HOME RANGE AND HABITAT USE OF FORAGING GRAY BATS *(MYOTIS GRISESCENS)* FROM FIVE MATERNITY SITES IN NORTHERN ARKANSAS

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ABSTRACT

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HOME RANGE AND HABITAT USE OF FORAGING GRAY BATS *(MYOTIS GRISESCENS)* FROM FIVE MATERNITY SITES IN NORTHERN ARKANSAS

Gray bats (*Myotis grisescens*) were listed as endangered in 1976 because of declining populations resulting from cave disturbance. The Gray Bat Recovery Plan recommends further study on foraging habits and home range. Yet, few data exist partly because gray bats have large home ranges, making ground-based tracking methods problematic. Accordingly, the objective was to assess gray bats' foraging habits using aerial tracking. In 2014-2015, five maternity sites in Arkansas were harp-trapped, and 112 adult reproductive female gray bats were radio-tracked from a Cessna 182 Skylane, gathering 1,293 time-independent locations from June 15-July 15. Fixed-kernel density with least square cross validation was used to determine home range (95% of locations), core-foraging area (50% of locations), and Minimum Convex Polygon of a sub-sample of 42 individuals with ≥15 independent locations. In 2014, mean 95% home range was 362.2 km² (SE= 24.9 km²), and 50% core-foraging was 83.2 km² (SE= 25.2 km²). In 2015, mean 95% home range was 57.9 km² (SE=8.6 km²), and 50% core-foraging was 13.0 km² (SE= 2.2 km²). A compositional analysis revealed that female gray bats traveled and foraged over water proportionally more than expected based on availability across the landscape when compared to other habitat types. With such large home ranges, management strategies for gray bats should go beyond protecting roost sites to include waterways and riparian areas for travel and foraging on sensitive aquatic insect species.

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1 st Chapter: General Introduction

1.1 Impacts of Threats to Bat Populations

Bats are vitally important within ecosystems they inhabit due to their roles in nutrient cycling and pest control. Insect consumption by foraging bats reduces pest loads on agriculture and natural environments (Kunz et al. 2011). Bat guano enhances N_2 mineralization in forests (Duchamp et al. 2010) and supports hundreds of imperiled, cave-obligate species such as the Ozark blind cave fish (*Amblyopsis rosae*; Willis and Brown 1985). Furthermore, bats are also prey items for predators such as owls, snakes and other small mammals.

There are nine endangered species of bats in the United States, of which four are cavernicolous (i.e., roost or hibernate in caves). Bats are sensitive to habitat fragmentation, threatened by public misunderstanding (Tuttle 1979, McCracken 1989), and cave species are susceptible to human disturbance. Specifically, bats enter torpor during winter and disturbance triggers arousal, requiring precious energy. Therefore, colonies hibernating in caves suffer from high mortality rates in disturbed caves due to unplanned arousals from torpor hence depleting fat reserves. Protecting caves and managing forested landscapes have increased bat numbers in many species (Hayes and Loeb 2007), from historical lows in the mid-2000s. However, the fungus *Pseudogymnoascus* (basionym = *Geomyces) destructans,* causing white-nose syndrome

(WNS), discovered in 2006 in New York has been spreading north and southwest. It has been decimating bat populations in caves where found. In addition, wind energy facilities, which are increasing in number, have contributed to increasing bat fatalities (Hayes 2013).

WNS currently affects seven bat species in 23 states and three Canadian provinces. This fungal cutaneous disease develops primarily on cave bat wing tissue during torpor and is transmitted through physical bat-to-bat contact and human intrusion of caves. WNS causes wing damage, abnormal arousals, starvation and dehydration (Cryan et al. 2010, 2013; Willis et al. 2011; Warnecke et al. 2012, 2013). Cave mortality ranges from 75-98% within a few years following introduction (Turner et al. 2011, Frick et al. 2010). It is estimated that up to 7 million bats have already died of WNS in the United States and Canada (USFWS 2012). Methods capable of protecting these populations while they slowly recover from human disturbance are vital to the longevity of at least four imperiled species in the eastern United States (i.e., *Perimyotis subflavus, Myotis lucifugus, M. sodalis,* and *M. grisescens*).

1.2 Gray Bat Population and Listing Status

Myotis grisescens, the gray bat, is a cave obligate, migratory species listed as federally endangered since 1976 (Federal Register 1976) under the Endangered Species Act (Brady 1982). Numbers began to recover from historical lows in the mid-twentieth century, and in 2006, *Myotis grisescens* was considered for de-listing (unpublished). However, this species is susceptible to WNS and because it occurs in the largest aggregations of any eastern cave species, its loss could create a domino effect of failing cave ecosystems and overabundant insect populations. Although crucial, little is known about their migration routes (Arkansas Wildlife Action Plan 2006) and foraging habitat requirements, primarily because they are highly mobile and difficult to track. While protecting caves and managing public land are standards in today's conservation practices, bats often use entire landscapes and waterways affected by industry and flood control (LaVal et al. 1977). Therefore, identifying areas primarily used by gray bats for foraging is crucial to assist in developing adequate management plans.

1.3 Gray Bat Biology

1.3.1 Description

Gray bats are gray to chestnut brown, generally, and weigh between 7-14 g, with a typical male at 8 g. Females are generally heavier, at 8-12 g. Forearm length ranges from 40-47 mm (USFWS 1997). Gray bats can migrate up to 500 km from summer roosting caves to winter hibernacula (Mitchell and Martin 2002).

1.3.2 Status and Threats

Gray bats are found in the limestone karst region of the eastern United States (Figure 1.1). Wintering populations use hibernacula in Alabama, Arkansas, Missouri, Tennessee, and Kentucky (Harvey 1992). Summer ranges extend into Kansas, Oklahoma, Virginia, North Carolina, Illinois, Indiana, and Florida (Mitchell and Martin 2002; Figure 1.1).

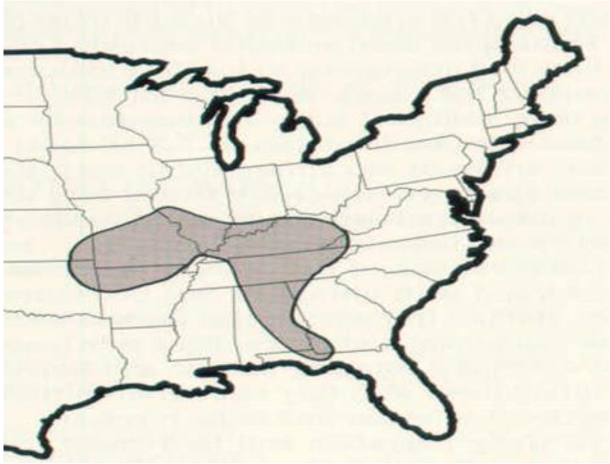


Figure 1.1. Geographic range of *Myotis grisescens,* inhabiting the eastern karst regions of states highlighted within the boundary (A.H. Howell 1909).

Current population estimates are around 2.3 million individuals (Mitchell and Martin 2002). The population was thought to have declined from two million in the 1960s to approximately 293,000 individuals in 1970 (Tuttle 1979). Human disturbance has been cited as a major reason for population decline from historical highs. According to data published over the last 30 years, most of the population hibernates in one of 9-15 caves located in karst limestone regions throughout the eastern United States (Harvey 1976). These are Priority 1 hibernacula (i.e., hosting more than 50,000 individuals), and account for 95% of the hibernating population (Tuttle 1979, Elder and Gunnier 1978). With so few caves, the potential effect for mass mortality caused by human intrusion is high.

When a bat is disturbed from torpor, by noise or physical contact, it responds by increasing its body temperature and heart rate. This increases calorie consumption, depleting fat reserves by 0.001-0.005 g in a bat of 8-12 g, at a time of year when food supplies are minimal. This can have detrimental effects over a long winter (Speakman et al. 1991, Boyles and Brack 2009). Since the use of cave gates and the general exclusion of human disturbance during hibernation and reproductive seasons, the population recovered over the next 35 years. Gray bat populations increased by significant margins, with 82% of maternity colonies showing significant increases in the western portion of the range (Sasse et al. 2007).

Though the population has recovered throughout its range, returning to the historical levels of the 1960s, its continued listing was brought about by the spread of WNS (Tuttle 1979). In 2012, WNS was found on tri-colored bats (*Perimyotis subflavus*) at Alabama's Fern Cave, home to over one million hibernating gray bats. The same year, the fungus was found on gray bats in Hawkins and Montgomery counties in Tennessee. Migratory behavior may cause widespread dispersal of *P. destructans*, which may trigger catastrophic population decline.

Another threat to gray bats is degradation of riparian zone and waterways on which these bats rely for food sources. Gray bats consume aquatic insect taxa such as Ephemeroptera and Plecoptera that are sensitive to pollution and sedimentation (Mitchell and Martin 2002). Bats also consume less sensitive taxa such as Lepidoptera and Diptera (Best et al. 1997). This, coupled with cave disturbance and WNS, could impact the population catastrophically. It is thus more important than ever to understand the foraging behavior of gray bats, especially in maternity colonies, to protect core areas from habitat degradation. While we may not be able to mitigate the impact of WNS, we can promote the longevity of the species by developing adequate conservation strategies.

Increased use of alternative energy has led to growing use of wind turbines across the landscape. A study by Hayes (2013) estimates mortality of 600,000 to 900,000 bats per year. This is issue affecting numerous species of migrating bats. However, no associated gray bat mortality has been recorded to date.

1.3.3 Life History

Gray bats usually enter hibernation in late October-early November. Females enter first, followed by males and juveniles, respectively (Elder and Gunier 1981). This coincides with the seasonal drop in insect activity. Hibernation occurs after the fall “swarm”, where sexually mature bats (2 years or more) copulate (Tuttle 1976a). Sperm is held over winter by the female in a strategy known as delayed fertilization. Clustering aids in the reduction of calorie loss through thermoregulation.

Hibernation caves usually consist of deep vertical caves that act as cold air traps (6-11° C; Tuttle 1979) to allow for an easy drop into torpor, conserving energy for winter. Normal arousal occurs several times throughout the winter, which is a behavior that restarts the immune system. Arousal is often triggered by evaporative water loss (Jonasson and Willis 2012). During this time, males may sneak copulations, and bats may move to several separate locations within the cave.

Gray bats emerge from late March onwards into May. Females emerge first, migrating to areas with suitable maternity caves. Highest mortality occurs at this time due to depleted fat reserves and high energy demand from migration (Tuttle and Stevenson 1977). During migration, females fertilize their eggs using sperm held since the fall. Reproductive females form maternity colonies just before parturition, generally in late May. After a gestation period of 60-70 days, young are usually born in late May to mid-June (Tuttle 1976b, Saugey 1978). A single pup is born to each female. The period until young are volant is usually 20-25 days. However, this rearing period is usually longer (30-35 days) in caves with disturbance. Distance to water, and therefore foraging grounds, may play a role in the survivorship of newly volant young (Tuttle 1976a).

Males and females migrate to what is considered a summer roosting complex. They may migrate as far as 500 km between summer roosting sites and winter hibernacula (Tuttle 1976b). These systems of cave roosts and foraging areas can be up to 70 km long (LaVal et al. 1977). This complex usually consists of a maternity cave and several caves occupied by males and non-reproductive females, with a few to tens of thousands of individuals (Sasse et al. 2007). Again, summer caves are warmer to marginalize the cost of thermoregulation.

Warmth is especially important in maternity roosts, where temperature may play a role in the amount of time it takes a pup to become self-sufficient. Therefore, in summer, gray bats prefer caves that possess dome-shaped ceilings, with warmer temperatures (14-25° C), acting as warm air traps (Brady 1982). They will also select for caves with running water for drinking and ridding of waste (Mitchell and Martin 2002).

Females often use back-up maternity roosts if the main roost is disturbed (Tuttle 1976b). Solitary males and non-reproductive females may change caves often, with several night roosts being common. These stopover sites are usually shallow and warm, occupied by just a few individuals. In short, these bats are highly mobile within a single cave and within a summer roosting complex.

1.3.4 Foraging Behavior

Bats in summer colonies have individual foraging preferences. Tuttle (1976a) observed more gray bats of a single colony moving to forage downstream, perhaps for larger pools in the river. Another group flew towards the obvious waterway 1 km away, while the rest of the colony moved overland 10 km to a separate river system (Tuttle 1976a). It is thought that movement either upstream or downstream is dependent on Ephemeroptera hatches (Tuttle 1976b).

Reproductive female gray bats, as with many species investing in parental care, are central place foragers, emerging and making a round trip back to the colony by daylight (Rosenberg and McKelvey 1999). Sometimes, there are stopover roosts in-between feeding bouts. However, lactating females must return to the roost site to feed their young. Likelihood of foraging decreases with distance, as the roost is often chosen with prime foraging grounds nearby (Orians and Pearson 1979). The cost of daily, round-trip energy expenditure is biologically justifiable in reproductive females, which is necessitated by offspring at the roost. Roost sites provide favorable conditions for rearing pups and maintaining thermo-neutrality (daily torpor) with less energy loss than elsewhere in the environment. Males and non-reproductive females use multiple roosts (Tuttle 1976b). They do not possess the same energy budgeting needs of reproductive females, making night roosts a matter of convenience. This conserves energy by not making long, round-trip flights.

Lactation is the most energetically expensive time in a mammal’s life cycle (Bronson 1985) and females will feed young milk several days after they are able to fly, a behavior that may aid in survival as they learn to forage (Tuttle 1976a). Females forage intensively, sometimes up to seven hours continuously, towards the end of the rearing period (Brady 1982). When insects are abundant during the first two hours after sunset, females can forage over water in groups of up to 15 individuals, feeding relatively slowly (up to 12 km/h; Brady 1982, LaVal et al. 1977). When insect activity drops, females exhibit territoriality, with non-reproductive females or males being chased away from these foraging locations (Goebel 1996). Gray bats generally forage over water, and have historically been observed in areas with high mayfly abundance (Tuttle 1979). Foraging height is typically 2-5 m (LaVal et al. 1977). One study found large amounts of Lepidopteran and Dipteran insect parts in fecal pellets, suggesting a broad and opportunistic diet based on availability (Best et al. 1997).

Foraging distance may coincide with insect abundance in general, rather than specific types. While many gray bats forage over pools in flowing water or over reservoirs, some were found to forage in riparian areas, field edges, and forested blocks. “Wetland depressions”, ephemerally flooded areas in forest and fields, have also been documented as a heavy use area in Tennessee (Lamb 2000, Mitchell and Martin 2002). When emerging, bats usually fly under the cover of trees to avoid predation on the way to foraging grounds. Gray bats can forage up to 70 km from roost sites (LaVal et al. 1977) within a home range of 97 km^2 (Thomas and Best 2000). This extensive foraging range may be a behavioral response to the differential hatching schedule of various aquatic insect emergences.

Distance to water is perhaps the most important aspect of cave choice in gray bats. Summer roosts for all gray bats are rarely over 1 km from a body of water; few were ever found more than 4 km from a body of water (Tuttle 1976a, Tuttle 1976b, Stevenson and Tuttle 1981). This allows quick access to foraging ground without extensive travel overland, where owl predation can occur.

1.3.5 Maternity Colonies

Major winter hibernacula have been adequately protected as a stipulation of the Gray Bat Recovery Plan (USFWS 1982). However, summer maternity colonies, in cave systems or manmade structures such as large storm drains (Mitchell and Martin 2002, Timmerman and McDaniel 1992), are greater in number, as bats disperse from the few winter caves. Females will aggregate in populations of several thousands to over 50,000 (Priority 1 maternity colony) individuals (Tuttle 1974). Protection for these smaller roosts is lacking due to the logistics of monitoring hundreds of caves. Usually, only lactating females with pups join the main aggregation within the maternity colony. Pregnant and post-lactating females may join smaller bachelor colonies in smaller caves throughout the summer roosting complex. (Harvey 1976). Maternity colonies form from late May to mid-June, and break up mid- to late July. Females usually join the colony from which they migrated as pups (Harvey 1976). The aggregation promotes thermoregulation and cluster protection from predators (Tuttle 1979).

