then passed through a 2-mm sieve prior to the particle size determination test via hydrometer. I followed Auburn University Soil Testing Lab particle size determination test guidelines (Gee et al. 1986), with 40 g of soil used for each test. To ensure sampling consistency, for every 10th round of testing (batch of 9 samples) I ran 3 replicate tests of each of three samples, confirmed that hydrometer readings for the 3 replicate tests were within 2 units of each other, and used the average of the 3 values for that sample.

My study assumed that pocket gophers truly were absent from sample sites classified as unoccupied in summer 2015. Pocket gopher mounds remain visible for 1-2 years for other species after formation (*Thomomys talpoides*; Whitehead et. al 2014) and observed in the field for up to at least 6 months, and most sites assumed to be unoccupied were at least 86 m away from occupied sample sites. When I revisited all sites in 2016 to collect soil samples; only 1 of the 62 unoccupied sites sampled in 2015 had evidence of mounds within the plot boundary in 2016, likely due to movement from a nearby area of known occupancy. As this activity was limited to 2 mounds near the plot edge and because I did not assume that sites unoccupied in 2015 were permanently unoccupied, I retained this as an unoccupied site.

Data Analysis

I summarized all vegetation variables measured in the field (Appendix C), but retained 9 for further examination (percentage cover of graminoids, forbs, woody vegetation, midstory, and overstory; stem density of non-viney and viney shrubs; and basal areas of pines and hardwoods), excluding the other variables from analysis based on lack of clear biological relevance (e.g. pine straw and leaf litter cover), limited range of variation in my data (bare ground), or redundancy with one or more other retained variables (e.g. hardwood canopy cover vs. hardwood basal area).

I summarized soil texture and texture classes for occupied and unoccupied sites and plotted data on USDA soil texture triangles (Buckman and Brady 1971) using the R package of Moeys et al. (2016).

Initial examination of soil texture data indicated that all occupied sites had very low clay levels at 0-20 cm depth, suggesting a threshold of suitability. To confirm the relative importance of this soil variable in discriminating occupied from unoccupied sites compared to other measured variables, I used logistic regression with occupancy status for each of the 124 sample sites as the binary response variable. I compared 18 models using an information-theoretic approach (Burnham and Anderson 1998) implemented with R package "MuMIn (Bartoń 2016), with each model including a stratum-specific intercept and a single soil texture or vegetation structure variable. To assess the generality of the potential soil threshold, I compared my data with soil texture data from Warren (2014) for sites occupied and unoccupied by southeastern pocket gophers at the Joseph W. Jones Ecological Research Center at Ichauway (The Jones Center). To confirm that vegetation conditions were not confounded with the putative clay threshold, I used permutational multivariate analysis of variance (function 'adonis' in package "vegan", Oksanen et al. 2017) to assess overall similarity in vegetation structure of unoccupied sites with less than 10% clay in soil texture samples vs. those with greater than 10% clay, using the 9 vegetation variables listed above. I repeated this comparison using an alternative 15% threshold for 0-20 cm clay to assess sensitivity of results to the assumed threshold.

Subsequently, I limited logistic-regression vegetation modeling to include only sites with <10% clay in the top 20 cm of soil, thereby examining vegetation only for sites with soils that appeared to be capable of supporting southeastern pocket gophers. I developed 17 alternative models and compared them with an information-theoretic approach. Because of the low number of unoccupied sites included in the modeling after excluding sites above the clay threshold, models included a maximum of two vegetation variables (Harrell 2001) in addition to a stratum-specific intercept parameter to account for matching of occupied and unoccupied sites at the stratum level. Ground cover models included all one and two variable combinations of grass, forb, woody vegetation, and non-viney shrubs. Canopy models included all one and two variable combinations of hardwood basal area, pine basal area, and total overstory cover. I hypothesized that probability of occupancy could be low in sites with extremes in canopy cover (i.e. very low and very high canopy cover) as canopy cover can influence understory composition and influence soil temperatures and therefore included an additional model with a linear and quadratic effect of total overstory cover. Due to correlation among variables, I did not include density of viney shrubs or midstory cover in the above model sets or combine overstory and understory variables in any model. Instead, I added a model integrating all 9 vegetation variables. I conducted a principal components analysis (PCA) of these variables, then used site scores for the first 2 principle component axes as derived habitat covariates included in a single logistic regression model. Using R package “rms” (Harrell 2017), I assessed explanatory power of top-ranked models using the probability of concordance (*c*) statistic, equivalent to the area under the Receiver Operating Curve (ROC) summary, with c = 0.5 indicating a model has no predictive ability y and c = 1.0 indicating perfect predictive ability (Harrell 2001). I repeated this comparison and subsequent logistic regression analyses using an alternative 15% threshold for 0-20 cm clay to assess sensitivity of results to the assumed threshold.

RESULTS

Soil and Vegetation Patterns

Occupied sites were either a loamy sand (44 sites) or a sandy loam (18 sites) texture class at a 0-20 cm depth, expanding to include additional texture classes at greater depths (Fig. 2.2). In contrast, unoccupied sites included additional texture classes at all depths. Occupied sites were located in 11 different SSURGO map units, with 4 of these units unique to occupied sites in my surveys when considering samples with less than 10% clay in the top 20 cm of soil (Table 1). There were 17 different soil profiles across all sites in the 10% clay threshold with most profiles grouped in the loamy sand texture class from 0-100 cm (LoS-LoS-LoS profile; Appendix E). All occupied sites contained clay content below 8.05% within the 0-20cm depth. While there was a similar sand threshold in that all occupied sites had >70% sand at 0-20 cm depth, clay at the same depth was more restrictive in separating occupied from unoccupied sites (15 out of 62 unoccupied sites had clay >8.05% while 26 had < 70% sand). Soil data form occupied sites from the most recent southeastern pocket gopher study conducted at the Jones Center (Warren et al. 2017a) were consistent with the threshold observed at Wehle-Barbour, with 49 of 50 occupied Jones Center sites having clay levels < 8.4% at 25cm depth; one occupied site had 14.4% clay at this depth.

In logistic regression modeling using all 124 sample sites and comparing single-variable habitat models, the model with shallow clay (percentage clay at 0-20 cm) received overwhelming support (AICc weight = 1.00); other single-variable soil-texture models had ΔAICc values at least 23 units greater than shallow clay model, while the highest-ranked single-variable vegetation model had a ΔAICc value 67 units greater than the shallow clay model (Table 2). Permutational multivariate analysis of variance indicated that vegetation structure was similar for unoccupied sites above and below a shallow clay threshold of 10% ($F_{1,60}$ =0.50 ,P = 0.74) and of 15% ($F_{1,60}$ = 1.16, P = 0.32).

Vegetation Modeling

For logistic regression modeling, limiting analysis to sites below 10% shallow clay threshold resulted in inclusion of 22 unoccupied sites for comparison with the 62 occupied sites; applying a 15% threshold, 30 unoccupied sites were included. Regardless of which threshold was used, the top-ranked models were the quadratic canopy cover model, the model incorporating principal component (PC) site scores as derived variables, and the understory model including grass and woody vegetation cover (Table 3, Appendix 15%). The model incorporating a quadratic effect of canopy cover had more support (AICc weight = 0.50) than the PC-score model (weight = 0.13) or grass + woody vegetation model (weight = 0.11). Based on the quadratic model, relative odds of occupancy peaked at ~49% canopy cover [e.g., odds of occupancy for a site with 49.5% canopy cover were 1.54 (95% C.I.: 0.87–2.74) times greater than for a site with 20% canopy cover, and 4.24 (1.64– 10.94) times greater than for a site with 80% canopy cover; log-scale parameter estimates: $\beta_{Canopy\ Cover}$ = 8.65 (S.E. = 3.28), $\beta_{Canopy\ Cover^{\wedge}2}$ = -10.33 (3.58), for canopy cover on a 0–1 scale]. However, data did not indicate that sites with low or high canopy cover were unsuitable, rather, occupied sites spanned nearly the full range of potential canopy cover levels, whereas there were no low-clay unoccupied sites with canopy cover values in the 20-74% range. The concordance statistic indicated moderately good predictive ability of the quadratic canopy cover model (C =0.74).

The logistic regression model incorporating PC site scores as derived vegetation variables indicated a positive relationship between log-odds of being occupied and scores on the first principal component [logit-scale β_{PC1} = 0.42 (SE = 0.17)]. Based on the vegetation variables’ loadings for the first principal component, this relationship suggested that log-odds of occupancy increased along a gradient of increasing grass cover, forb cover, and viney shrub density (loadings 0.36, 0.32, and 0.28) and decreasing overstory cover (-0.46), midstory cover (-0.43), and hardwood basal area (-0.45). There was not a strong relationship between log-odds of occupancy and scores on the second component [β_{PC1} = -0.24 (0.21)]; loadings for individual variables did not lead to a clear interpretation of the second component.

The top ground-cover model included both grass and woody vegetation cover (Table 3) Estimated model parameters indicating that occupied sites had higher cover of grass [β_{grass} = 3.49 (1.73)] and woody vegetation [$\beta_{woody\_vegetation}$ = 4.35 (2.50)], with cover of both variables on a 0–1 scale. Predictive ability of the model was moderately low (C=0.69). Models including density of non-viney shrubs were not supported compared to the models including woody vegetation cover, which incorporated cover of viney and non-viney shrubs. Because viney shrub stems on average made up 68% of all shrub stems in stem-density counts for sites with <10% clay at 0-20 cm, the positive association between occupancy and woody vegetation cover appeared to be driven by cover of viney shrubs.

DISCUSSION

With any habitat study it is important to be able to define resources that are available to a species and those that are not. Failing to distinguish between the two can lead to skewed estimates of habitat preference (Johnson 1980) and can hinder conservation efforts. In the case of my study, I found that a majority of the unoccupied sites surveyed (65%) were unavailable to southeastern pocket gophers, as these sites had clay levels greater than the maximum observed in my occupied sites (8.05% in top 20 cm). Presence of southeastern pocket gophers appeared to be limited much more by clay levels in the top 20 cm of soil compared to deeper depths, as 0-20 cm is the depth at which foraging occurs (Scheffer 1931, Brown and Hickman 1973). Burrowing comes with physiologically high costs, which can become more demanding when clay contents increase (Reichman and Smith 1990), and supports the notion that clay composition can act as a barrier to suitability (Davis et al. 1938, Busch et al. 2000, Connior et al. 2010, Cortez et al. 2015).

My data supports the idea that soil is more important than vegetation for defining areas occupied by southeastern pocket gophers (i.e. Warren et al. 2017). Southeastern pocket gophers within the study area utilized loamy sands and sandy loams that are within the range of sandy to loam soils that *Geomys* prefer (Baker 2003) as these soil are facilitatory to the claw digging mode of tunneling that is associated with the genus (Busch et al. 2000). Soil data form occupied sites from at the Jones Center (Warren et al. 2017a) were consistent with the threshold observed at Wehle-Barbour, with most of the Jones Center sites having clay levels < 8.4% at 25cm depth when compared to 8.05% at my study sites. My results were also similar to the range of clay conditions found for the Ozark pocket gopher (*Geomys bursarius*) with a maximum clay content observed at 11.8% (Connier et al. 2010). Marcey et al. (2013) found a higher clay cutoffs of around 30% when examining two subgenera of California pocket gophers (*Thomomy*s spp.) with the subgenus *Megascapheus* having the ability to access harder, clay rich soils due to tooth-digging adaptations.

My results also suggest that when soil is taken into consideration, canopy cover is important for predicting southeastern pocket gopher occupancy within my study area. Within the top 50 cm of soil, soil temperatures can fluctuate throughout the day (Soil Survey Staff 1999). Some portion of canopy cover, could play a role with ameliorating fluctuations associated with daily temperature changes (Hungerford and Babbitt 1987, Chen et al. 1993, Brosofske et al. 1997), possibly through retaining soil moisture. Canopy cover may be more beneficial for burrowing rodents when habitable soils are shallow making it more difficult for rodents to escape thermal stress through digging. During dry seasons, tunnel depths have been reported to extend an additional 15 cm below normal shallow tunnel depths to moisture levels that will maintain tunneling structure (Brown and Hickman 1973). However, the effects of canopy cover may be a result of sites sampled as unoccupied sites that were available to pocket gophers had either high canopy cover or low canopy cover with no sites within the middle canopy cover range. Occupied sites conversely ranged from 0-100%.

More interesting is that occupied sites tended to have higher grass cover, but understory was not a top model. Grasses such as bahiagrass (*Paspalum notatum*), bermudagrass (*Cynodon dactylon*) and wiregrasses (*Aristida* spp and *Sporobolus* spp) have been documented as being consumed or cached by southeastern pocket gophers (Barrington 1940, Ross 1976) though forbs were also documented as being cached. Increased level of grass could indicate sufficient food supplies. Warren et al. (2017a) also found higher percent cover of grasses on active sites of southeastern pocket gophers. Wagner et al. (2017) demonstrated that probability of use for the Baird's pocket gopher (*Geomys breviceps*) in longleaf of west central Louisiana, increased with increasing forb cover and decreased with increasing small tree stems (DBH< 25 cm; comparable in size to my midstory) and increasing pine basal area. However, Wagner did not take into consideration clay content.

While I expected occupied sites to have well-developed grass cover, less clear was why I did not detect a positive relationship with forb cover, while the positive relationship with shrub cover was the opposite of what I expected. Forbs were not included in any of my top models, yet other researchers have identified forbs as an important food source for pocket gophers (Vaughn 1967, Luce et al. 1980, Wagner et al. 2017) and I expected it to be an important resource. This association may reflect frequency of burning in combination with a heterogeneous distribution of suitable soils as forbs can occur more frequently burned areas when compared to unburned areas (Gates and Tanner 1988). In addition, woody vegetation, especially viney shrubs such as blackberries, were associated with used sites. This could also reflect timing and frequency of fire on the landscape as decreased fire can result in landscapes with increased shrub cover (Lewis and Harshbarger 1976). In addition, annual winter fires could promote blackberry growth (Lewis and Harshbarger 1976).