Protecting gray bat maternity colonies is as important as protecting winter hibernacula and is possible via cave gates and monitoring (Sasse et al. 2007). Young pups are susceptible to disturbance, human or predator, and can easily fall from the ceiling when disturbed (Tuttle 1974). Most of these bats die from starvation or drown in running water, usually present in maternity caves. In addition, pups can take longer to mature when stressed (Tuttle 1976a). As lactation is the most energetically demanding time in the life of a mammal, foraging behavior of lactating females is an important aspect to consider when constructing a plan of habitat management, such as water quality protection within a specified distance from a maternity colony (Mitchell and Martin 2002).

1.4 Aerial Radio-tracking

Radio-telemetry provides valuable animal movement data. Some animals that are difficult to track can be fitted with GPS (global positioning system) units; however, GPS platforms are heavy. As a unit cannot exceed 5% of an animal's total body weight, VHF (very high frequency) transmitters remain the only current option with which to track bats. This requires tracking in the field while the individual is moving (Mech and Barber 2002). For species with small home ranges, locations can be estimated from the ground. However, highly mobile species often travel well out of receiver range for ground-based telemetry to be suitable. In these instances, some bats and birds are tracked with higher accuracy using aerial techniques than with ground-based methods (Marzluff et al. 1994).

Aerial techniques have evolved to satisfy requirements of estimating a precise location of birds and large mammals (Kunkel et al. 2005). Dual Yagi antennas, one mounted on each plane wing, give a directional representation of signal strength. A toggle switch is used to activate either Yagi or both at once. Higher signal strength on one side alludes to the target's directionality. Some search patterns use grids, turning into the signal with a spiral, until the signal's strength is the same on both sides (Seddon and Maloney 2004). At this time, the target is directly below the plane and a precise location can be recorded. In linear searches, flying a sigmoidal pattern allows the searcher to plot locations as the target is flown over, without turning into the signal (Whitehouse and Steven 1977), which allows for multiple individuals to be located in a limited time frame.

Only two radio-telemetry studies have been performed with gray bats. The first used light tags and observers, both on the ground and in a helicopter, to observe distance traveled and habitat types used while foraging (LaVal et al. 1977). The second used ground-based radio-telemetry to track gray bats at a reservoir in Alabama (Thomas and Best 2000). Both found that ground-based methods were inadequate to successfully track gray bats that have large home ranges, travel long distances, and fly quickly through mountainous terrain. As a result, tracking by fixed-wing aircraft might a better option.

1.5 Statement of the Problem

Myotis grisescens is a federally protected species which has recovered from large population declines in the 1960s by protecting major hibernacula. However, the recent occurrence of WNS in the range of the gray bat warrants closer scrutiny into their foraging and ecology for better habitat management; primarily minimizing and restoring riparian degradation.

Information on the foraging ecology of gray bats is lacking (Mitchell and Martin 2002). In addition, some of the unaddressed fundamental objectives of the Gray Bat Recovery Plan include the determination of baseline information on foraging behavior and home range size, which is crucial for the continuation of the recovery process. The study of foraging and home range for a given population is necessary to gain a comprehensive understanding of a species' life history, which can be used for better management practices.

This research study provides baseline understanding of gray bat foraging behavior and home range. During this two-year study, 112 lactating female gray bats were tracked along two distinct river systems in northern Arkansas (i.e., White River and Illinois River). Because ground-based telemetry has proved ineffective, bats were tracked from fixed-wing aircraft for up to six hours after emergence. The results of this study will serve management agencies to protect or improve existing habitat, work with private landowners to improve buffer habitat, or monitor likely locations of presence to determine population fluctuations (Ober et al. 2012). In addition, the Illinois River Watershed Partnership, which works to restore the catchment area and educate the public, can serve as a model for water quality protection and riparian restoration.

1.6 Specific Objectives

My goal was to better understand the foraging ecology and landscape use of gray bats, specifically reproductive females, which exhibit the most complex behavior during the active season. My specific objectives were as follows:

Objective 1. Determine the feasibility of using aerial radio-telemetry to track nightly foraging bouts of adult female gray bats.

Gray bats fly to foraging locations that have been recorded up to 70 km away from a roost site in a linear fashion (Tuttle 1976a). They seem to have home ranges too large for traditional ground-based telemetry methods. I hypothesized aerial telemetry to be more appropriate to radio-track long distance foragers like gray bats, especially in mountainous terrain.

Feasibility could be assessed by the number of locations garnered for each individual. If more than 10 individuals are tracked per site, with adequate locations to perform fixed-kernel density and classification-based modeling (15 or greater), then fixed-wing tracking of gray bats could be noted as a more adequate, cost-effective, and precise method than ground-based telemetry or light-tagging in regards to gray bat foraging.

Objective 2. Determine home range size of reproductive adult female gray bats.

Previous ground-based telemetry studies were limited by sample size (i.e., number of individuals and locations, being of equal importance) (Seaman et al. 1999). Using locations gained from aerial tracking, home range could be determined on a landscape scale using fixed-kernel density (Worton 1987). A study by Thomas and Best (2000) concluded the minimum home range of a non-reproductive gray bat to be 97 km². As reproductive females must care for young on a nightly basis, I predicted a smaller minimum home range than 97 km².

Objective 3. Characterize foraging ecology of reproductive adult female gray bats.

Gray bats are typically associated with over-water feeding, where insect abundance is high (Best et al. 1997). They usually follow large waterways as their primary foraging habitat (Laval et al. 1977, Thomas and Best 2000). Previous studies and netting records have shown gray bats foraging over smaller order streams as well as main waterways. In addition, they forage over fields, in forests, in wetlands, and riparian areas (Lamb 2000, Mitchell and Martin 2002).

Distance traveled (energy expenditure) is expected to be a function of food availability. Where gray bats forage can be an indicator of insect abundance and preference. If food is scarce, females may be forced to forage further, and reproductive demands may lead to increased foraging times (Tuttle 1976a). This would coincide with heavier milk demand from larger pups. Distance to water and insect abundance affect the size and survival probability of pups, which is typically 50% (Tuttle 1974).

1.7 Literature Cited

Arkansas wildlife action plan. 2006. *Arkansas Game and Fish Commission*.

Best, T.L. and Hudson, M.K. 1996. Movements of gray bats (Myotis grisescens) between roost sites and foraging areas. *Journal of the Alabama Academy of Science*. 67: 6-14.

Best, T.L., Milam, B.A., Haas, T.D., Cvilikas, W.S., and Saidak, L.R. 1997. Variation in diet of the gray bat (Myotis grisescens). *Journal of Mammalogy*. 78: 569-583.

Boyles, J.G. and Brack Jr., V.2009. Modeling survival rates of hibernating mammals with individual-based models of energy expenditure. *Journal of Mammology*. 90: 9-16.

Brady, J. 1982. Gray bat recovery plan. *The Service*.

Bronson, F.H. 1985. Mammalian reproduction: an ecological perspective. *Biology of reproduction*. 32: 1-26.

Cryan, P.M., Meteyer, C.U., Blehert, D.S., Lorch, J.M., Reeder, D.M., Turner, G.G., Webb, J., Behr, M., Verant, M., Russell, R.E., and Castle, K.T., 2013. Electrolyte depletion in white-nose syndrome bats. *Journal of Wildlife Diseases*. 49:398-402.

Cryan, P.M., Meteyer, C.U., Boyles, J.G., Blehert, D.S. 2010. Wing pathology of white-nose syndrome in bats suggests life-threatening disruption of physiology. *BMC biology*. 8: 135.

Duchamp, J.E., Sparks, D.W., and Swihart, R.K. 2010. Exploring the “nutrient hot spot” hypothesis at trees used by bats. *Journal of Mammology*. 91: 48-53.

Elder, W.H. and Gunier, W.J. 1981. Dynamics of a gray bat population (*Myotis grisescens*) in Missouri. *American Midland Naturalist*. 105: 193-195.

Federal Register. 1976. Title 50: determination that two species of butter flies are threatened species and two species of mammals are endangered species. 41:83: April 28.

Frick, W.F., Pollock, J.F., Hicks, A.C., Langwig, K.E., Reynolds, D.S., Turner, G. G., and Butchkowski, C.M. Kunz, T. H. 2010. An emerging disease causes regional population collapse of a common North American bat species. *Science*. 329: 679-682.

Goebel, A.B. 1996. Temporal variation in movement patterns of adult female *Myotis grisescens* (Chiroptera: Vespertilionidae). Master’s Thesis, Auburn University, Auburn, AL.

Harvey, M.J. 1976. Homing of gray bats, *Myotis grisescens*, to a hibernaculum. *American Midland Naturalist.* 96: 497–498.

Harvey, M.J. 1992. Bats of the eastern United States. *Kentucky Department of Fish and Wildlife.*

Hayes, M.A. 2013. Bats killed in large numbers at United States wind energy facilities. *BioScience*. 63: 975-979.

Howell, A.H. 1909. Species description of the gray bat (*Myotis grisescens*).

Jonasson, K.A. and Willis, C.K. 2012. Hibernation energetics of free-ranging little brown bats. *The Journal of Experimental Biology*. 215: 2141-2149.

Kunkel, K., Mack, C.M., and Melquist, W.E. 2005. An assessment of current methods for surveying and monitoring wolves. *Nez Perce Tribe, Lapwai, Idaho, USA*.

Kunz, T.H, Braun de Torrez, E., Bauer, D., Lobova, T., and Fleming, T.H. 2011. Ecosystem services provided by bats. *Ann NY Acad Sci*. 1223:1.

Lamb, J.W. 2000. "Section 10 permit number SA 97-34 annual report for *Myotis grisescens* and *Myotis sodalis* on Arnold Air Force Base/ Arnold Engineering Development Center (AEDC)", Unpublished Report, ASC Environmental Services, Conservation, Arnold Air Force Base, TN

LaVal, R.K., Clawson, R.L., LaVal, M.L., and Caire, W. 1977. Foraging behavior and nocturnal activity patterns of Missouri bats, with emphasis on the endangered species *Myotis grisescens* and *Myotis sodalis*. *Journal of Mammalogy*. 58: 592-599.

Marzluff, J.M., Vekasy, M.S., and Coody, C. 1994. Comparative accuracy of aerial and ground telemetry locations of foraging raptors. *The Condor.* 96: 447–454.

McCracken, G.F. 1989. Cave conservation: special problems of bats. *NSS Bulletin.* 51: 49-51.

Mech, L.D. and Barber, S.H. 2002. A critique of wildlife radio-tracking and its use in national parks. A report to the U.S. National Park Service.

Mitchell, W.A. and Martin, C.O. 2002. *Cave-and Crevice-Dwelling Bats on USACE Projects: Gray Bat (Myotis grisescens)* (No. ERDC-TN-EMRRP-SI-25). Engineer Research and Development Center Vicksburg, MS.

Ober, H.K., Hayes, J.P., Press, A., and Hall, R. 2012. Influence multiple of vegetation spatial scales on bat use of riparian. *The Journal of Wildlife Management.*72: 396–404.

Orians, G.H. and Pearson, N.E. 1979. On the theory of central place foraging. *In Analysis of ecological systems*. Ohio State University press, Columbus, Ohio. p.155-177.

Rosenberg, D.K. and McKelvey, K.S. 1999. Estimation of habitat selection for central-place foraging animals. *The Journal of wildlife management*. 63: 1028-1038.

Sasse, D.B., Clawson, R.L., Harvey, M.J., and Hensley, S.L. 2007. Status of populations of the endangered gray bat in the western portion of its range. *Southeastern Naturalist.* 6: 165–172.

Saugey, D.A. 1978.Reproductive biology of the gray bat, *Myotis grisescens*, in north-central Arkansas. Master's Thesis, Arkansas State University, Jonesboro, AR.

Seaman, D.E., Millspaugh, J.J., Kernohan, B.J., Brundige, G.C., Raedeke, K.J., and Gitzen, R.A. 1999. Effects of sample size on kernel home range estimates. *The Journal of Wildlife Management.* 63: 739-747.

Seddon, P.J. and Maloney, R. 2004. Tracking wildlife radio-tag signals by light fixed-wing aircraft. Wellington, New Zealand: Department of Conservation.

Stevenson, D.E. and Tuttle, M.D. 1981. Survivorship in the endangered gray bat (Myotis grisescens). *Journal of Mammalogy*. 62: 244-257.

Speakman, J.R., Webb, P.I., and Racey, P.A. 1991. Effects of disturbance on the energy expenditure of hibernating bats. *Journal of Applied Ecology*. 28: 1087-1104.

Thomas, D. P. and Best, T. L. 2000. Radiotelemetric assessment of movement patterns of the gray bat (*Myotis grisescens*) at Guntersville reservoir, Alabama. *Occasional Papers of the North Carolina Museum of Natural Sciences and the North Carolina Biological Survey*. 12: 27-39.

Timmerman, L., and McDaniel, V.R. 1992. A maternity colony of gray bats in a non-cave site. *Arkansas Academy of Science.* 46: 108-109.

Turner, G.G., Reeder, D., Coleman, J.T.H. 2011. A five-year assessment of mortality and geographic spread of White-Nose Syndrome in North American bats, with a look to the future. Update of White-Nose syndrome in bats. *Bat Research news.* 52: 13-27.

Tuttle, M.D. 1974. Population ecology of the gray bat (*Myotis grisescens*): factors influencing early growth and development. *Occasional Papers of the Museum of Natural History, University of Kansas.* 36: 1-24.

Tuttle, M.D. and Stevenson, D.E. 1977. An analysis of migration as a mortality factor in the gray bat based on public recoveries of banded bats. *American Midland Naturalist*. 97: 235–240.

Tuttle, M.D. 1976(a). Population ecology of the gray bat (*Myotis grisescens*): factors influencing growth and survival of newly volant young. *Ecological Society of America 57*: 587–595.

Tuttle, M.D. 1976(b). Population ecology of the gray bat (*Myotis grisescens*): philopatry, timing, and patterns of movement, weight loss during migration, and seasonal adaptive strategies. *Museum of Natural History, University of Kansas*. Volume 54.

Tuttle, D.M. 1979. Status, causes of decline, and management of endangered gray bats. *The Journal of Wildlife Management.* 43: 1-17.

United States Fish and Wildlife Service. 1982. Gray bat recovery plan. United States Fish and Wildlife Service, Washington, DC.

United States Fish and Wildlife Service. 1997. Gray bat fact sheet (*Myotis grisescens*). http://www.fws.gov/midwest/Endangered/mammals/grbat_fc.html

United States Fish and Wildlife Service. 2012. White-nose syndrome: The devastating disease of hibernating bats in North America. *white-nose_fact_sheet_9-2012_0.pdf.*

Warnecke, L., Turner, J.M., Bollinger, T.K., Lorch, J.M., Misra, V., Cryan, P.M., Wibbelt, G., Blehert, D.S., and Willis, C.K. 2012. Inoculation of bats with European Geomyces destructans supports the novel pathogen hypothesis for the origin of white-nose syndrome. *Proceedings of the National Academy of Sciences*. 109: 6999-7003.

Warnecke, L., Turner, J.M., Bollinger, T.K., Misra, V., Cryan, P.M., Blehert, D.S., Wibbelt, G., and Willis, C.K. 2013. Pathophysiology of white-nose syndrome in bats: a mechanistic model linking wing damage to mortality. *Biology letters*. 9: 20130177.

Whitehouse, S. and Steven, D. 1977. A technique for aerial radio tracking. *The Journal of Wildlife Management*. 41: 771-775.

Willis, C.K., Menzies, A.K., Boyles, J.G., and Wojciechowski, M.S. 2011. Evaporative water loss is a plausible explanation for mortality of bats from white-nose syndrome. *Integrative and Comparative Biology*. p.icr076.

Willis, L.D. and Brown, A.V. 1985. Distribution and habitat requirements of the Ozark cavefish, Amblyopsis rosae. *American Midland Naturalist*. 114: 311-317.

Worton, B.J. 1987. Kernel methods for estimating the utilization distribution in home-range studies. *Ecolog*

2nd Chapter: Methods

2.1 Study Sites

Four gray bat maternity colonies in or adjacent to the Ozark Plateau, northern Arkansas (Figure 2.1) were originally selected for study in the 2014-2015 maternity seasons, but after the 2014 field season, with funding from the Arkansas Natural Heritage Commission, a fifth site was added for the 2015 season.

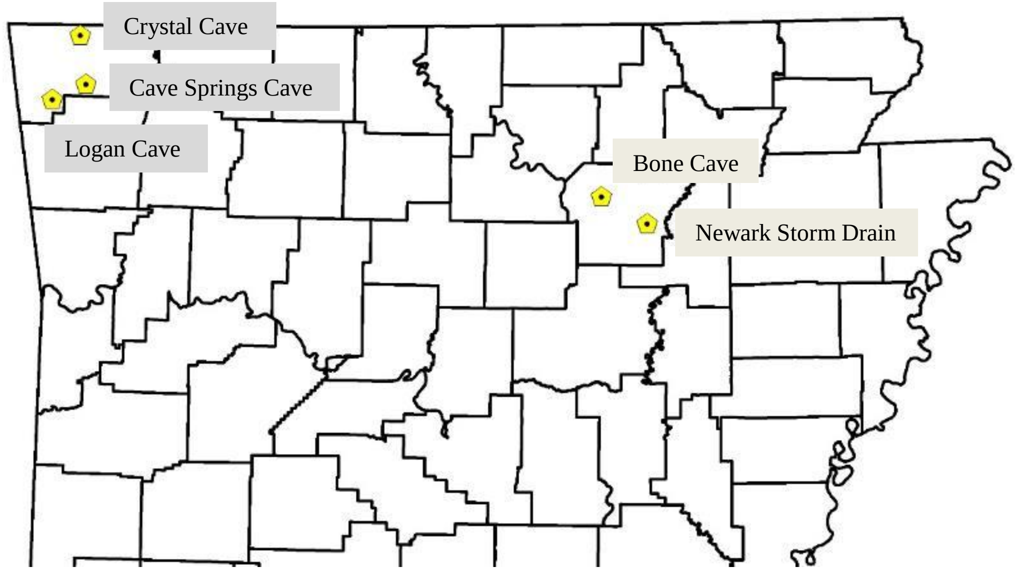


Figure 2.1. Gray bat maternity colony sites selected for study across northern Arkansas. Light gray labels represent 2014 sites, whereas dark gray indicates 2015 caves.

The five sites differ in their surrounding landscape and colony size (Table 2.1). Newark storm drain, located in downtown Newark, Independence County, was monitored starting on 15 June 2014, whereas trapping at Bone cave, 7.8 km northwest of Batesville in the same county, occurred on 1 July 2014. Both sites are in the Ozark foothills region in north-central Arkansas. Between the sites, foothills transition into delta farmland. Both sites are located near the White River, which is the major drainage of the Ozark and Springfield plateaus. In addition, the Black River, also considered a large low-order river, drains into the White River south of Newark, AR. Distance between the two caves is ~26 km (Figure 2.2).

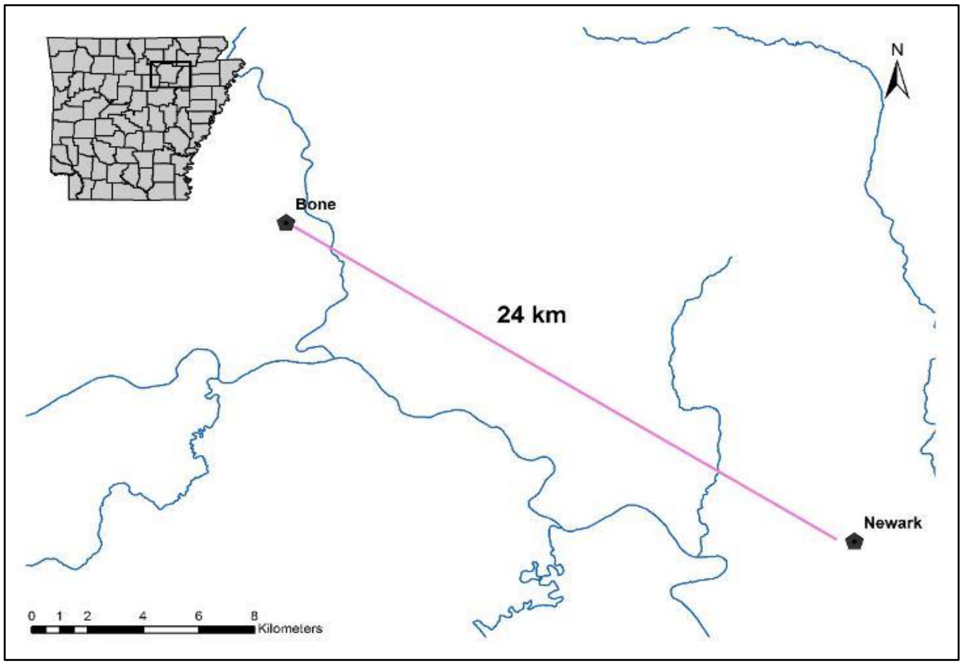


Figure 2.2. Straight-line distance between roost-sites in 2014.

Logan cave, in the Logan Cave National Wildlife Refuge, Benton County, was trapped on 14 June 2015 using the bottom stream entrance. In the same county, bats from Cave Springs cave were trapped on 22 June 2015 and tracked concurrently with Logan cave bats. Logan and Cave Springs caves are about 16 km apart (Figure 2.3). The last site, Crystal cave, located in a residential area of Bella Vista,was trapped on 30 June 2015. For both Cave Springs and Crystal caves, juveniles were already volant at the time of trapping. The region around these three Benton caves is characterized as the Springfield Plateau ecoregion, with multiple karst features. Due to development, the landscape is fragmented with a mix of forest patches, pasture, and urban areas. The Illinois River, located near Logan Cave in the south of the project area, is a large low-order river that drains the county and parts of NE Oklahoma and SW Missouri. The center of the study area is fragmented into smaller creeks and cattle ponds, whereas the northern boundary is forested with large chain lakes and streams.

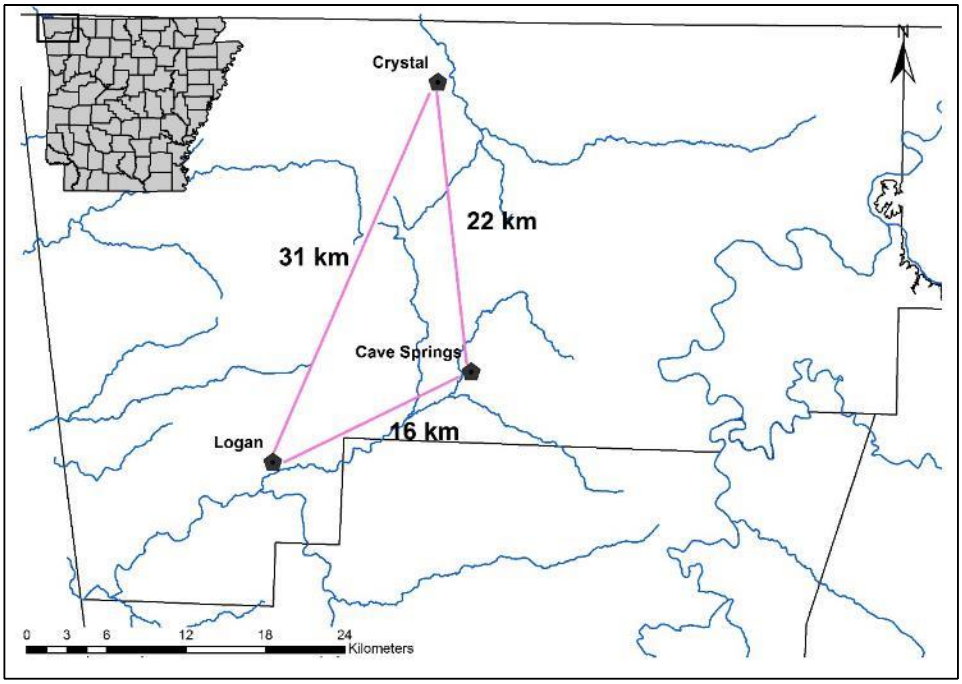


Figure 2.3. Straight-line distance between roost-sites in 2015.

Newark storm drain, Logan Cave, and Cave Springs Cave exhibit the interior water feature that is often sought-after as a daytime drinking source, and a method for ridding the cave of waste. However, while there are small, warm domes, these caves do not exhibit the large, high domes found in Bone and Crystal Caves. Bone and Crystal caves do not have a known interior water source, but the colonies are found in high areas that act as warm air traps. There is very little air flow as opposed to the other three with running water.

Table 2.1. Characteristics of study sites showing county location, year flown, colony size, and landscape characteristics.

Site	County	Year Monitored	Colony Size	Landscape
Newark Storm Drain	Independence	2014	~4,500	Urban
Bone Cave	Independence	2014	~53,000	Rural
Logan Cave	Benton	2015	~14,000	Rural
Cave Springs Cave	Benton	2015	~4,500	Urban
Crystal Cave	Benton	2015	~4,800	Urban

At each cave, trapping began at sunset (between 2015 and 2030) and 25 females were equipped with radio-transmitters (see section 2.2), except at Cave Spring where only 12 females were transmittered.

2.2 Field Methods

2.2.1 Calibration

Transmittered bats were radio-tracked from a plane (see section 2.3), which implies a different bias than with ground-based telemetry. Therefore, a calibration trial was conducted in the Optimus section of the Ozark-St. Francis National Forest to gather relative signal strength data with distance and bearing that were then used to determine difficult bat locations based on their signal strengths. This trial consisted of a test flight during which signal strength was determined for known and unknown transmitter locations from different directions. Three Holohil LB-2X transmitters (Holohil Systems, Ltd. Carp, Ontario) were placed on poles in known locations. Transmitter 1 was placed below a bluff line, Transmitter 2 in forested cover, and Transmitter 3 in an open field adjacent to the White River (Figure 2.4).The antenna on each transmitter pointed south as to mimic the likely direction of foraging bouts. As they were approached, the distance to signal acquisition was recorded. The aircraft flew toward and away from each transmitter in all four cardinal directions three times to determine range. Signal strength at every half kilometer was recorded for every direction, and standardized by calculating the mean for each half kilometer. This method was used as a template to gauge relative distance for bat locations that would not be acquired by flying directly over a radio-tagged bat. Approach angles and interference of mountains adjacent to the river valley also lent standardization in location acquisition, allowing suitable inference. Any signal that was below 91 was deemed too far from the plane to accurately determine error.

In addition, a blind study was performed. A colleague on a 2004 Honda Foreman was fitted with a helmet-mounted Holohil LB-2X transmitter. Two squares (0.8 km^2 and 0.4 km^2), each with four predetermined locations, were mapped to the landscape (Figure 2.4). Within each square (trial), the mobile transmitter moved to one of the four locations. This location was unknown to the aerial team. During the flyover, the aerial team determined the location of the mobile transmitter. The true error of signal strength was then estimated as a function of distance from the airplane. The calibration trial resulted in largest error used at 1.2 km from the plane. These errors were often associated with signal strength

<90. Any location with such error was excluded from the analyses. The average error for suitable signal strength >90 was 0.4 km in radius from the plane, with the exception of Crystal Cave. Crystal Cave experienced >45-knot winds and error was widened to 0.8 km.

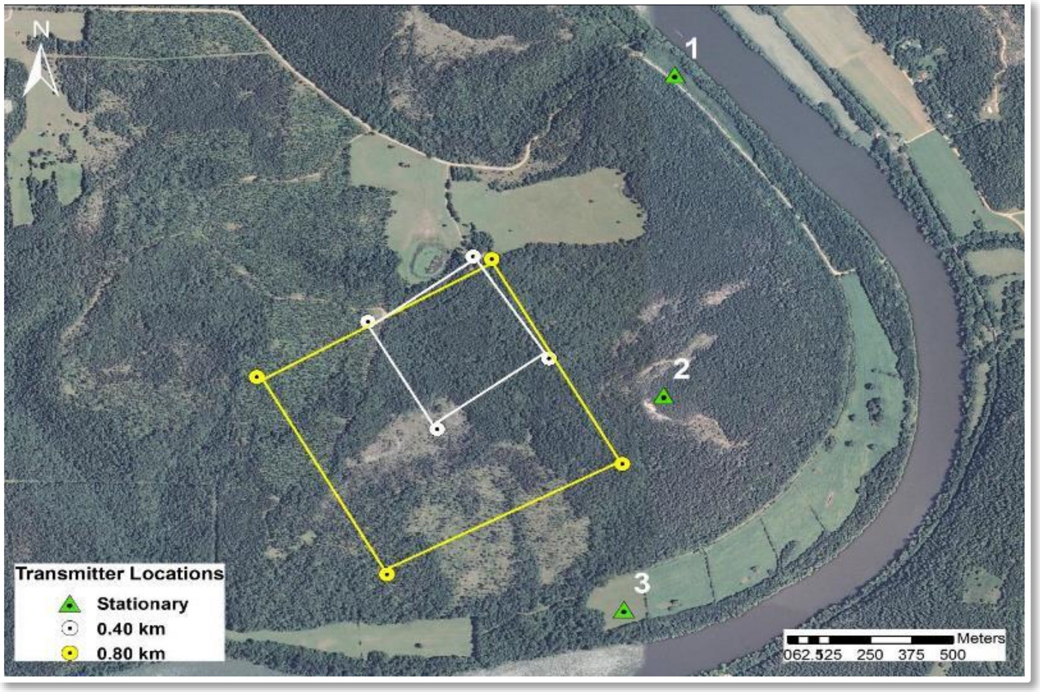


Figure 2.4. Optimus calibration trial by the White River, AR. Triangles indicate the fixed known location of three transmitters (1) below the bluff line, (2) in forested cover, and (3) in an open field. Squares depict four pre-determined locations both 0.4 (white) and 0.8 km (yellow) apart, unknown to aerial team, for determining location error.

2.2.2 Bat Captures

Bats were harp-trapped using a G6 Forest Strainer (Bat Conservation and Management Inc., Carlisle, PA), whose net area totaled 6.7 m^2. For each site, the harp trap was placed at the maternity colony entrance prior to emergence, using tarps to block any escape routes and to funnel bats through the trap. The first 40 females captured (lactating in 2014 or post-lactating in 2015) were placed in holding bags. The harp trap remained open to band additional bats, but was closed within 60 min of opening to avoid further disturbance to the colony. Extra captures were a precautionary measure, as some emerging bats may not meet the weight or body condition requirements for telemetry.

Each captured bat was identified to species, sexed, and weighed, their forearm length measured, and their reproductive status and general health (e.g., presence of parasites or wing damage) assessed. A metal flanged band bearing the prefix “ARK” was fitted to the appropriate forearm (left for female and right for male). Of the 40 reproductive female bats, 25 lactating or post-lactating individuals were equipped with 0.31-g Holohil LB-2X radio-transmitters in the 150.000-151.999 MHz range. The transmitter did not exceed 5% of the body weight as recommended by the American Society of Mammalogists (Sikes et al. 2011).

Transmitters were glued between the shoulder blades of the animal using Perma-Type Surgical Cement (Perma-Type Surgical, Inc., Plainville, CT). The adhesive fails after several days to several weeks, minimizing any detrimental long-term effects to the bat. Transmitters were soldered before harp-trapping began to minimize handling time. Actual handling time of an individual bat did not exceed 5 min, although time spent in bags before and after processing lasted up to 40 min. Bats exhibiting signs of stress were placed back in bags until prepared to fly.

After processing and banding, a handler held each bat in place, often with a bag over the head to reduce stress. Hair was cut down to the skin between the shoulder blades using surgical scissors. Adhesive was applied to the back of the transmitter and held until stuck. After the transmitter was applied, the top of the transmitter was covered in adhesive, and surrounding hair folded over it. After holding and often blowing on the transmitter for 30 s, the bat was placed back into a holding bag for final drying before released. Transmitter signal was checked at the point of attachment using an Advanced Telemetry Systems R4500 scanner receiver (Advanced Telemetry Systems, Inc., Isanti, MN).