Conservation efforts will need to focus on defining areas of suitable soil when considering habitat restoration projects or relocation areas for this species. However, it is exceedingly difficult to define areas, based off of SSURGO data, which could be suitable for pocket gophers. This is partly due to the fact that habitats in soil can range in size from micro-niches to entire landscapes (Brevik et al. 2015). Soil maps readily provided by the NRCS are composed of smaller map units that are delineations of similarly grouped soils. These map units can be composed of a variety of different soil series, i.e. unique soil types. The scale of SSURGO map units may be too coarse to effectively identify smaller pockets of soils that are suitable for southeastern pocket gophers. However, SSURGO data has been developed into a variety of tools including cell phone applications that can be easily accessed in the field making it a useful tool for field excursions, though I caution relaying only on utilizing digital soil data provided through SSURGO. Of the sites surveyed, 7 of the 62 occupied sites, making up 36% of the used map unit types, were located in map units that had clay ratings over 10% clay when looking at the top 20 cm through the web soil survey, a resource produced by the National Cooperative Soil Survey that provides online access to soil data and information (NCRS 2017). These 7 map units made up 20% of the study area before removing lowland soils. Furthermore, occupied and unoccupied sites surveyed in the same map units sometimes had drastically different clay contents. These obscurities can make it difficult in defining suitable habitat, when suitable habitat seems to require soils with clay content < ~8%.

Management Implications

When soils are inadequate, vegetative properties are of minor importance for determining pocket gopher occupancy. This is most likely due to high clay contents causing soils to be energetically costly to burrow in for fossorial rodents (360 to 3400 times as much energy burrowing when compared to traveling above ground; Vleck 1979). However, on suitable soils, vegetation may play a role in limiting occupancy. Therefore, managers will need to focus on habitat restoration and conservation in areas of suitable soils if there is to be any chance of promoting population growth through normal dispersal or translocation. Managers may rely on readily available SSURGO data for selecting areas suitable for pocket gophers, but site specific texture tests should be conducted before any habitat restoration or relocation work is done. This will help to ensure that the areas have acceptable clay levels for southeastern pocket gophers. Field based methods such as hand textures can help land managers narrow in on more suitable sites. However particle size analysis should be conducted for higher precision. This is especially important when hand textures yield sandy loam results as almost half of all combinations of sand/silt/clay for sandy loams have clay conditions above 10%. In areas where soils have been degraded through soil compaction or years of erosion from land use practices, it may be necessary to locate alternative patches of suitable soils on maps and target those areas for minimally invasive habitat enhancement procedures that will promote intermediate canopy covers with well-developed grassy understories when considering relocating individuals.

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Table 2.1. Soil texture class (0-20 cm) and soil survey geographic data (SSURGO Soil Survey Staff 2017) map unit and unit description for 62 sites occupied by southeastern pocket gophers and 62 unoccupied sites in Barbour WMA and Wehle FWT (Barbour and Bullock Counties, AL), 2015-2016. Soil samples collected at occupied sample sites were either loamy sands or sandy loams, while unoccupied sample sites had additional texture classes[1].

Map Unit	**Description**	**Occupied**		**Unoccupied**		
		Loamy Sand	**Sandy Loam**	**Loamy Sand**	**Sandy Loam**	**Other**
BaE	Blanton loamy sand, 8 - 20 % slopes	1	0	0	0	1
BbB	Blanton-Bonifay loamy sands, 2 - 8 % slopes	18	6	1	0	0
BnB	Blanton-Bonneau complex, 0 - 5 % slopes	4	2	0	1	0
CeC	Conecuh sandy loam, 5 - 8 % slopes	2	1	1	2	3
CeC2	Conecuh sandy loam, 5 - 8 % slopes, eroded	0	0	1	2	2
CeD	Conecuh sandy loam, 8 - 20 % slopes	0	0	1	4	5
CeE	Conecuh sandy loam, 8 - 20 % slopes	1	0	1	1	8
CmD	Cowarts-Maubila Complex, 8 - 15 % slopes, flaggy	3	3	0	0	0
LcB	Lucy loamy sand, 0 - 5 % slopes	0	2	0	0	0
LeD	Luverne sandy loam, 8 - 15 % slopes	2	0	0	0	0
LnB	Luverne loamy sand, 2 - 8 % slopes	3	0	0	1	3
LnE2	Luverne loamy sand, 8 - 20 % slopes, eroded	10	3	3	3	5
LsE	Luverne-Springhill complex, 15 - 45 % slopes	0	0	0	4	0
LtF	Luverne-Blanton-Cowarts complex, 15 - 45 % slopes	0	0	1	0	0
LyA	Lynchburg loamy fine sand 0 - 2 % slopes*	1	0	2	0	3
OcA	Ocilla loamy fine sand, 0 - 2 % slopes*	0	0	2	1	0
Total		**45**	**17**	**13**	**19**	**30**

[1] Clay, clay loam, Loam, Sandy clay, Sandy clay loam

Table 2.2. Model-selection results for logistic regression modeling comparing single-variable habitat models of southeastern pocket gopher occupancy on Barbour WMA and the Wehle FWT (Barbour and Bullock counties, AL) in 2015. Models are ranked by Akaike's Information Criterion adjusted for small sample size (AICc) scaled as difference between each model's AICc score and the score for the top-ranked model (ΔAICc), and Akaike weight (Wi). Modeling compared 62 occupied sites and 62 unoccupied sites
.

Model	**Parameters**	**Log-likelihood**	**ΔAICc**	**Wi**
Clay 20	3	-40.49	0.00	1.00
Sand 20	3	-51.99	23.00	0.00
Clay 60	3	-59.72	38.47	0.00
Sand 60	3	-62.56	44.14	0.00
Sand 100	3	-74.03	67.08	0.00
Clay 100	3	-74.13	67.28	0.00
Midstory Cover	3	-76.68	72.38	0.00
Woody Vegetation	3	-82.59	84.20	0.00
Silt 20	3	-83.01	85.04	0.00
Grass	3	-83.77	86.57	0.00
Viney Shrub	3	-83.87	86.75	0.00
Pine Basal Area	3	-84.26	87.55	0.00
Non Viney Shrub	3	-84.45	87.91	0.00
Hardwood Basal Area	3	-84.47	87.95	0.00
Canopy Cover	3	-84.82	88.65	0.00
Intercept Only	2	-85.95	88.82	0.00
Forb	3	-85.54	90.09	0.00
Silt 100	3	-85.85	90.71	0.00
Silt 60	3	-85.95	90.92	0.00

Table 2.3. Model-selection results for logistic regression modeling of southeastern pocket gopher occupancy on Barbour WMA and the Wehle FWT (Barbour and Bullock counties, AL) in 2015. Models are ranked by Akaike's Information Criterion adjusted for small sample size (AICc) scaled as difference between each model's AICc score and the score for the top-ranked model (ΔAICc), and Akaike weight (Wi). Modeling was limited to sites with < 10% clay threshold within the first 20 cm of soil depth, (62 occupied sites and 22 unoccupied sites).

Model	**Parameters**	**Log-likelihood**	**ΔAICc**	**Wi**
Canopy Cover2 + Canopy Cover	4	-42.56	0	0.5
PC1+PC2	4	-43.88	2.66	0.13
Grass + Woody Vegetation	4	-44.04	2.96	0.11
Grass	3	-45.72	4.13	0.06
Woody Vegetation	3	-46.34	5.36	0.03
Hardwood Basal Area	3	-46.67	6.03	0.02
Grass + Non Viney Shrub	4	-45.62	6.12	0.02
Forb +Woody Vegetation	4	-45.65	6.18	0.02
Intercept Only	2	-48.05	6.62	0.02
Woody Vegetation +Non Vine Shrub	4	-46.2	7.3	0.01
Hardwood Basal Area + Pine Basal Area	4	-46.3	7.48	0.01
Canopy Cover	3	-47.59	7.87	0.01
Forbs	3	-47.65	7.98	0.01
Canopy Cover + Hardwood Basal Area	4	-46.65	8.18	0.01
Pine Basal Area	3	-47.91	8.5	0.01
Non Viney Shrub	3	-48.05	8.78	0.01
Canopy Cover + Pine Basal area	4	-47.59	10.07	0
Forb + Non Viney Shrub	4	-47.62	10.14	0

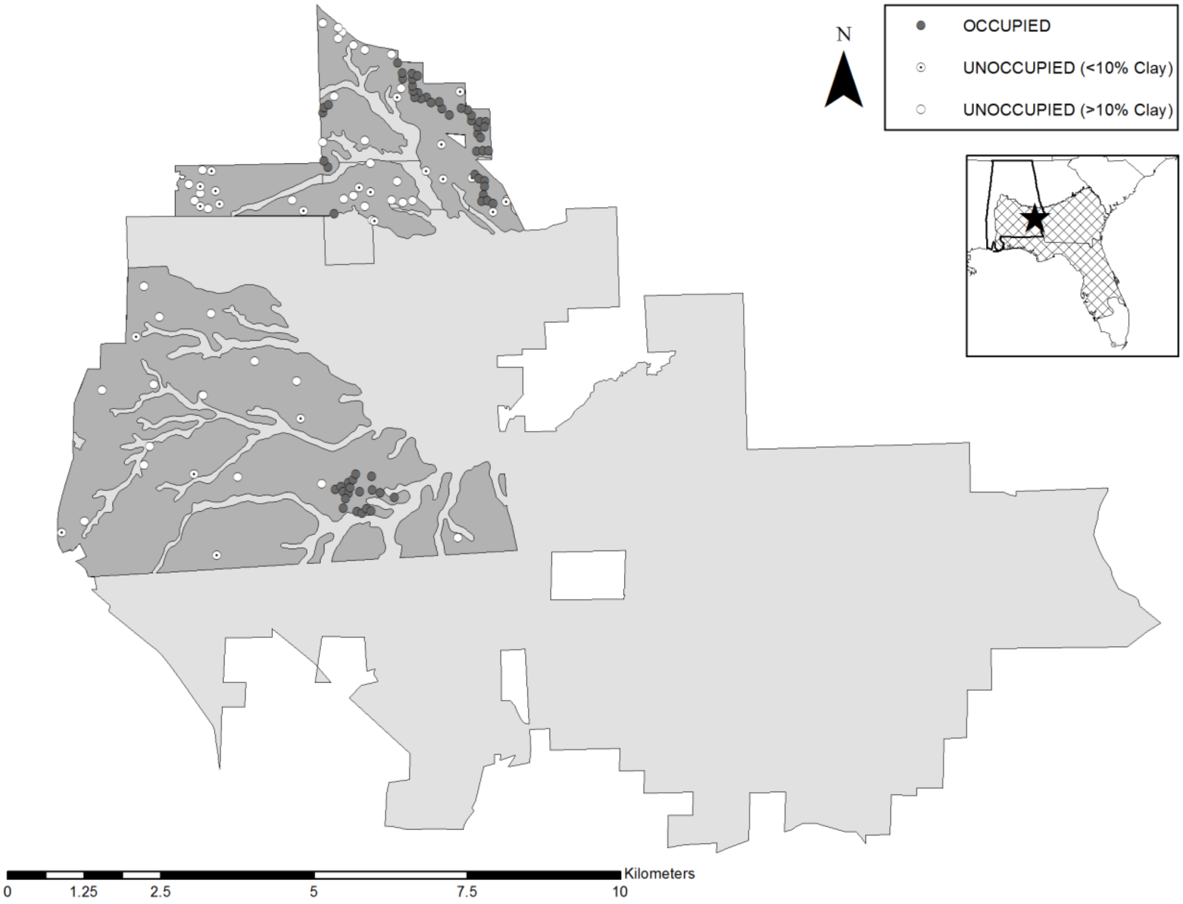
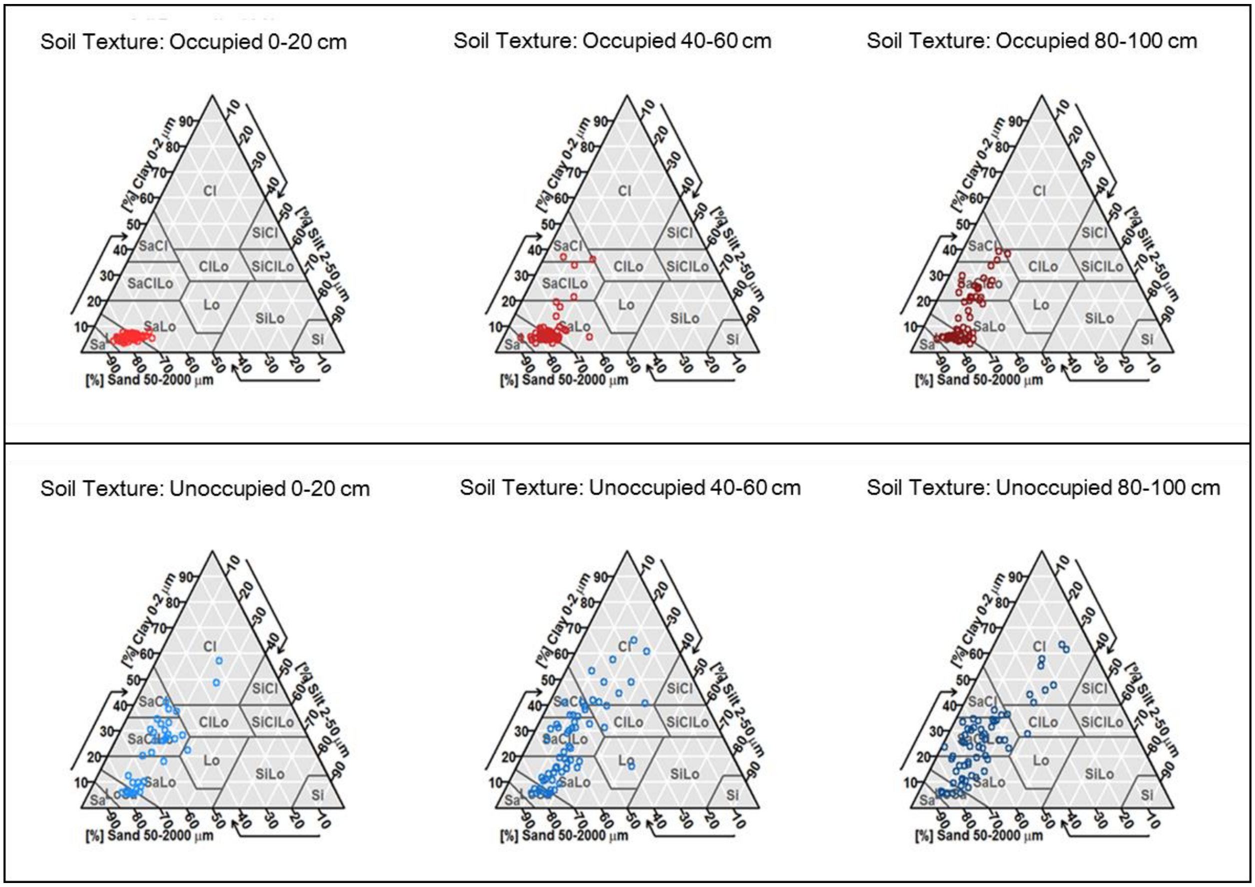


Figure 2.1. The study site is composed of three main parcels of land: The Wehle Nature Center (32.03019, -85.45586), The Wehle Forever Wild Tract (32.03192, -85.46973), and the Barbour WMA (31.97803, -85.44317) in Barbour and Bullock Counties, Alabama. The survey area has been restricted to include only 9,141ha of potentially sandy soils as delineated by the Natural Resource Conservation Service soil surveys (grey area).