2.2.3 Aerial Tracking

The Arkansas Wing of the Civil Air Patrol flew the sorties using Jonesboro squadron (120th Composite), Rogers squadron (115th Composite), and Little Rock squadron (42nd Composite) on a rotating schedule of pilot availability. The plane provided was a Cessna 182 Skylane single-engine prop (N971CP). A four-element ATS Yagi antenna was mounted on each wing strut and connected to a switch-box in the cab using 3-m coaxial cables. The switch box was connected to an R4500 scanner-receiver and GPS attachment, recording plane location.

For each maternity roost, radio-tagged bats were tracked up to 14 days, starting the day following capture. In 2014, the plane left Batesville Municipal Airport in Independence Co., AR at 2020 to be on-site at 2040. Tracking sessions lasted 3 h, landing between 2320 and 2345. Two nights were flown from 2330-0230 to determine foraging duration. In 2015, the plane flew out of Bentonville Municipal Airport in Benton Co., AR. Flights lasted longer (~5 h), from 2220 until 0000, and 0030-0230, after landing for refueling. All sorties and durations of sorties were dependent on weather conditions, such as wind, rain, and visibility.

Locations were recorded by either flying close to an acquired bat frequency and using the error method, or circling in 360° maneuvers for exact locations. When flying past an individual with a signal strength of 100 or greater, a designated error ellipse based on the Optimus Calibration Trial was applied. The fly-by method was used often during periods of early evening bat travel to foraging locations, when locations from multiple individuals were being gathered. For locations where bats were relatively stationary, circling maneuvers were conducted, which often resulted in a Yagi on one side of the plane pointing down directly at the bat, often with a signal strength >120. This point was marked as a precise location beside the plane, as the wing was often at a 45° angle. Scanning for signals was performed by switching from right to left Yagi to gain directionality, or using both Yagis simultaneously to assess distance ahead or behind the plane. As locations were being recorded, precise locations were recorded on a tablet running Trimble Outdoors Navigator (2015 Trimble Navigation Limited), based on signal strength and orientation from the plane. These time-stamped locations and signal strengths were used for comparison with scanner-receiver output for later 3rd-order compositional analysis.

When locations from multiple bats were acquired within an area that could be flown in 5 min, those individuals were all tracked in tandem. Locations were taken from each bat successively and then the tracking regimen for those bats would begin again. Bats that foraged away from other transmittered individuals were tracked up to an hour during a single flight to ensure enough locations for individual analysis. When 15 locations were gathered, priority for that individual dropped and the focus shifted to bats with <15 locations.

In 2014, initial tracking at emergence was executed with an expanding square search pattern common among aerial search-and-rescue pilots. The pattern had 16 “sides” of concentric squares 1 km apart, starting at the roost site (Figure 2.5A). This pattern was flown to gain individual directionality at emergence. After the completion of the initial pattern (15 min), rivers and creeks were flown to determine foraging or additional traveling locations. Overland flights (away from major creeks, rivers or other major water sources) were conducted every night, but were largely unsuccessful in gathering locations as most bats were found over water sources.

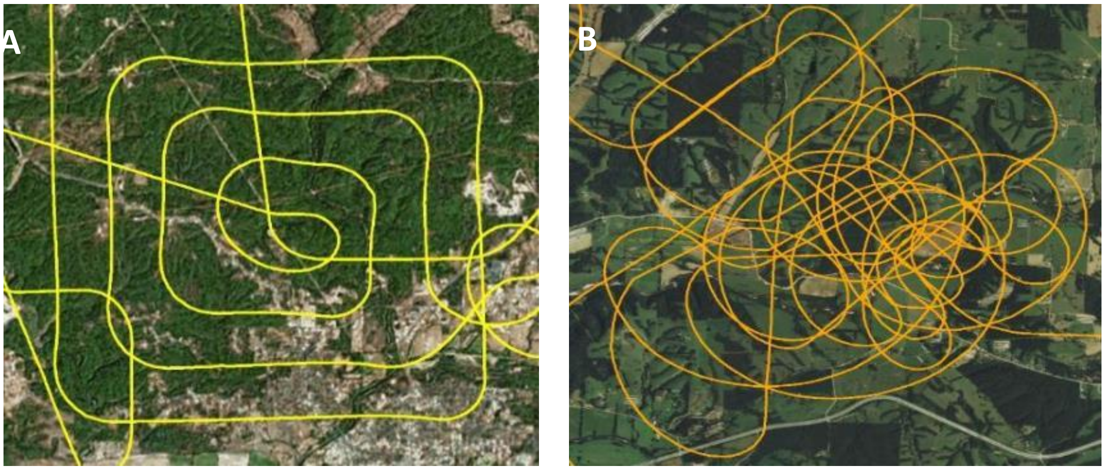


Figure 2.5. Flight search pattern in a square (A) and circle (B) patterns, used in 2014 and 2015, respectively.

In 2015, expanding square search patterns were abandoned for on-station circling of the cave at emergence (Figure 2.5B). After 15 min, major creeks and adjacent areas were flown, and locations recorded. These locations were often the same between nights, and the plane could return to these areas for additional location gathering. Overland flights were also conducted, with greater success.

Tracking altitude was 786 m, the same as the calibration flights conducted in 2014. The scanner-receiver acquired locations when scanning through predetermined channels and acquiring a signal on that frequency. On normal sorties, all 25 frequencies were scanned at 2.5-s intervals. When Logan and Cave Springs were flown together for seven days, a frequency table for all 37 bats was used. Though frequencies were never dropped from the table after several days of no acquisition (possibility of roost-switching), frequencies could be skipped manually to allow for a greater chance of acquisition of known active bats.

2.2.4 Roost-Switching Behavior

In 2015, scanner-receivers were placed at the cave from which gray bats were actively tracked and the closest cave included in this study to document emergence/return times and any roost-switching behavior. Adjacent caves (Bone and Newark in 2015, Logan/Cave Springs and Cave Springs/Crystal in 2015) were monitored in pairs, as these were where exchanges were the most likely.

Lotek Wireless SRX-800MD and SRX-800D scanner-receivers/loggers (Lotek Wireless Inc.) were placed in waterproof bins, powered by 12-V AGM batteries, and connected to 5-element Yagi antennas. These units were placed inside the gates of cave entrances (all cave had perimeter fencing) and the Yagi pointed away from the entrance. During the first tracking period of 2015 (Logan cave), the SRX-800D was placed at the sinkhole entrance, and the SRX-800MD placed at the Cave Springs cave entrance. Both receivers switched frequencies every 2.5 s and scanned all 37 active frequencies that were between Logan cave and Cave Springs cave during the first two-week period. Then, the

SRX-800D was moved to Crystal cave to determine roost-switching behavior between Crystal cave and Cave Springs cave. Data were downloaded every three days using Lotek Wireless software.

2.3 Data Analysis

Data points were taken by the R4500 scanner-receiver every four pulses from a given frequency. Data included signal strength and location of the airplane.

Home range estimation methods require time-independent locations because autocorrelated locations can lead to an underestimate of the home range size (Rooney et al. 1998). Schoener's index (Schoener 1981) is an accepted method to determine if locations are truly independent (Swihart and Slade 1985). However, this type of method, by completely removing autocorrelation, may mask important behaviors (Solla et al. 1999). The time interval necessary to consider two locations as time-independent should thus account for the error associated with the location, the species' travel speed, and distances travelled.

During the Optimus Calibration Trial, the largest error was 1.2 km from the aircraft. To determine the gray bat's average travel speed, 3 bats each season were recorded from emergence (from Bone Cave in 2014 and Logan Cave in 2015) and detected again 20 min later in 2014 and after one hour in 2015. Assuming a straight-line distance from point of emergence and point of contact, the average speed was estimated at 38 km/h. Because bats often follow waterways and rarely travel in a straight line, travel speed was likely higher. At 38 km/h, a bat can travel up to 1.9 km in 5 min, which is outside the largest error of 1.2 km. Although previous tracking studies on gray bats, using VHF telemetry

(Thomas and Best 2000) and light tags (LaVal et al. 1977) did not mention time independence, the choice of 5 min falls in the range of time intervals used in studies of other species, from 4 min (Carter 1998) to 60 min (Rooney et al. 1998). Additionally, gray bats used home ranges much larger (100-1,000 ha) than cavernicolous bat species in other studies (<10 ha; e.g., Clark et al. 1993) and traverse this range nightly. Thus, locations were considered time-independent when at least 5 min apart (Figure 2.6). An additional filter was applied to exclude locations with a signal strength <95 dB.

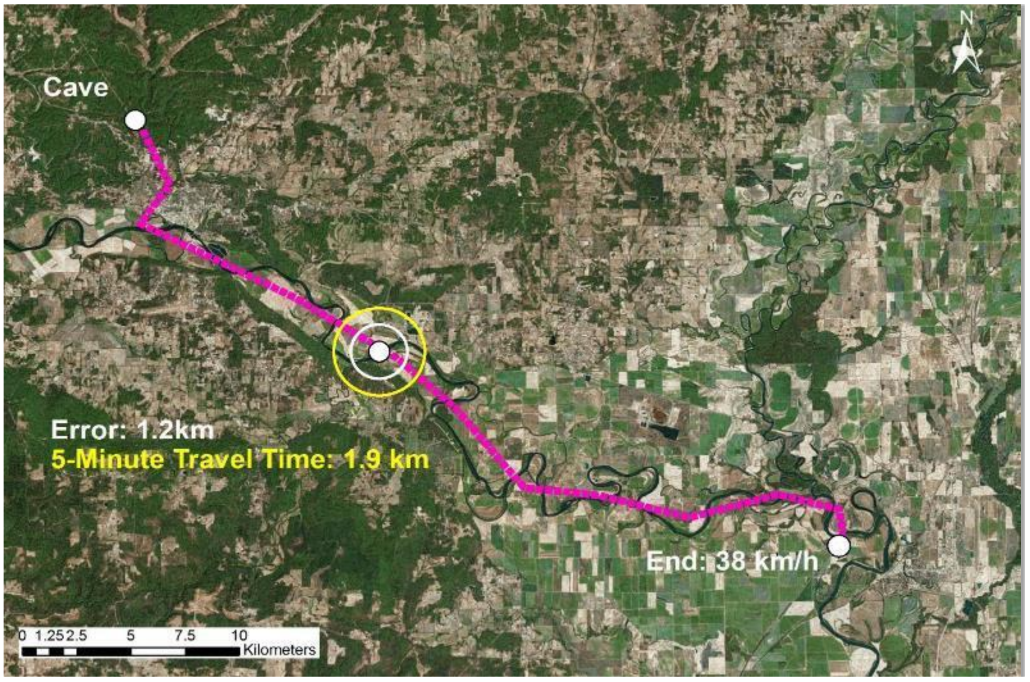


Figure 2.6. Tracking error and travel time of a given bat. The pink line shows how a bat may have traveled, while speed was determined using straight-line distance.

2.3.1 Home Range and Core-foraging Areas

Home range and core foraging areas were estimated at both the cave and individual levels. For the individual-level analysis, only females with at least 15 time-independent locations were considered, whereas all females with one or more locations were included (provided that the locations were time-independent) in the cave-level analysis. Some studies recommend 30 or more locations to reach optimal smoothing parameters for uniform distribution (Seaman et al. 1999), while others call for at least 10 (Swihart and Slade 1985) to show a normal (or uniform) distribution. A decision was made to use ≥15 time-independent locations was chosen because of the constraints with tracking a large number of individuals over such a large area. In this regard, the smoothing parameter for least-square cross validation (LSCV) (method for choosing grid sizes for based on number of locations that influence the size of a kernel) may be larger than those with ≥ 30 locations, possibly overestimating the size of the home range. As such, the average furthest distance traveled by year is also important. Thirty locations is the asymptotic number where gathering more than this number of locations will result in the same size home range (Seaman et al. 1999).

The fixed-kernel (FK) density estimation method was used with least-squares cross validation for all cave-level and individual-level home range (95% of all locations) and core-foraging area (50% of all locations) analyses. All analyses were performed using the "adehabitatHR" package (Calenge 2015) in Program R (R Core Development Team 2014). Home ranges and core foraging areas were also estimated with the minimum convex polygon (MCP) method (in Program R) for comparative purposes with other studies. Ninety-five percent FK and MCP reflected the overall portion of the landscape used by an individual or colony, whereas 50% FK depicted where an individual or colony spent 50% of their time; this latter area, being of highest use, was assumed to be the core foraging area.

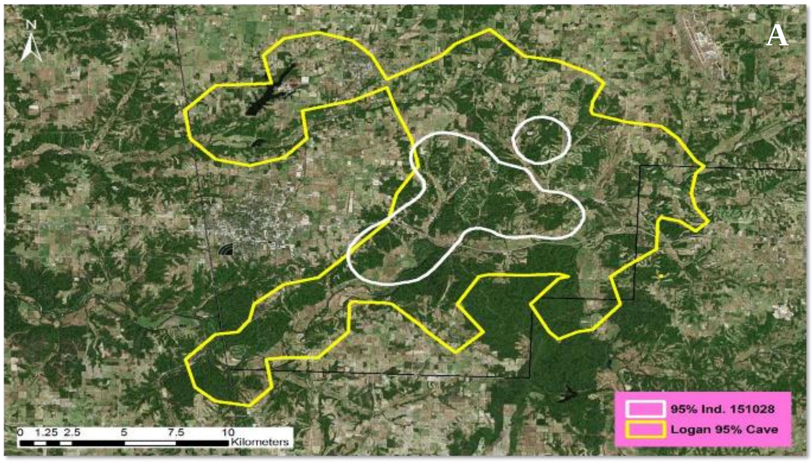
Averages of 95% FK home range and 50% FK core-foraging area per year were reported ± 1 standard error.

A linear mixed-effect model was built in program R with the “lme4” package, to test for a difference in home range and core foraging area between years. The fixed and random effects were year and site respectively. Home range and core-foraging area were log-transformed to meet the normality assumption. The year-effect models were compared to the null model using a likelihood ratio test.

2.3.2 Habitat Selection

All FK home range and core foraging area polygons generated by Program R were imported in Arc GIS 9.3.1 (ESRI 2009). Polygons were clipped to the 2006 Land Use Land Cover (LULC) map (NLCD 2006). Within each polygon, a given number of pixels denotes each habitat type. These pixels were gathered from each clipped polygon’s attribute table and converted into proportions. LULC habitat types include water (two categories), developed (four categories), barren (one category), forest (three categories), shrubland (two categories), herbaceous (four categories), cultivated (two categories), and wetlands (two categories). Habitats present on the landscape were combined where applicable, as multiple LULC types or categories were very similar. Habitat types considered thus included open water, developed, marginal (barren, shrubland, herbaceous), forested, pasture, crop, and wetland.

Compositional analysis compares percentages of available land cover types to percentages of used habitat to determine a rank of habitat use (Aebischer et al. 1993) at a given scale. Johnson (1980) defined four scales of habitat use. The first order relates to habitat use at the species range scale; the second and third orders focus on habitat use at the landscape and home range scales, respectively; and the fourth order is rather defined as prey than habitat selection, at the location scale. Here, I focused on second- and third-order habitat use and performed a compositional analysis in Program R using package “adehabitatHS” with function “compana” (Calenge 2015). For the second-order analysis, the habitat in the 95% FK home range of a given individual was compared with the available habitat in the cave-level 95% FK home range (Figure 2.7A). For the third-order analysis, the habitat at the individual locations was compared to the available habitat in that individual’s 95% FK home range (Figure 2.7B).



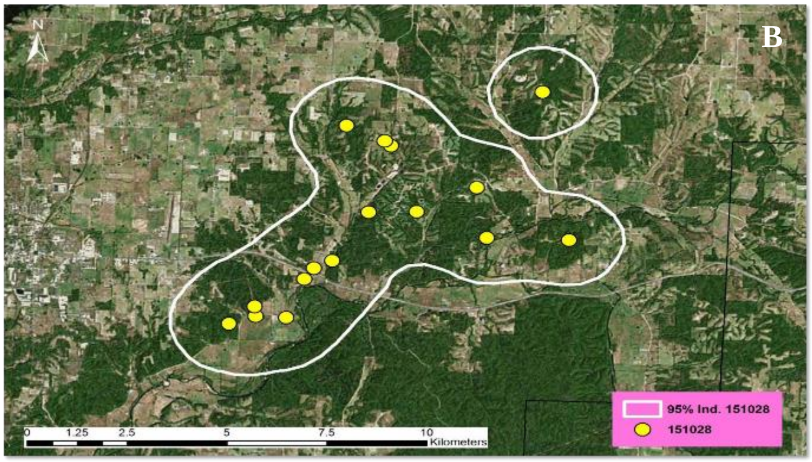


Figure 2.7. Representation of a second-order (A) and third-order (B) compositional analysis.