Soil Texture: Occupied 0-20 cm

Soil Texture: Occupied 40-60 cm

Soil Texture: Occupied 80-100 cm

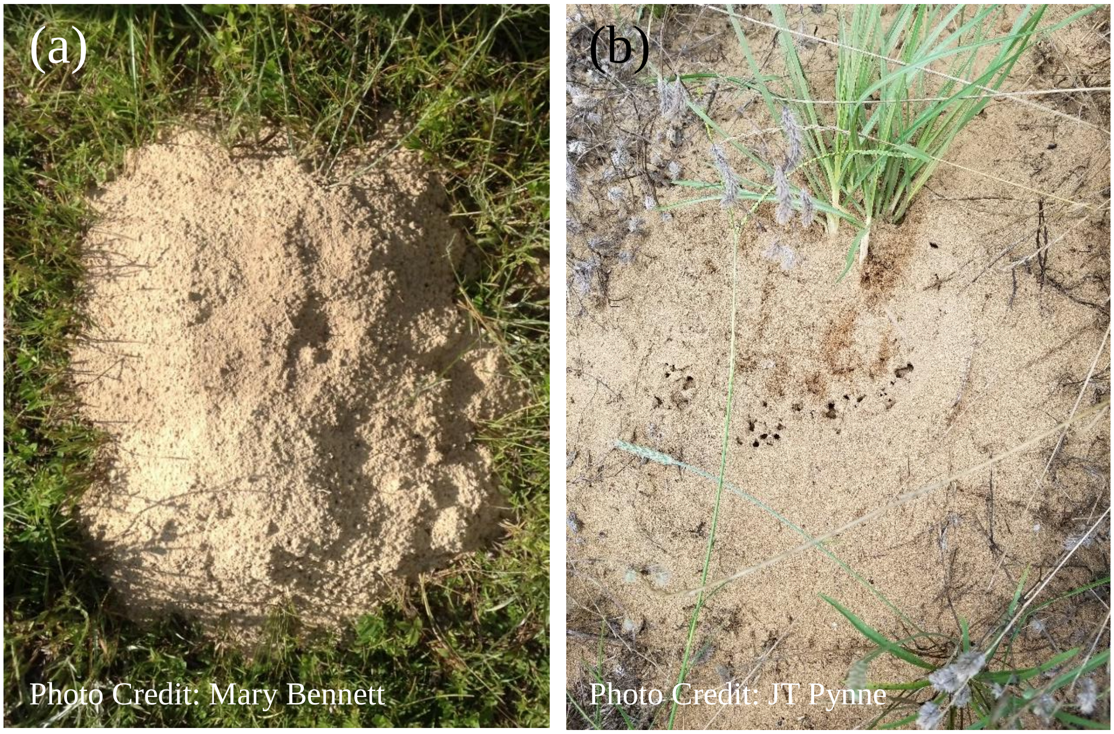
Soil Texture: Unoccupied 0-20 cm

Soil Texture: Unoccupied 40-60 cm

Soil Texture: Unoccupied 80-100 cm

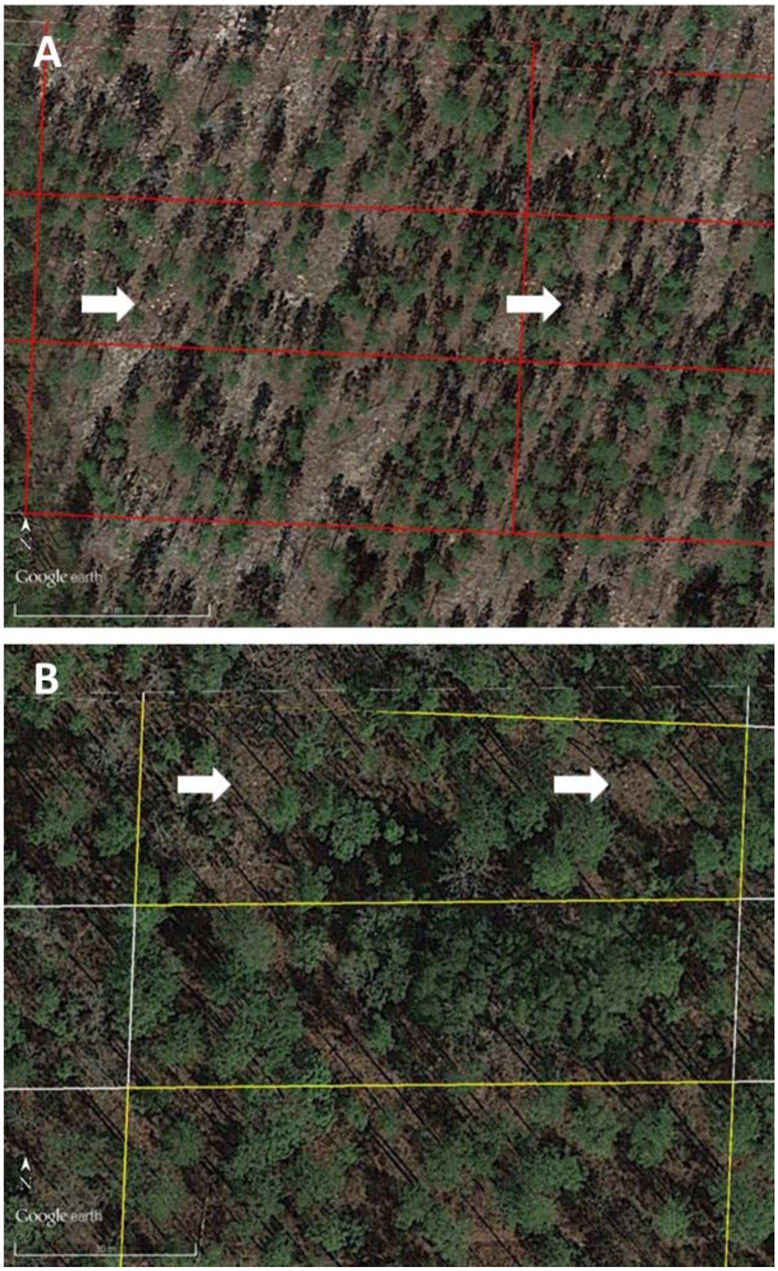
Figure 2.2. Southeastern pocket gophers occupy loamy-sand and sandy-loam soils, especially within the first 20cm of soil. Red circles indicate USDA soil textures of sites occupied by southeastern pocket gophers at three depths. Blue circles indicate sites not occupied by pocket gophers at three depths.

APPENDIX 1.A. MOUND COMPARISON



Appendix 1.A. View from above of southeastern pocket gopher mound vs. red imported fire ant mound. (a) The southeastern pocket gopher mound is easily identified by its fan like shape and loose soil when freshly excavated. (b) The red imported fire ant mounds are easily identified by the presence of ants or ant tunnels.