Habitat at the individual locations for third-order analysis was determined from data recorded on precise locations from Trimble Outdoors Navigator software which was used during every flight. When a compared location between scanner-receiver data and Trimble Outdoors Navigator was time-stamped correctly, the location was considered exact. When no exact location was recorded, a 0.4-km buffer was placed around the aircraft location for all sites except Crystal Cave, which received a 0.8-km buffer due to constant 83-km/h winds from the southeast, making exact location tracking difficult. These buffers were clipped to the LULC layer in ArcGIS, and the dominant land-cover type was used as the habitat designation. The compositional analyses were run at $\alpha = 0.05$.

2.4 Literature Cited

Aebischer, N.J., Robertson, P.A., and Kenward, R.E. 1993. Compositional analysis of habitat use from animal radio-tracking data. *Ecology*. 74: 1313-1325.

Calenge, C. 2015. Analysis of animal movements in R: the adehabitatLT Package.

Carter, T.C. 1998. The Foraging Ecology of Three Species of Bats at the Savannah River Site, South Carolina. Thesis, University of Georgia, Athens, GA.

Clark, B.S., Leslie, D.M., and Carter, T.S. 1993. Foraging activity of adult female Ozark big-eared bats (*Plecotus townsendii ingens*) in summer. *Journal of Mammalogy*. 74: 422-427.

Johnson, D.H. 1980. The comparison of usage and availability measurements for evaluating resource preference. *Ecology*. 61: 65-71.

LaVal, R.K., Clawson, R.L., LaVal, M.L., and Caire, W. 1977. Foraging behavior and nocturnal activity patterns of Missouri bats, with emphasis on the endangered species *Myotis grisescens* and *Myotis sodalis*. *Journal of Mammalogy*. 58: 592-599.

R Development Core Team. 2008. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.

Rooney, S.M., Wolfe, A., and Hayden, T.J. 1998. Autocorrelated data in telemetry studies: time to independence and the problem of behavioral effects. *Mammal Review.* 28: 89-98.

Schoener, T.W. 1981. An empirically based estimate of home range. *Theoretical Population Biology*. 20: 281-325.

Seaman, D.E., Millspaugh, J.J., Kernohan, B.J., Brundige, G.C., Raedeke, K.J., and Gitzen, R.A. 1999. Effects of sample size on kernel home range estimates. *The Journal of Wildlife Management.* 63: 739-747.

Sikes, R.S. and Gannon, W.L., 2011. Guidelines of the American Society of Mammalogists for the use of wild mammals in research. *Journal of Mammalogy*. 92: 235-253.

Solla, D.E., Shane, R., Bonduriansky, R., and Brooks, R.J. 1999. Eliminating autocorrelation reduces biological relevance of home range estimates. *Journal of Animal Ecology*. 68: 221-234.

Swihart, R.K. and Slade, N.A. 1985. Testing for independence of observations in animal movements. *Ecology*. 66: 1176-1184.

Thomas, D.P. and Best, T.L., 2000. Radiotelemetric assessment of movement patterns of the gray bat (Myotis grisescens) at Guntersville Reservoir, Alabama. *Occasional Papers of the North Carolina Museum of Natural Sciences and the North Carolina Biological Survey*. 12: 27-39.

3rd Chapter: Results

A total of 112 reproductive female gray bats were banded and fitted with radio-transmitters across five sites (50 lactating in 2014 and 62 post-lactating in 2015), with an additional 108 individuals banded but not transmittered. For 102 individuals, there was at least one location recorded, totaling 18,416 locations. Data filtering resulted in 42 individuals with 15 independent locations or more, for a total of 865 time-independent locations (Appendix A). Seventy individuals were transmittered but not used in individual analysis due to lack of sufficient locations (Appendix B).

The aircraft spent 120.6 h tracking bats, and flew 19,093 km over 37 tracking days. Inclement weather such as low visibility and storm events resulted in a loss of 19 tracking days. Transmitter attachment periods ranged from 1-14 days, with up to half of remaining transmitters lost after a rain event. In 2014, females foraged from sunset to at least 0230 (time at which tracking ceased), whereas bats in 2015 returned to the roost after 3 h at Crystal Cave, although most would foraged for the entire tracking duration.

3.1 Home Range and Core-foraging Areas

3.1.1 Cave Level

At the cave scale, all time-independent locations (n = 1,293) were used, regardless of the number of locations for an individual bat. These independent locations were separated by site (Table 3.1). Largest ranges were found at Bone cave, which also hosted the largest colony.

Table 3.1. Cave-level gray bat 95% FK, 50% FK, and 95% MCP ranges (in ha), with colony sizes and number of time-independent locations (n).

Year	**Site**	**95% FK**	**50% FK**	**95% MCP**	**Colony Size**	**n**
2014	Newark	34,932	4,431	54,657	4,500	253
2014	Bone	100,694	14,618	129,337	53,000	306
2015	Crystal	12,731	2,513	13,333	4,800	313
2015	Cave Springs	10,626	2,228	9,910	4,500	166
2015	Logan	26,828	4,117	30,680	14,000	251

In 2014, home ranges (95% FK and MCP) for Bone cave and Newark storm drain overlapped along the White and Black river drainages (Figure 3.1 and 3.2), but core-foraging areas were independent of each other, centered in the immediate areas around the cave (Figure 3.3).

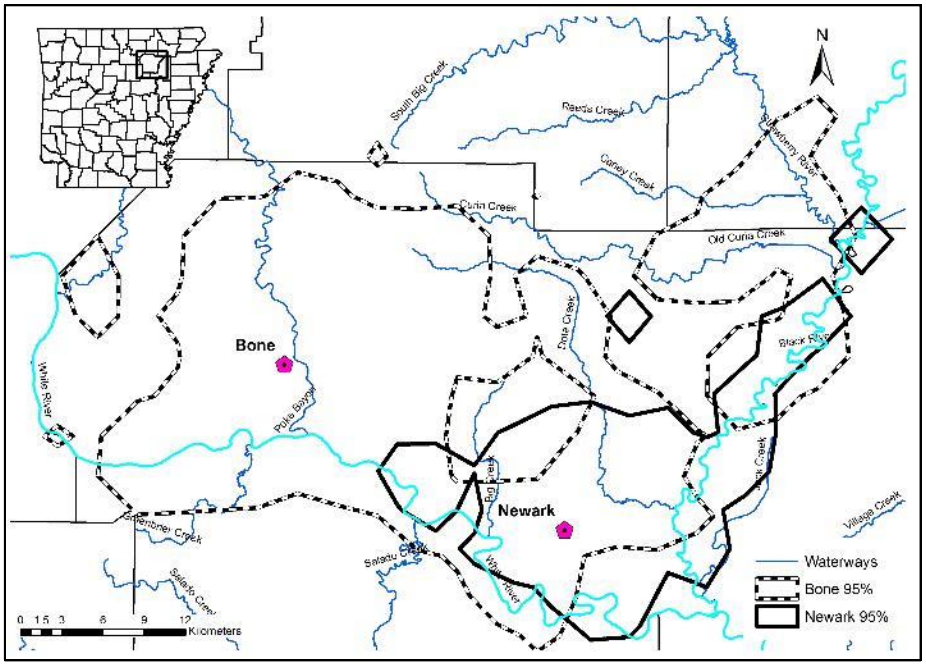


Figure 3.1. Bone (100,694 ha, n = 306 locations, 25 individuals) and Newark (34,932 ha, n = 253 locations, 23 individuals) sites' 95% FK home ranges. White and Black rivers are highlighted, and pentagons represent the caves.

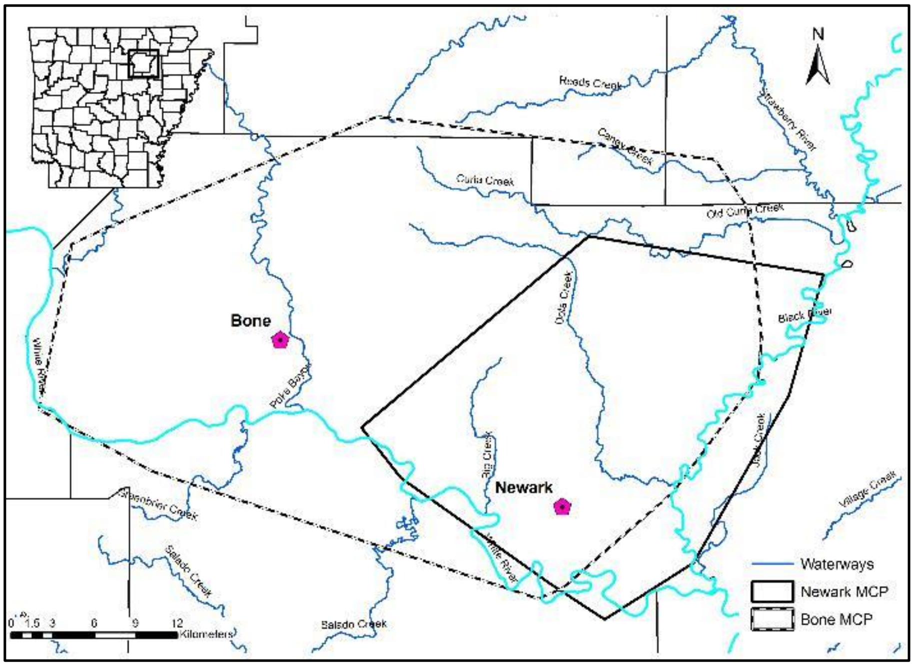


Figure 3.2, Bone (129,337 ha, n = 306 locations, 25 individuals) and Newark (54,657 ha, n = 253 locations, 23 individuals) sites' MCP areas. White and Black rivers are highlighted, and pentagons represent the caves.

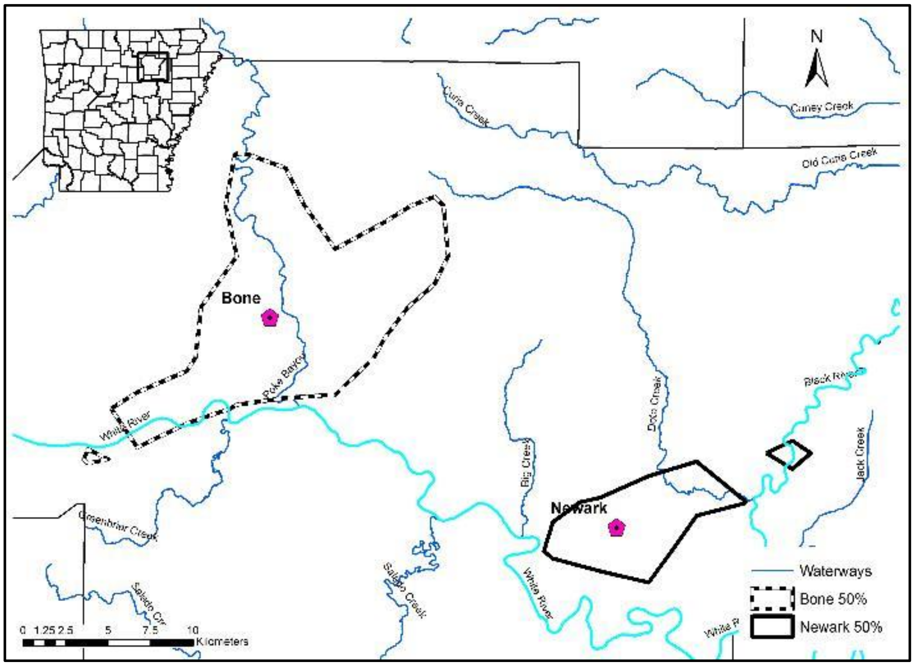


Figure 3.3. Bone (14,618 ha, n = 306 locations, 25 individuals) and Newark (4,431 ha, n = 253 locations, 23 individuals) sites' 50% FK core-foraging areas. White and Black rivers are highlighted, and pentagons represent the caves.

Conversely, in 2015, 95% FK home ranges between Logan, Crystal, and Cave Springs caves had little overlap, limited to a small area between Logan and Cave Springs (Figure 3.4). There was no overlap in 95% MCP home ranges (Figure 3.5) or core-foraging areas (Figure 3.6). Females from Logan Cave foraged along the Illinois River. Those from Cave Springs Cave foraged along Osage Creek, Little Osage Creek, and various cattle ponds. Those from Crystal Cave foraged over major reservoir lakes in Bella Vista, AR.

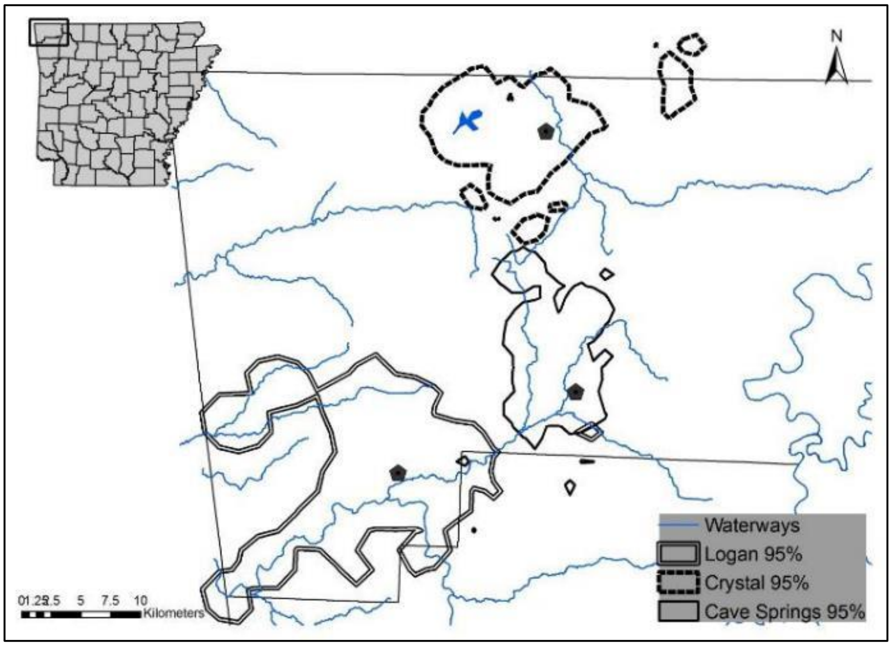


Figure 3.4. Logan (26,828 ha, n = 251 locations, 18 individuals), Cave Springs (10,626 ha, n = 166 locations, 10 individuals), and Crystal (12,731 ha, n = 313 locations, 24 individuals) 95% FK home ranges. Pentagons represent the caves.

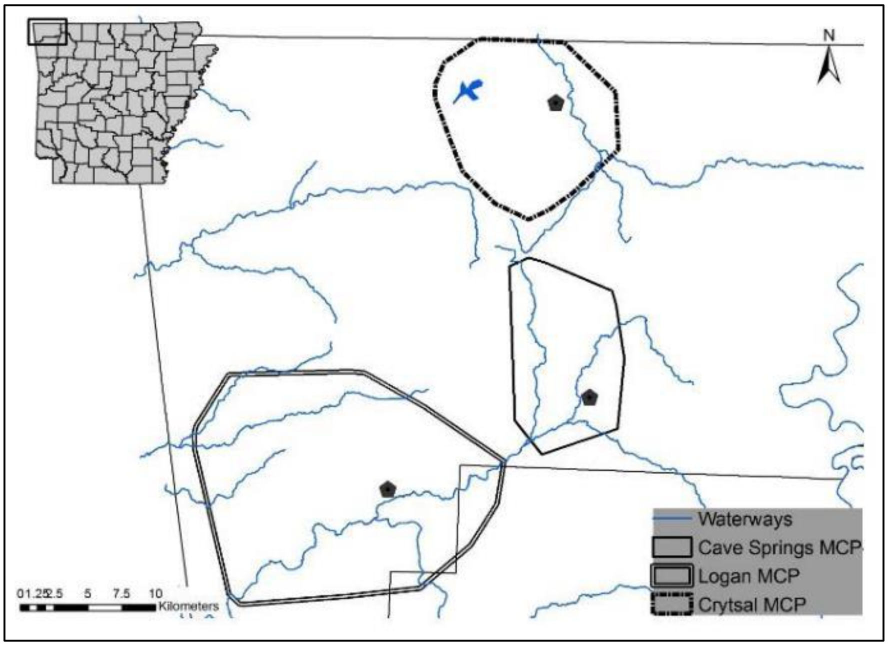


Figure 3.5. Logan (30,680 ha, n = 251 locations, 18 individuals), Cave Springs (9,910 ha, n = 166 locations, 10 individuals), and Crystal (13,333 ha, n = 313 locations, 24 individuals) 95% MCP areas. Pentagons represent the caves.

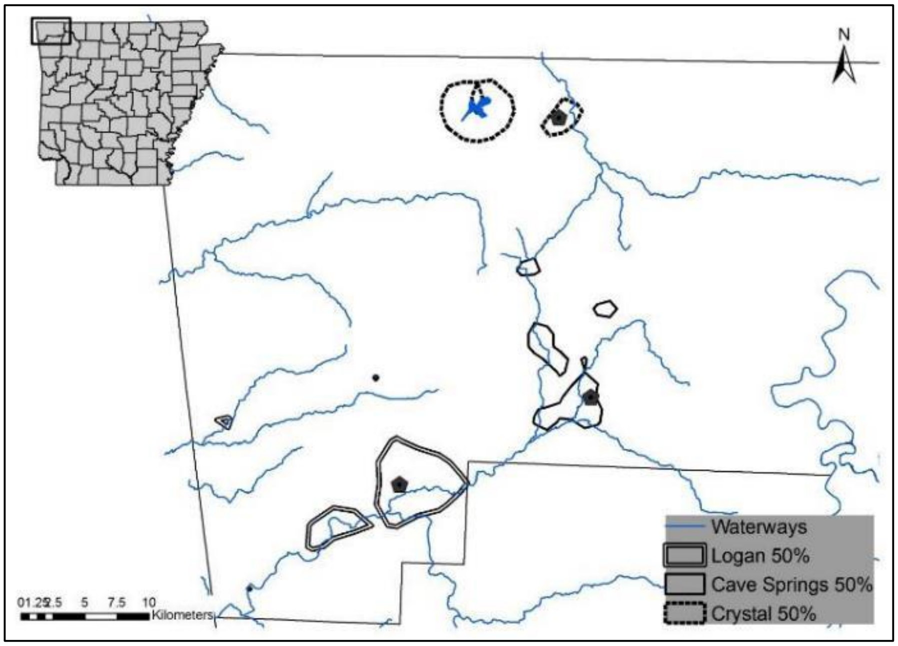


Figure 3.6. Logan (4,117 ha, n = 251 locations, 18 individuals), Cave Springs (2,228 ha, n = 166 locations, 10 individuals), and Crystal (2,513 ha, n = 313 locations, 24 individuals) 50% FK core-foraging areas. Pentagons represent the caves

3.1.2 Individual Level

All sites, with the exception of Cave Springs (12 individuals), had 25 transmittered females. The number of individuals (N) with >15 locations are shown below (Table 3.2).

Table 3.2. Mean individual home ranges (95%), core-foraging area (50%) and MCP by site, with number of individuals (N) having ≥15 time-independent locations.

Year	Location	# Radios	N (>15 locations)	95% FK (ha)	50% FK (ha)	MCP (ha)
2014	Newark	25	5	30,205 ± 9,412	6,415 ± 2,564	16,800 ± 4,101
2014	Bone	25	9	39,565 ± 13,788	9,378 ± 3,725	17,354 ± 4,765
2015	Logan	25	10	7,338 ± 1,886	1,692 ± 463	2,759 ± 429
2015	Cave Springs	12	6	2,781 ± 412	517 ± 100	1,175 ± 287
2015	Crystal	25	12	6,008 ± 1,074	1,370 ± 292	2,599 ± 351

Mean 95% FK and MCP home range estimates for all bats with >15 locations (42 individuals with 865 locations) were 15,935 ± 3,806 ha and 7,286 ± 1,536 ha, respectively. Mean 50% FK was 3,641 ± 980 ha.

At the individual level, 50% FK analysis showed female gray bats having 1-4 core foraging areas with an average of 2 (Figure 3.7). There was substantial variation among individuals, with 600-126,387 ha for 95% FK, 262-48,224 ha for 95% MCP, and 233-33,367 ha for 50% FK (Appendix C).

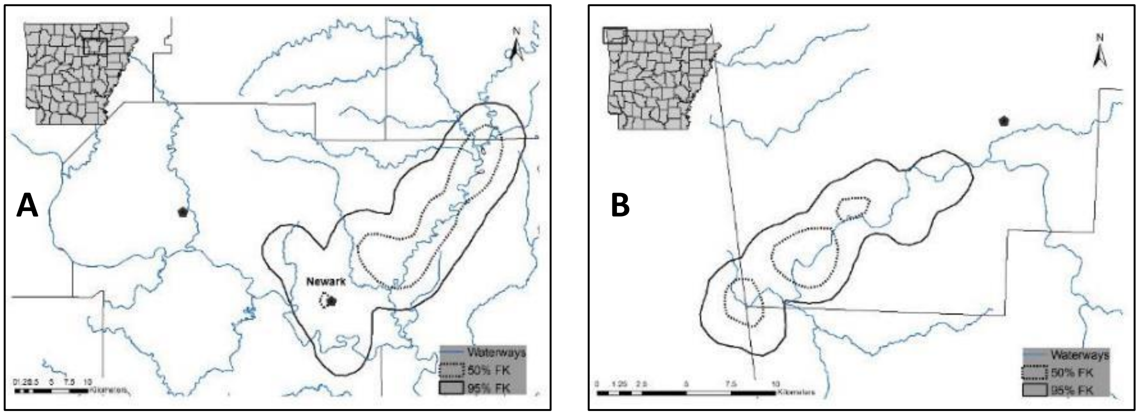


Figure 3.7 Individual home ranges and core-foraging areas of (A) a lactating female from Newark (95% FK = 54,900 ha; 50% FK = 14,023 ha) and (B) a post-lactating female from Logan (95% FK = 7,130 ha; 50% FK = 1,545 ha).

The likelihood ratio test revealed that individuals in 2014 (n = 14 individuals, 301 locations) had on average significantly larger 95% FK home ranges ($\chi^2_{(1)}=11.4$, $p<0.001$) and greater 50% FK core-foraging areas ($\chi^2_{(1)}=9.6$, $p=0.002$) than individuals in 2015 (n=28 individuals, 568 locations; Table 3.3).

Table 3.3. Combined site, year-specific mean individual-level 95% FK, 50% FK, and 95% MCP (± 1 SE ha) with reproductive status and number of individuals in each sample.

Year	95% FK	50% FK	95% MCP	Repro. Status	# Ind.
2014	36,223 ± 2490	8,320 ± 670	17,156 ± 880	Lactating	14
2015	5,791 ± 4,539	1,302 ± 1,156	2,351 ± 1,306	Post-lactating	28

Mean furthest distance traveled from a roost in 2014 was 21 km ± 2.9 and 9 km ± 0.7 in 2015. The furthest point traveled was 41 km from the roost, by an individual from Bone. The closest foraging area to a roost location was <2 km. There is continuity with major streams between Logan and Cave Springs, yet no overlap in home range occurred. Mean distance of roosts to major water (large lake/class three stream or larger) was 1.3 km (0.23-3.9 km).

3.2 Habitat Selection

For the second-order compositional analysis, habitat used (individual-level 95% FK home range) and available habitat (cave-level 95% FK home range combined by year) were not significantly different in 2014 (λ_8 = 0.43, P = 0.17; Table 3.4), but were significant in 2015 (λ_7 =0.34, P = 0.001; Table 3.4). At the landscape scale, wetlands were used proportionally more than expected in 2015.

Table 3.4. Second-order compositional analysis by year, with used land-cover types in order of preference (i.e., Rank 1 is the most preferred).

Year	**Location**	**Rank 1**	**Rank 2**	**Ranked Least**	**P-value**
2014	Newark/Bone	Developed 7.7/6.2	Forest 41.2/37.0	Crop 4.5/6.0	0.17
2015	Logan/Cave Springs/Crystal	Wetland 1.0/0.8	Developed 16.8/15.7	Open Water 1.8/1.4	<0.001

For the third-order compositional analysis, habitat used at a given location and available habitat (individual 95% FK home range) differed significantly at all sites and in both years (Table 3.5), with Open Water being the predominantly preferred habitat type, at the home range level, whereas developed land and forests seemed to be avoided.

Table 3.5. Third-order compositional analysis by site, with used land-cover types in order of preference (i.e., Rank 1 is the most preferred). Under each ranked habitat, the first number is the percent used and the second number is percent available.

Year	Location	Rank 1	Rank 2	Ranked Least	P-value
2014	Newark	Open Water 66.8/11.2	Pasture 14.0/25.7	Developed 0.7/5.5	<0.001
2014	Bone	Open Water 62.6/1.3	Marginal <0.01/0.4	Forest <0.01/54.3	<0.001
2015	Logan	Open Water 83.1/2.4	Marginal <0.01/0.2	Developed <0.01/6.7	<0.001
2015	Cave Springs	Open Water 87.1/0.4	Pasture 63.7/8.2	Forest 0.7/18.3	<0.001
2015	Crystal	Open Water 86.2/4.3	Marginal <0.01/0.1	Developed <0.01/24.8	<0.001

3.3 Roost Switching

In 2014, signals from inside Newark storm drain were audible from the air. Two individuals from Bone Cave, on one occasion each, were found to be inside the storm drain. One had left the drain during the tracking period, and the other had not left by the end of tracking. The next day, both were found inside Bone Cave when checked with the ATS R4500 scanner-receiver. In addition, one individual no longer documented at Bone Cave, was found leaving a valley at emergence 8 km west of Bone Cave in an area with previously unknown karst features.

In 2015, the equipment used for documenting duration of foraging bouts and roost switching could not simultaneously scan and document all signals. Foraging bouts of the four bats with data from Logan and Crystal caves showed foraging bouts of 3-7 h. Foraging continued during rain events. However, one bat from Cave Springs cave roosted in Logan cave for one day before returning to Cave Springs.

4th Chapter: Discussion

Aerial tracking of gray bats using fixed-wing aircraft is a first-of-its-kind study. By employing aerial techniques, bats could be detected over larger areas when compared to ground-based methods. Multiple time-independent locations from multiple individuals allowed for identification of resource use on a landscape scale. With female gray bats using such large home ranges, it was more effective to use a single aircraft than even large ground-based tracking teams. Thomas and Best (2000) reported a 22% success rate in gathering two or more locations on transmittered bats. In this study, the success rate using the same parameters was 92%. In addition, this study showed a high degree of affinity for water (streams, rivers, lakes) in female gray bats. This method of tracking bats has thus proven successful and portrays a more complete picture of landscape use for highly mobile organisms.

4.1 Aerial-tracking Feasibility

The first objective was to determine if aerial-based tracking was feasible and to compare its effectiveness with that of ground-based tracking. Although ≥15 independent locations were not obtained for 50 individuals, 102 female gray bats were tracked by fixed-wing aircraft, 42 of which had >15 independent locations, which represents the largest sample size (i.e., 42 reproductive females) of any tracking study of gray bats (e.g., N=14; Thomas and Best 2000). Therefore, this study shows that aerial radio-telemetry is a feasible method and can be used to track foraging bouts of highly mobile bats. Furthermore, using a fixed-winged aircraft allowed location acquisition of females in private and inaccessible places (e.g., rugged terrain).

Other advantages of aerial tracking over ground tracking include less coordination and personnel, and stronger signals at long distances. A study performed by LaVal et al. (1977) used four ground observers and one helicopter to track gray bats equipped with Chem-light glow sticks. Thomas and Best (2000) had five teams consisting of two people for radio-tracking. Also, with ground-based techniques, signals can often not be acquired beyond 1 km in mountainous terrain (Istvanko 2015), whereas aerial tracking can detect signals at up to 10.8 km as shown by the Optimus Calibration Trial.

Aerial tracking, particularly of gray bats, was also associated with some drawbacks including patterns in individual bat behavior, the size of home ranges, the number of individuals tracked, and weather. After learning site fidelity, locations could be gathered more effectively. However, bats chose different foraging areas, which were as much as 50 km apart. Transit time between bats also reduced time spent gathering locations. However, this challenge is exacerbated on the ground. Finally, weather contributed to the loss of 19 tracking nights, but this problem is not specific to aerial telemetry; Chem-lights also could only be observed on nights with less than half full moons and no rain events (LaVal et al. 1977).

Aerial tracking is not always useful across all project types. Estimating home range may be better served by a ground-based team for animals with small home ranges, and with multiple tracked individuals in adjacent areas. In bats, these studies would include most Myotis, such as the Indiana bat (*Myotis sodalis*) (95% FK 204.52 ± 28.87 ha), during summer months (Womack et al. 2013). Also, some forest dwelling bats, such as the Evening bat (*Nycticieus humeralis*) were shown to have small home ranges (95% FK of 197 ± 30 ha) (Istvanko 2015). Bats with larger home ranges such as lactating female red bats (1,041-1,588 ha) (Amelon et al. 2014) may be better served by aerial tracking, as the complete home range can be better quantified. My aerial tracking study of gray bats confirms Marzluff et al.'s (1994) finding on raptors that aerial tracking is more accurate (409-m error) and viable on highly mobile species as overflying allows estimating a location with a smaller degree of error. This contrasts with the error usually found in ground-based telemetry (i.e., 1,826 m).

To gain essential knowledge to assist in making best management decisions, one should always consider adding an aerial component to a migration or foraging study. While more expensive, there may be a greater success rate in location acquisition across a broad area. While there are not a large number of published papers that specifically address bats, studies are currently underway that will help determine finer patterns of bat behavior, and methodology relating to tracking bats by air.

4.2 Home Range Size of Reproductive Adult Female Gray Bats

4.2.1 Year Effects

Because of the gray bat tracking study by Thomas and Best (2000), I expected the minimum home range of female gray bats in Northern Arkansas to be <97 km^2. Although most tracked gray bats in my study (62%, N=42) had home ranges <97 km^2 (Appendix 1), the smallest 95% FK home range was 6 km^2 and the average was 159 km^2. This discrepancy may be explained by the difference in sexes and reproductive status of individuals tracked between studies, as Thomas and Best (2000) tracked both females and males, whereas I focused on reproductive females only.

Because males and non-reproductive females do not have the same energetic constraints as reproductive females, it is possible that reproductive females must travel farther to meet their energy demands than males or non-reproductive females, thus increasing their home range. A similar reproductive status effect was suggested by Amelon et al. (2014). Additionally, Henry et al. (2002) showed, in little brown bats (*Myotis lucifugus*), a 51% reduction in home range size and a 35% decrease in flight distances between pregnant and lactating bats. The difference in home range size detected between years in my study supports this idea of an effect of reproductive status, though in the opposite direction. Indeed, mean foraging distance and home range in 2014 when only lactating females were tracked were larger than in 2015 when only post-lactating females were tracked. Specifically, my study showed an 84% reduction in mean home range and a 58% reduction in mean foraging distance between lactating and post-lactating colonies.

Alternatively, the difference between years may be due to a difference in habitat continuity amongst sites in 2015 vs. 2014, or in insect abundance (Fukui et al. 2006). In 2014, habitat was well connected between the two maternity colonies; by the large White River corridor. Several bats from Bone Cave would travel down the White River, past the Newark site, and continue upstream to the Black River, mimicking the behavior of many bats from the Newark site. Large waterways were also more often used in 2015, with the addition of features such as lakes and cattle ponds. Larger waterways were probably exploited because increased light penetration to water increases system productivity and higher insect loads (Stanford and Ward 1988, Ward and Tockner 2001). Shaded, smaller streams do not receive the same amount of sunlight, and consequently, are not as productive.