APPENDIX 1.B. CONDIFENCE DESCRIPTIONS

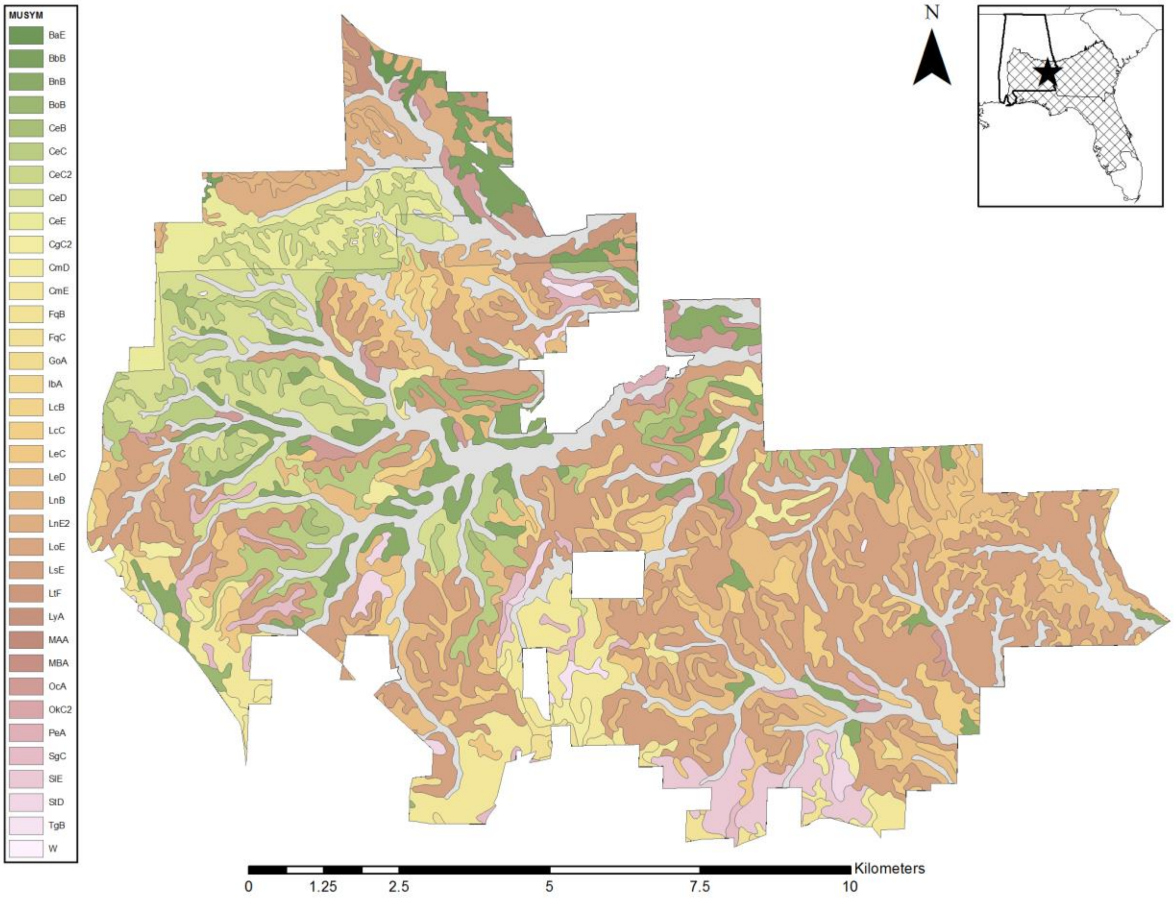


Appendix 1.B. Examples of Google Earth imagery of sites categorized as (A) high confidence detection with mounds clearly visible over a vast extent in both line and mound clusters (white arrows) or (B) low confidence detection with faint or dull marks in the top of the survey grid that could be pocket gopher mounds (white arrows).

APPENDIX 1.C. SITE FLORIDA 8

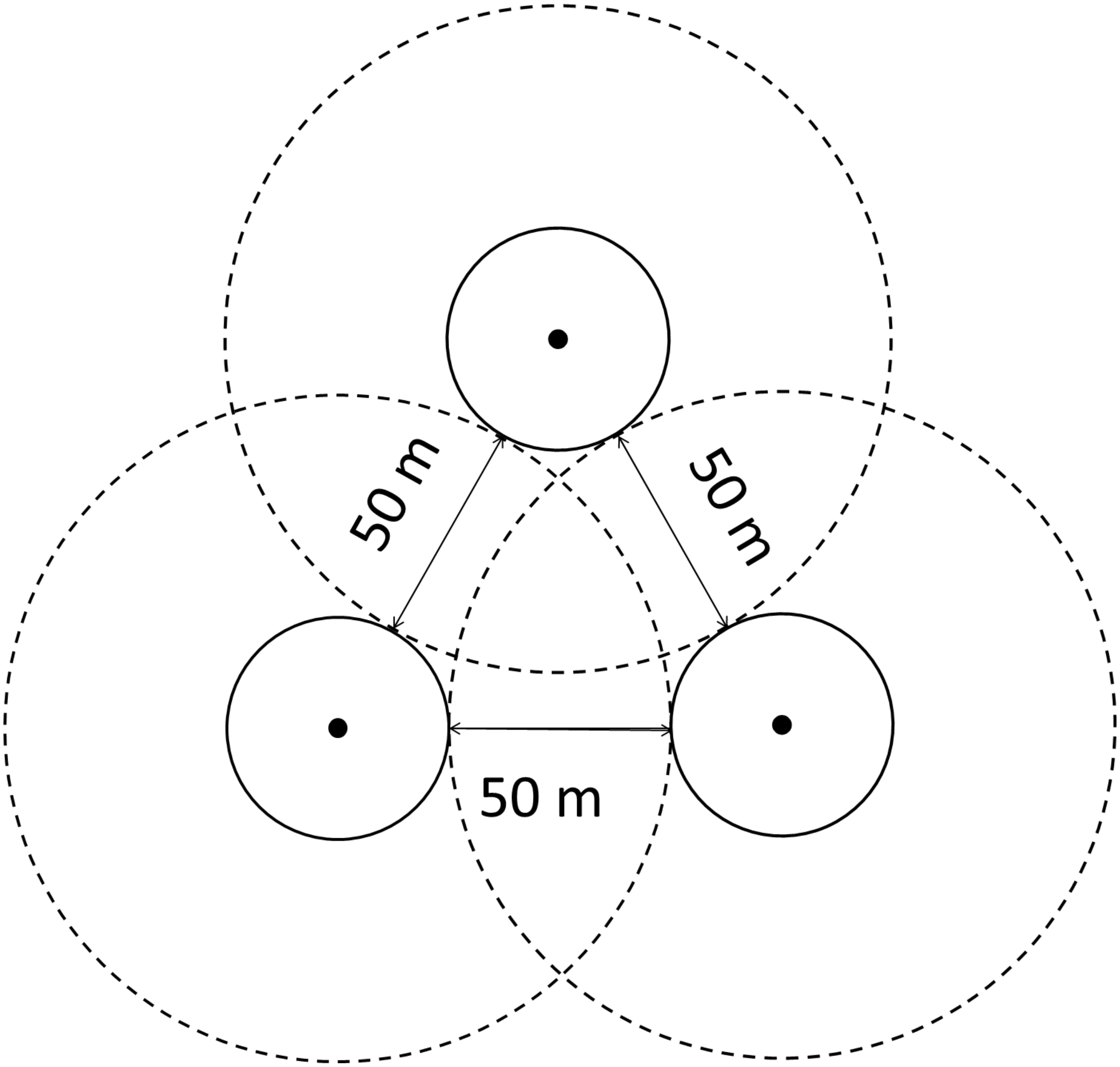
Appendix 1.C. Site Florida 8 (FL8; Belmore State Forest in Clay County, FL). This site had no field detections and had a high-confidence Google Earth Detection. In the image, there are small white patches that form in a line along the roadside and scattered white patches throughout the open field that extend outside of the grid. These formations are indicative of pocket gopher mounding.