Low insect abundance may influence the behavior relating to overlap or partitioning of home ranges. Studies by Tuttle (1976b) and Best et al. (1997) showed a preference for emerging aquatic insects, particularly Ephemeroptera. Tuttle (1976b) has also found territoriality among reproductive female gray bats. He theorizes that mayfly hatches last past the first peak of insect activity, allowing for long periods of feeding. However, Lacki et al. (1995) found no Ephemeroptera in gray bat fecal samples, of which the content suggested opportunistic foraging. The insect abundance within the 2014 home ranges may have allowed for overlap in resource utilization, though more individuals (~58,000) were using the area than in 2015 (~24,000 individuals). In 2014, with twice as many gray bats, density issues may have necessitated bats foraging farther for a food source. Due to increased runoff associated with development in the 2015 home range area of northwest Arkansas, insect availability could be reduced, resulting in territoriality between roost sites (Hickey and Fenton 1990, Racey and Swift 1985).

Home range and core-foraging area sizes are most likely directly related to the reproductive status of a bat in any given species. Gestation and migration are energetically expensive, but lactation is even more so. With such large lactating home ranges documented through this study and others, it allows future projects to plan for intensive effort at this time. This intense effort could be offset as lactating bats move into post-lactating periods, when foraging distances are reduced.

4.2.2 Roost-site Selection

Summer-roosting complexes, a network of gray bat roosting caves up to 70 km long, located along waterways, are anchored by maternity colonies and involve roost-switching behavior (Harvey 1976). It is possible that some of these maternity colonies are within some of these networks. There were several instances of roost-switching among sites. In 2014, a female that was thought to have moved from Bone Cave was found at emergence coming out of an area on Lock 3 road in Independence Co., 15.9 km from the maternity site. This area on Lock 3 road is near where landowners have previously described a cave with large clusters of bats. A similar instance happened with an individual on the Strawberry River, 40 km from Bone Cave, disappearing abruptly from tracking, but detected flying the next night. This coincides with Tuttle's (1979) observations of roost-switching between several caves, with a travel corridor in this study of up to 41 km, shorter than in a previous study (Tuttle 1976b). While distances observed during my study did not extend past the foraging distances of 30-70 km described by Tuttle (1976b), many were much shorter, with an average of 21 km in 2014, and 9 km in 2015.

Two bats from Bone Cave were also found to be using the Newark storm drain as a stopover roost after foraging, (the signal could be heard through the concrete/sewer openings) and were found at Bone Cave the next day when signals were checked.

In 2015, scanner-receivers were placed at every active cave. While the receivers did not provide much usable data, there was one instance of roost switching from Cave Springs to Logan Cave. While males and non-reproductive females were not transmittered, the observations suggest widespread gray bat use of habitat in this region, and awareness of other colonies within the area. Inter-season roost-switching has been documented in big brown bats, Indiana bats, and Northern long-eared bats (Willis and Brigham 2004, Britzke et al. 2006, Patriquin et al. 2010), but little data are available for gray bats.

Roost-switching happens among all species of bats. Disturbance, insect availability, or climatic variables may cause bats to move to backup roosts. In tree bats, published data could be modeled to find prime roosting areas if the bats are lost. In cave bats, the knowledge of caves in the area will give researchers a chance to find bats that have switched, whereby being on station over the cave at emergence, or by visiting the location during the day.

While roost-switching may have been an expected behavior in 2015, given the post-lactating status of the bats, it was unexpected in 2014. Lactating gray bats are central-place foragers, returning nightly to the roost to feed their young. If young are alive, and not yet volant and independent, it would be expected that the mothers would occupy the same roost nightly. However, the roost-switching during 2014 may have occurred because of recent pup mortality or weaning. Pups have been observed decomposing on dry cave floors, and floating in the effluent of caves with running water. Either way, the behavior observed in both years suggests a network of caves known to gray bats does exist, corroborating Harvey's (1976) observations of a summer-roosting complex.

Large home ranges and roost-switching behavior show that protecting major caves from disturbance is vital but not all-encompassing. Smaller, secondary roosts used by both males and females must also be considered. Also, the foraging areas of gray bats, being so extensive, are important to note to prevent future degradation of habitat.

4.2.3 Foraging intensity/duration

Foraging times were extensive during both years. In 2014, bats were foraging when the plane landed between 2330-0000. On nights when flights took off between 2330-0000, bats were flying throughout the 3-h tracking session. In 2015, when tracking sessions regularly lasted until 0230-0330, bats were still foraging. Crystal Cave, a post-lactating colony tracked from 1 July 2015- 11 July 2015, showed some abatement in foraging duration, with bats often returning to the roost between 2300-2330, and not all reemerging for a second feeding bout. This intensity of feeding is in line with Tuttle (1976), who also found duration of foraging to last well into the typical second feeding bout. Studies have shown no difference in foraging duration between male and female big brown bats (Wilkinson and Barclay 1997), but females were found to forage longer as lactation progressed in Hoary bats (*Lasiurus cinerius*). Duration may be species-specific, but it may also be a function of reproductive status.

4.3 Habitat Selection

As predicted, compositional analysis of habitat type showed significant use of open water over all other habitat types in the third- order, finer-scale analysis. Using open water for traveling and foraging has been documented in several published papers (La Val et al. 1977, Tuttle 1979, Brady 1982, Lamb 2000, Thomas and Best 2000, Mitchell and Martin 2002). Because of the 400-m error and the close interface between wetland

and river, some bats foraging along the Illinois River may have been over adjacent wetlands, as reported by Lamb (2000).

Feeding locations varied by habitat availability across most sites. In 2014, bats used the major drainages of the White and Black rivers, with some use along the Strawberry River (Figure 4.1 and 4.2). Two bats used ponds (including a coal power plant fly ash pond), and one was located over a catfish farm near Tuckerman, AR. In 2015, bats from Logan Cave used the major feature of the Illinois River, along with many 3rd-order streams that drain to the Illinois (Figure 4.3).

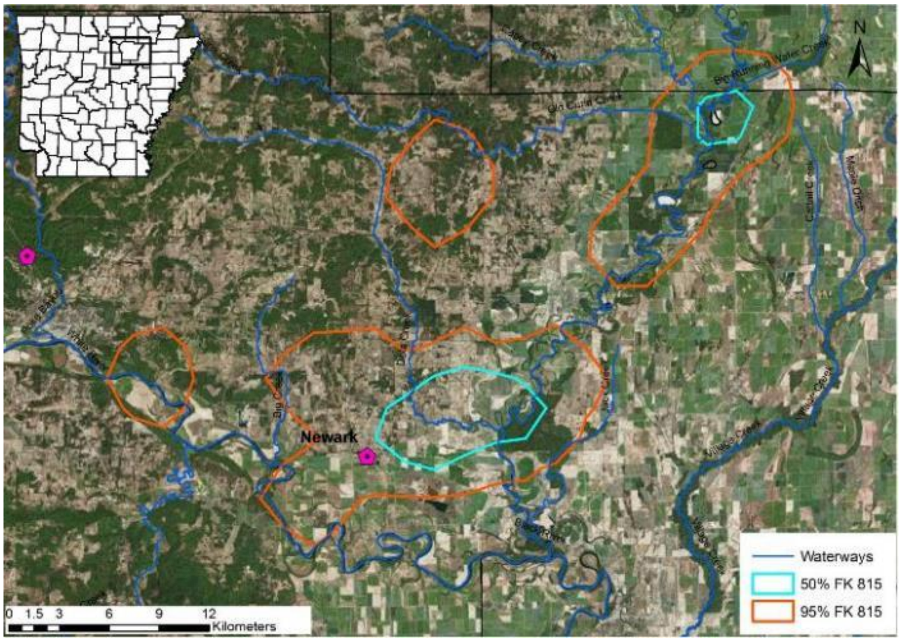


Figure 4.1. Individual home range and core-foraging area of an individual lactating female gray bat from Newark storm drain using larger streams, as well as the White (southern boundary of home range) and Black (eastern boundary of home range) rivers (15 June – 30 June 2014).

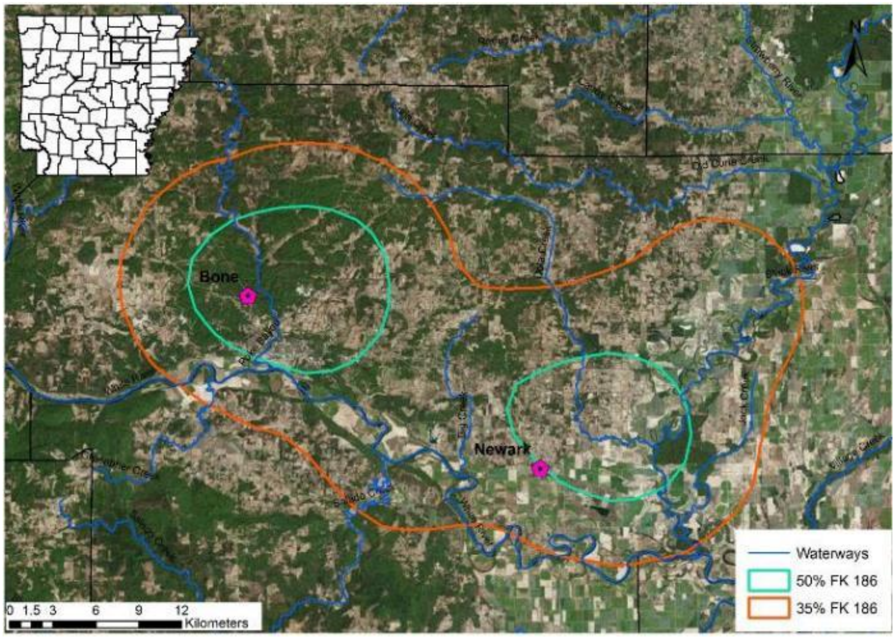


Figure 4.2. Individual home range and core-foraging area of an individual lactating female gray bat from Bone Cave using larger streams, as well as the White (southern boundary of home range) and Black (eastern boundary of home range) rivers (1 July – 15 July 2014).

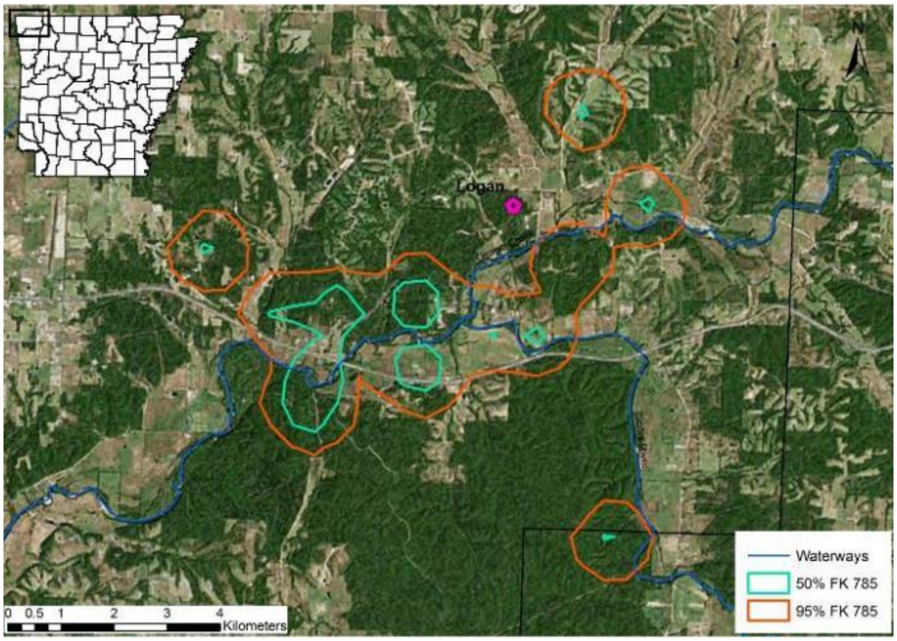


Figure 4.3. Individual home range and core-foraging area of an individual post-lactating female gray bat from Logan Cave using Osage Creek and the Illinois River. This bat may also be using wetlands adjacent to the Illinois River (15 June – 30 June 2015).

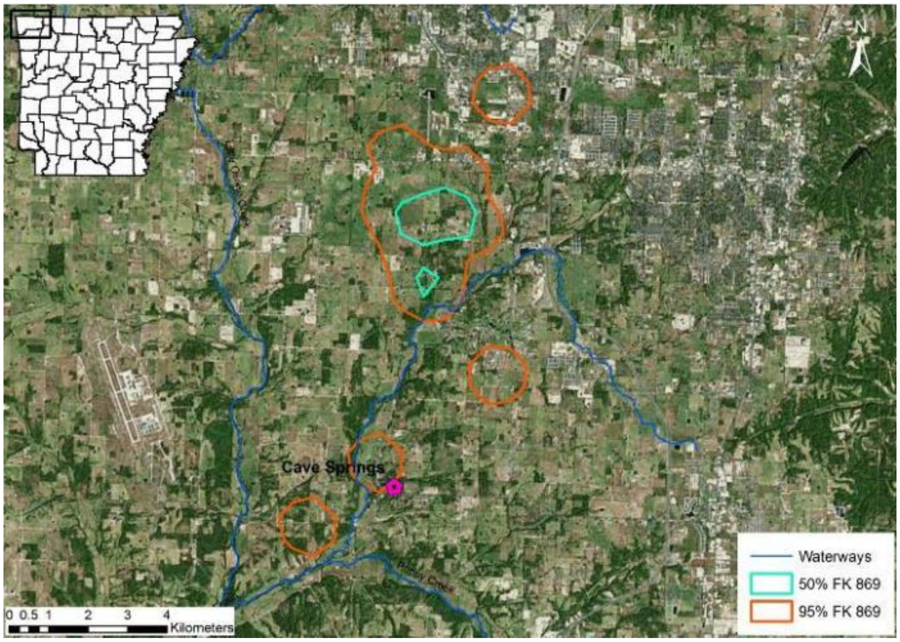


Figure 4.4. Individual home range and core-foraging area of an individual lactating female gray bat from Cave Springs Cave using cattle ponds as its core-foraging areas near the roost (22 June – 2 July 2015).

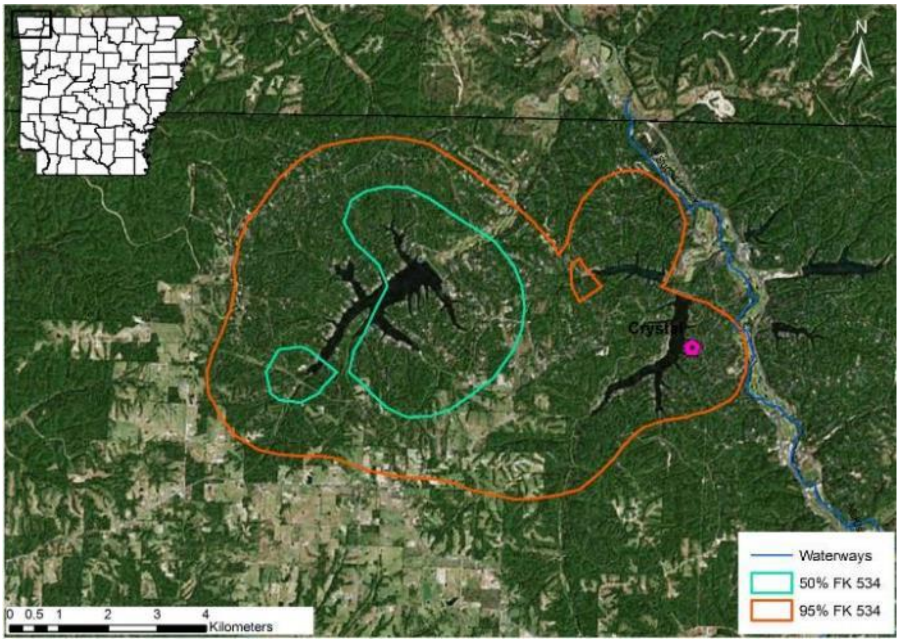


Figure 4.5. Individual home range and core-foraging area of an individual lactating female gray bat from Crystal Cave using large reservoir lakes to forage. Due to high winds, these polygons would be shifted 400 m to the southwest (1 July – 15 July 2015).