APPENDIX 2.A. SOIL DISTRIBUTION MAP



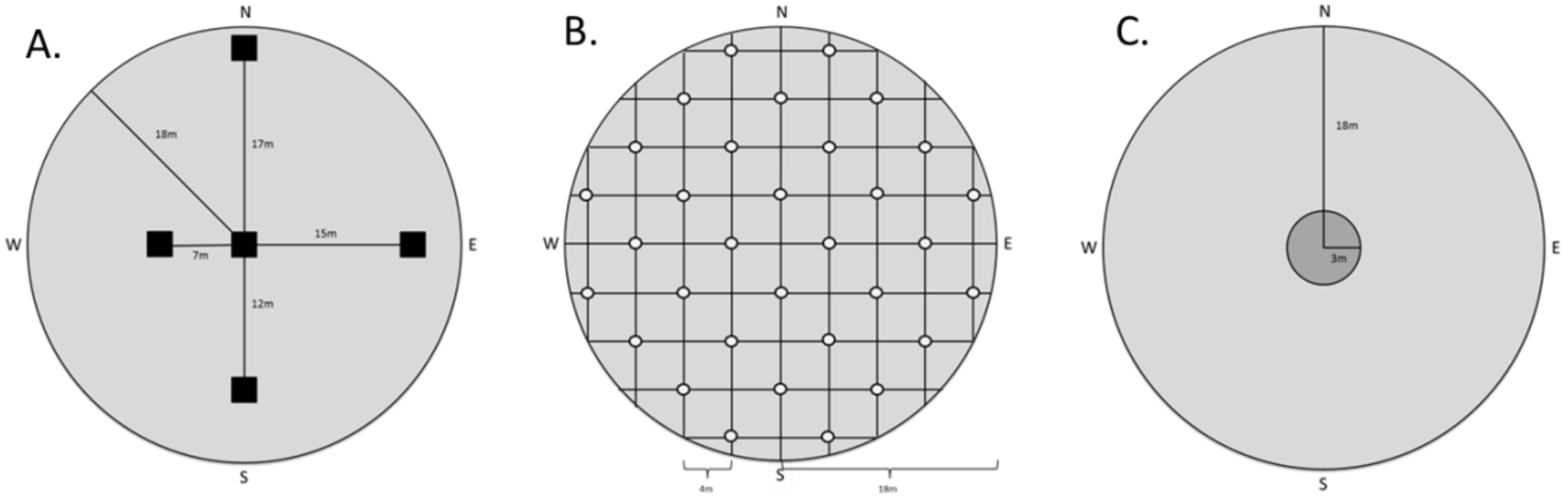
Appendix 2.A. Distribution of soil map-units across Barbour Wildlife Management Area and the Wehle Forever Wild Tract, Barbour and Bullock counties, AL. *BaE=Blanton loamy sand, 8 to 20 percent slopes; BbB=Blanton-Bonifay loamy sands, 2 to 8 percent slopes; BnB=Blanton-Bonneau complex, 0 to 5 percent slopes; BoB=Bonifay loamy sand, 0 to 5 percent slopes; CeB=Conecuh sandy loam, 2 to 5 percent slopes;CeC=Conecuh sandy loam, 5 to 8 percent slopes; CeC2=Conecuh sandy loam, 5 to 8 percent slopes, eroded; CeD=Conecuh sandy loam, 8 to 20 percent slopes; CeE=Conecuh sandy loam, 8 to 20 percent slopes; CgC2=Cowarts loamy sand, 5 to 8 percent slopes, eroded; CmD=Cowarts-Maubila Complex, 8 to 15 percent slopes, flaggy; CmE=Cowarts-Maubila complex, 15 to 25 percent slopes, flaggy; FqB=Fuquay loamy sand, 0 to 5 percent slopes; FqC=Fuquay loamy sand, 5 to 8 percent slopes; GoA=Goldsboro loamy fine sand, 0 to 2 percent slopes; IbA=Iuka-Bibb complex, 0 to 1 percent slopes, frequently flooded; LcB=Lucy loamy sand, 0 to 5 percent slopes; LcC=Lucy loamy sand, 5 to 8 percent slopes; LeC=Luverne sandy loam, 2 to 8 percent slopes; LeD=Luverne sandy loam, 8 to 15 percent slopes; LnB=Luverne loamy sand, 2 to 8 percent slopes;LnE2=Luverne loamy sand, 8 to 20 percent slopes, eroded; LoE=Luverne-Blanton loamy sand, 5-20 percent slopes;LsE=Luverne-Springhill complex, 15 to 45 percent slopes; LtF=Luverne-Blanton-Cowarts complex, 15 to 45 percent slopes; LyA=Lynchburg-Ocilla complex, 0 to 2 percent slopes, rarely flooded; MAA=Mantachie, Kinston, and Iuka soils, 0 to 1 percent slopes, frequently flooded; MBA=Mantachie, Iuka, and Bibb soils, 0 to 1 percent slopes, frequently flooded; OcA=Ocilla loamy fine sand, 0 to 2 percent slopes;OkC2=Oktibbeha clay loam, 3 to 8 percent slopes, eroded; PeA=Pelham loamy sand, 0 to 2 percent slopes; SgC=Springhill loamy sand 5 to 8 percent slopes; SlE=Springhill-Lucy complex, 15 to 25 percent slopes; StD=Springhill-Troup complex, 8 to 15 percent slopes; TgB=Troup-Alaga complex, 0 to 5 percent slopes; W=water

APPENDIX 2.B. SITE SELECTION DIAGRAM



Appendix 2.B. Diagram of how potential occupied sites were selected for sampling on the Barbour Wildlife Management Area and the Wehle Forever Wild Tract, Barbour and Bullock counties, AL in 2015.

APPENDIX 2.C. VEGETATION SAMPLING DIAGRAM



Appendix 2.C. Diagram of vegetation surveys conducted on the Barbour Wildlife Management Area and the Wehle Forever Wild Tract, Barbour and Bullock counties, AL in 2015 illustrating the location of sub plots (A.), the GRS Densitometer hits (B.), and stem counts (C.)

APPENDIX 2.D. ALL FIELD VARIABLES

Variable	Abrv	Unit	Field Description	Field Collection	Lab Methods	
Understory						
Bare Ground	BG	% (0-1)	Percent of bare ground within 5 1-m Quadrat	Ocular Estimation	Average of 5 plots	
Leaf Litter	LL	% (0-1)	Percent of leaf litter within 5 1-m Quadrat	Ocular Estimation	Average of 5 plots	
Pine Straw	PS	% (0-1)	Percent of pine straw within 5 1-m Quadrat	Ocular Estimation	Average of 5 plots	
Forbs	FB	% (0-1)	Percent of forbs within 5 1-m Quadrat	Ocular Estimation	Average of 5 plots	1
Woody Vegetation	WV	% (0-1)	Percent of woody vegetation (shrub + saplings) within 5 1-m Quadrat	Ocular Estimation	Average of 5 plots	1
Woody Weeds	WW	% (0-1)	Percent of woody weeds within 1m Quadrat	Ocular Estimation	Average of 5 plots	
Grass	GR	% (0-1)	Percent of bare grass within 1m Quadrat	Ocular Estimation	Average of 5 plots	1
Saplings	SP	stem/m^2	Percent of sapling stems within a 3m radius	Stem Counts	Total Stem/ $(\pi*3^2)$	
Vine-Shrub	VS	stem/m^2	Percent of viney shrubs (i.e. blackberry) within a 3m radius	Stem Counts	Total Stem/ $(\pi*3^2)$	
NonVine-Shrub	NVS	stem/m^2	Percent of sapling Non-Viney shrubs within a 3m radius	Stem Counts	Total Stem/ $(\pi*3^2)$	1
Total Shrubs	TS	stem/m^2	Percent of all shrub stems within a 3m radius	Stem Counts	Total Stem/ $(\pi*3^2)$	
Total Stems	TST	stem/m^2	Percent of all stems (shrub and sapling) within a 3m radius	Stem Counts	Total Stem/ $(\pi*3^2)$	
Over Story						
Canopy	CC	% (0-1)	Total presence of trees in the Canopy layer	GRS Densitometer	Hits/32	
Pine Canopy	PC	% (0-1)	Presence of Pine in the Canopy	GRS Densitometer	Hits/32	
Hardwood Canopy	HC	% (0-1)	Presence of Hardwoods in the Canopy (>5m)	GRS Densitometer	Hits/32	
Mid-story Canopy	MS	% (0-1)	Presence of mid-story woody stemmed plants (including pines, hardwoods, and large shrubs; 2-5m)	GRS Densitometer	Hits/32	
Shrub Cover	SH	% (0-1)	Presence of shrubs (including saplings; <2m)	GRS Densitometer	Hits/32	
Total Canopy Cover	TO	% (0-1)	Presence of trees in the canopy	GRS Densitometer	Hits/32	2
Basal Area	BA	BA/acre	Cross sectional area of trees at breast height	10 Factor Prism	Hits*10	
Pine Basal Area	BAP	BA/acre	Cross sectional area of pine trees at breast height	10 Factor Prism	Hits*10	2
Hardwood Basal Area	BAH	BA/acre	Cross sectional area of hardwood trees at breast height	10 Factor Prism	Hits*10	2
Soil						
CLAY20		% (0-1)	Clay from depths 0-20cm	Soil Auger - Depth 0-20 cm	Particle Size Determination Via Hydrometer	
SILT20		% (0-1)	Silt from depths 0-20cm	Soil Auger - Depth 0-20 cm	Particle Size Determination Via Hydrometer	
SAND20		% (0-1)	Sand from depths 0-20cm	Soil Auger - Depth 0-20 cm	Particle Size Determination Via Hydrometer	
CLAY60		% (0-1)	Clay from depths 40-60cm	Soil Auger - Depth 40-60 cm	Particle Size Determination Via Hydrometer	
SILT60		% (0-1)	Silt from depths 40-60cm	Soil Auger - Depth 40-60 cm	Particle Size Determination Via Hydrometer	
SAND60		% (0-1)	Sand from depths 40-60cm	Soil Auger - Depth 40-60 cm	Particle Size Determination Via Hydrometer	
CLAY100		% (0-1)	Clay from depths 80-100cm	Soil Auger - Depth 80-100 cm	Particle Size Determination Via Hydrometer	
SILT100		% (0-1)	Silt from depths 80-100cm	Soil Auger - Depth 80-100 cm	Particle Size Determination Via Hydrometer	
SAND100		% (0-1)	Sand from depths 80-100cm	Soil Auger - Depth 80-100 cm	Particle Size Determination Via Hydrometer	

Appendix 2.D. Descriptions of vegetation and soil variables measured within an 18 m radius for sites occupied and unoccupied by southeastern pocket gophers in Barbour and Bullock Counties, AL, 2015.

APPENDIX 2.E. SOIL PROFILES

SOIL Profile	Count	%
LoSa-LoSa-LoSa	18	29.03
LoSa-LoSa-SaClLo	5	8.06
LoSa-SaLo-SaClLo	5	8.06
LoSa-SaLo-SaLo	5	8.06
LoSa-LoSa-SaLo	4	6.45
SaLo-SaLo-LoSa	4	6.45
SaLo-SaLo-SaClLo	4	6.45
SaLo-SaLo-SaLo	4	6.45
LoSa-SaLo-LoSa	3	4.84
LoSa-SaCl-SaClLo	2	3.23
SaLo-LoSa-SaClLo	2	3.23
LoSa-LoSa-SaCl	1	1.61
LoSa-SaClLo-SaCl	1	1.61
SaLo-LoSa-SaClLo	1	1.61
SaLo-LoSa-LoSa	1	1.61
SaLo-SaClLo-SaClLo	1	1.61
SaLo-SaLo-Cl	1	1.61
Total	62	100

Appendix 2.E. Count of unique soil profiles (texture classification for the three depths of soil) of sites occupied by southeastern pocket gophers on Barbour WMA and the Wehle FWT (Barbour and Bullock counties, AL

APPENDIX 2.F. AIC TABLE AT 15% CLAY

Model	**Parameters**	**logLik**	**ΔAICc**	**Wi**
Canopy Cover2 + Canopy Cover	4	-42.56	0.00	0.50
PC1+PC2	4	-43.88	2.66	0.13
Grass + Woody Vegetation	4	-44.04	2.96	0.11
Grass	3	-45.72	4.13	0.06
Woody Vegetation	3	-46.34	5.36	0.03
Hardwood Basal Area	3	-46.67	6.03	0.02
Grass + Non Viney Shrub	4	-45.62	6.12	0.02
Forb +Woody Vegetation	4	-45.65	6.18	0.02
Intercept Only	2	-48.05	6.62	0.02
Woody Vegetation +Non Vine Shrub	4	-46.20	7.30	0.01
Hardwood Basal Area + Pine Basal Area	4	-46.30	7.48	0.01
Canopy Cover	3	-47.59	7.87	0.01
Forbs	3	-47.65	7.98	0.01
Canopy Cover + Hardwood Basal Area	4	-46.65	8.18	0.01
Pine Basal Area	3	-47.91	8.50	0.01
Non Viney Shrub	3	-48.05	8.78	0.01
Canopy Cover + Pine Basal area	4	-47.59	10.07	0.00
Forb + Non Viney Shrub	4	-47.62	10.14	0.00

Appendix 2.F. Variables, number of parameters, Akaike's Information Criterion adjusted for small sample size (AICc), difference between model AICc and the best model for model groups (ΔAICc), and Akaike weight (Wi) for models used to predict the presence of southeastern pocket gophers on Barbour WMA and the Wehle FWT (Barbour and Bullock counties, AL) in 2015. Models take into account a 15% clay threshold within the first 20 cm of soil depth.