Bats from Cave Springs used Osage and Little Osage creeks, but some individuals were detected foraging nightly over cattle and retention ponds (Figure 4.4). Osage and Little Osage creeks may have been impacted due to development, which may have affected the carrying capacity of the area. Crystal Cave is located adjacent to large reservoir-lakes, which bats used. Use of large lakes coincide with findings by Thomas and Best (2000). Most bats tracked from Crustal Cave used these lakes, in particular Lake Loch Lomond (Figure 4.5). Within Lake Loch Lomond, up to 12 individuals were documented using a single cove. Others used major 3rd- and 4th-order streams in the area.

Contrary to the prediction, bats did not always forage downstream. In 2014, some bats did forage downstream over the White River, but the remainder foraged in the smaller upland streams or traveled upstream on the Black River to feed. In 2015, bats in Logan Cave foraged up and down the Illinois River, as well as other streams. Bats from Cave Springs used Osage and Little Osage creeks in both directions from the cave, and bats from Crystal Cave also showed no apparent preference. Although reproductive female gray bats in my study did not all forage downstream, the shortest distance of roosts to major water sources was about 1.3 km and always < 4km, as reported by Tuttle (1976b).

Not only do gray bats use water as a main source for foraging and travel, the dominant lentic or lotic water feature of the area is used (lakes, streams, ponds, or lakes). This foraging points to possible plasticity in insect types consumed by gray bats, as seen in fecal analysis performed by Best et al. (1997) and Lacki et al. (1995). The opportunistic feeding behavior may help in population level resiliency in cases where water systems may degrade. However, the availability of aquatic insects seems to be essential, and massive degradation of waterways will affect population levels.

Literature Cited

Amelon, S.K., Thompson, F.R. and Millspaugh, J.J. 2014. Resource utilization by foraging eastern red bats (*Lasiurus borealis*) in the Ozark Region of Missouri. *The Journal of Wildlife Management*. 78: 483–493.

Best, T.L., Milam, B.A., Haas, T.D., Cvilikas, W.S., and Saidak, L.R.1997. Variation in diet of the gray bat (*Myotis grisescens*). *Journal of Mammalogy*. 569-583.

Brady, J.T., Kunz, T.H., Turtle, M.D., and Wilson, D.E. 1982. "Gray bat recovery plan," U.S. Fish and Wildlife Service, Denver, CO

Britzke, E.R., Hicks, A.C., Von Oettingen, S.L., and Darling, S.R. 2006. Description of spring roost trees used by female Indiana bats (*Myotis sodalis*) in the Lake Champlain Valley of Vermont and New York. *The American midland naturalist*. 155: 181-187.

Fukui, D., Murakami, M., Nakano, S., and Aoi, T. 2006. Effect of emergent aquatic insects on bat foraging in a riparian forest. *Journal of Animal Ecology*. 75:1252-1258.

Harvey, M.J. 1976. Homing of gray bats, *Myotis grisescens*, to a hibernaculum. *American Midland Naturalist.* 96: 497–498.

Henry, M., Thomas, D.W., Vaudry, R., Carrier, M. 2002. Foraging distances and home range of pregnant and lactating little brown bats (Myotis lucifugus). *Journal of Mammalogy*. 83: 767-774.

Hickey, M.B.C., Fenton, M.B., 1990. Foraging by red bats (*Lasiurus borealis*): do intraspecific chases mean territoriality? *Canadian Journal of Zoology*. 68: 2477-2482.

Istvanko, D.R. 2015. Sex-specific foraging habits and roost characteristics of the evening bat (*Nycticeius humeralis*) in an intensively managed forest in north-central Arkansas. Master's Thesis. Arkansas State University, Jonesboro, AR.

Lacki, M.J., Burford, L.S., and Whitaker, J.O. 1995. Food habits of gray bats in Kentucky. *Journal of Mammalogy*. 76:1256-1259.

Lamb, J. W. (2000). "Section 10 permit number SA 97-34 annual report for *Myotis grisescens* and *Myotis sodalis* on Arnold Air Force Base/ Arnold Engineering Development Center (AEDC)", Unpublished Report, ASC Environmental Services, Conservation, Arnold Air Force Base, TN.

LaVal, R.K., Clawson, R.L., LaVal, M.L., and Caire, W. 1977. Foraging behavior and nocturnal activity patterns of Missouri bats, with emphasis on the endangered species *Myotis grisescens* and *Myotis sodalis*. *Journal of Mammalogy*. 58: 592-599.

Marzluff, J.M., Vekasy, M.S., and Coody, C. 1994. Comparative accuracy of aerial and ground telemetry locations of foraging raptors. *The Condor*. 96: 447–454.

Mitchell, W.A., and Martin, C.O. 2002. *Cave-and Crevice-Dwelling Bats on USACE Projects: Gray Bat (Myotis grisescens)* (No. ERDC-TN-EMRRP-SI-25). Engineer Research and Development Center, Vicksburg, MS.

Patriquin, K.J., Leonard, M.L., Broders, H.G., and Garroway, C.J. 2010. Do social networks of female northern long-eared bats vary with reproductive period and age? *Behavioral Ecology and Sociobiology*. 64: 899-913.

Racey, P.A. and Swift, S.M. 1985. Feeding ecology of *Pipistrellus pipistrellus* (Chiroptera: Vespertilionidae) during pregnancy and lactation foraging behaviour. *Journal of Animal Ecology*. 54: 205–215.

Stanford, J.A. and J.V. Ward. 1988. The hyporheic habitat of river ecosystems. *Nature*. 64-66.

Thomas, D. P. and Best, T. L. 2000. Radiotelemetric assessment of movement patterns of the gray bat (*Myotis grisescens*) at Guntersville reservoir, Alabama. *Occasional Papers of the North Carolina Museum of Natural Sciences and the North Carolina Biological Survey*. 12: 27-39.

Tuttle, M. D. 1976. Population ecology of the gray bat (*Myotis grisescens*): philopatry, timing, and patterns of movement, weight loss during migration, and seasonal adaptive strategies. *Museum of Natural History, University of Kansas*. Volume 54.

Tuttle, D.M. 1979. Status, causes of decline, and management of endangered gray bats. *The Journal of Wildlife Management.* 43:1-17.

Ward, J. V., Tockner, K. 2001. Biodiversity: towards a unifying theme for river ecology. *Freshwater Biology*. 46: 807-820.

Wilkinson, L.C. and Barclay, R.M.R. 1997. Differences in the foraging behaviour of male and female big brown bats (*Eptesicus fuscus*) during the reproductive period. *Ecoscience*. 279-285.

Willis, C.K. and Brigham, R.M. 2004. Roost switching, roost sharing and social cohesion: forest-dwelling big brown bats, *Eptesicus fuscus*, conform to the fission–fusion model. *Animal Behaviour*. 68: 495-505.

Womack, K.M., Amelon, S.K., and Thompson, F.R. 2013. Summer home range size of female Indiana bats (*Myotis sodalis*) in Missouri, USA. *Acta Chiropterologica*. 15: 423-429.

5th Chapter: Conclusion

5.1 Summary

Rearing pups in bats is as critical a time as hibernation, and foraging habitat is critical during this time, as lactation is the most energetically expensive time in any mammals' life. Studies specific to gray bats have not addressed the recommendation set in the Gray Bat Recovery Plan to increase understanding of gray bat foraging ecology (Brady 1982, Mitchell and Martin 2002). Gray bats have been an endangered species success story by protecting the hibernacula, of which so few cave systems provide the necessary requirements (Tuttle 1976a). However, foraging habitat requirements and recommendations for protection have never been addressed. With the spread of white-nose syndrome (WNS), a more comprehensive management approach should be taken to not only ensure species survival, but continued growth.

My study has addressed this need, at least partially. First, using aerial telemetry to track foraging movements has demonstrated its appropriateness for highly mobile species with large home ranges. Second, while estimating home ranges from five maternity colonies, four factors that may affect the differences in sizes emerge: habitat continuity, insect abundance, weather, and reproductive status. Also, roost-switching behavior was reported even in lactating females, suggesting the existence of a roost network. Finally, this study confirmed and highlighted the high dependence to water for foraging and traveling. The results suggest the need for management at the landscape level, not just at the cave level.

5.2 Implications

Protection of roosts is vitally important. However, this study has shown the extent of the landscape used by gray bats. They prefer water for use as travel corridors and foraging locations, which is consistent with other studies (LaVal et al. 1977, Thomas and Best 2000). Despite some accounts of opportunistic feeding, other studies point to the ecologically sensitive aquatic insect order of Ephemeroptera (Lacki et al. 1995, Tuttle 1976b). In general, insect emergence seems to be a key component of areas used by foraging gray bats (Elder and Gunier 1981). Protection of the species should be extended to the food source (Brady 1982). Flow disruption, sedimentation and introduction of phosphorus and nitrogen into aquatic systems may inhibit the frequency and size of adult aquatic insect emergence (Lemly 1982), which may affect the carrying capacity of colonies in the way disturbance may affect populations during critical times (Tuttle 1976a).

Like many species, gray bats are affected by urbanization and agricultural ingress, which not only increases roost disturbance, but changes the capacity of waterways to produce aquatic food sources (Cramer and Jensen 2001). Gray bats may respond to changes in habitat in similar ways to aquatic insects. Aquatic systems are extremely sensitive to environmental change, and with gray bats being so closely tied to the food source, populations of this species within certain areas may fluctuate with food availability.

With roost-switching behavior documented through the cave network used during the summer months (considered critical habitat similar to winter hibernacula), effort must be expanded to monitor populations and reduce disturbance (Harvey 1976). Disturbance of caves used by reproductive females can cause roost abandonment and inhibits survival rates of pups living to the age of recruitment (second year) (Tuttle 1979). Cave gates have also been documented as a reason for behavioral changes in cave use at entrances, whereas bats using these caves no longer used that particular gated entrance or cave (Tuttle 1986, Ludlow and Gore 2000). Care must be taken to not only reduce human disturbance but also disturbance from implementation of structures to prevent human disturbance.

5.3 Recommendations

5.3.1 Conservation

Cave gates have shown to be a boon in minimizing human disturbance (Brady 1982), but an issue in regards to continued bat use at the entrance where gates are erected. Observations by Tuttle (1976b) showed emerging gray bats immediately breaking left, right, or up at emergence, making fences more ideal in reducing disturbance. Other studies have shown benefits to bats using interior gates (Martin et al. 2003) and outside fences (Tuttle 1986). Gates present a management issue, especially with critical hibernacula or maternity colonies. In areas of high human traffic, where fences can be circumvented, interior gates are recommended. In areas of low human encroachment, fences may be the best alternative to minimize disturbance.

Continued monitoring of caves is vital to detect changes in behaviors and populations. In addition, multiple caves along the summer-roosting complex should be monitored, as roost-switching behavior seen in this study may implicate other caves in having sizeable colonies. Exit counts, as opposed to interior counts, should be used to assess maternity colonies to reduce disturbance.

Incentives for landowners with private caves should continue to expand. At the sites in this study, regulatory agencies and non-profits worked jointly and with landowners to secure cave easements for roost-protection. Incentive programs have proven successful at all caves in this study with the exception of the Newark storm drain. Though bats continue to use the storm drain, public disturbance in 2014 caused disruption in the number of bats using the cave during the study period. With so few caves being optimal for hibernacula or maternity use, protection and public education (minimize caving on private land during critical periods) are essential to higher pup survival.

Cave Springs Cave, with a recharge zone of 5,065 ha, is experiencing issues detrimental to continued gray bat use (Drainage Criteria Manual 2015). With increased impervious surface due to urbanization within the zone, runoff is reaching the cave quicker. Observed water levels in 2015 were 25 cm from the roof of the cave. Interior flooding and passage constriction could result in high mortality. Steps are being taken to reduce heavy flow into the cave, both for gray bat and Ozark cavefish (*Amblyopsis rosae*).

Protections should extend beyond roosts to foraging areas. While public lands manage for endangered species, many private landowners contribute to water quality decline from runoff, riparian degradation, or erosion. Cattle and farming, lack of best management practices to combat erosion during and after construction, and environmental disasters contribute to the decline of aquatic biota. A mechanism is already in place (mitigation and easements) to protect areas for endangered species habitat, to provide safe haven in the wake of human impacts (Bonnie 1999). Increased incentives (money per linear stream foot, wetlands, or riparian areas) could be offered for lands where gray bats not only roost, but also forage. Incentives may increase protection in higher elevation streams, where overall health of a drainage area for major rivers begins (Ward and Tockner 2001). In addition, adhering to the Clean Water Act (1972) and levying fines accordingly would greatly assist in continued health of aquatic systems.

5.3.2 Aerial- vs. ground-based telemetry for bat foraging studies

Project cost using aerial tracking is far greater than ground-based telemetry. However, this study has shown the benefits in accuracy and location acquisition in large-scale tracking. Equipment costs are \$3,000-\$8,000 more for a single configuration in an airplane than three ground-based configurations. While there is only one salary (tracker) to pay in aerial applications as opposed to three, the cost is quickly absorbed by the hourly pilot/plane/fuel charges (Table 5.1).

Table 5.1. Hypothetical comparison of costs between aerial tracking and ground-based telemetry (3 stations) using 10 radios for 28 days.

	Amounts	**Aerial**	**Ground-Based**
Equipment		\$8,500	\$5,200
Radios	10	\$2,000	\$2,000
Salary	\$1,500/per	\$1,500	\$4,500
Mileage	5,000 miles		\$2,750
Plane/Fuel/Pilot	\$240/h @ 6 hrs/28 days	\$53,760	
Totals		\$65,760	\$14,450

Two types of flying services can be used for aerial applications. A government organization can contract Civil Air Patrol to fly tracking missions. This cost is an hourly meter plus fuel, with the pilot as a volunteer, and was the method used in this study. With aviation fuel at $5.00 per gallon, the cost is $140/h. The second option is a private service, which gives the study more flexibility. As the study is paying for the pilot's time, flights can be longer and vary in time. The price for pilot/plane/fuel using the same fuel figure is $200-$300/h.

As many studies are cost prohibitive, choosing the cheaper route after deciding on aerial tracking may garner more flight hours. However, a study conducted by Hoskinson (1976) showed greater accuracy in aerial tracking with experienced bush pilots when compared to commercial flying outfits (7-m for bush pilot, 40-m for commercial). It is important to understand that aerial tracking success comes with a learning curve, and literature on methodology is scarce. In the future, literature reviews on methods may result in better understanding in aerial tracking, specifically on bats. Aerial tracking will lead to better location acquisition regardless of the entity flying the tracking missions.

5.3.3 Future Studies

Bats with more than one core-foraging areas, including one centered on the cave, are showing survey bias. As the plane often flew on-station at emergence, some locations were gathered right away. The plane should only circle the roost for two to three days to gather directional habits on individual bats. After the initial period, the plane should begin the tracking evening circling 2-4 km from the roost site. The most effective method for tracking in this study was the "moth to flame" method, using 360° maneuvers with one Yagi pointed directly at the located individual. Staying with that individual for an hour would result in 20 time-independent locations. If other individuals are in the area, alternating between the two or even three every 5 min would maximize flight time usage. The same individual could be tracked on multiple nights within a 7-10 day period, making the study more robust by sampling over time.

With weather and the large foraging ranges of female gray bats, the number of bats to fit with a transmitter from Bone, Newark, Logan, and Crystal caves should have been reduced to 12-15 individuals per harp-trapping session for a more effective gathering of the minimum number of locations. Tracking 25 bats moving in several directions in a few hours per night is difficult if not unrealistic. Therefore, future tracking studies on gray bats and similar species is recommended to harp-trap each cave twice (once a week), transmittering 12 females at each event, staggering introduction of bats into the study, as a way to maximize location gathering. However, the disturbance to the maternity colonies could be excessive. Spending 7-10 days per colony, with 12-15 individuals transmittered, would be ideal if multiple colonies are in the area.

Due to the quick transition into post-lactation stages in 2015, a multi-year study on foraging of lactating females could not be conducted, but this has raised interesting questions regarding the role of reproductive status in foraging behavior. Therefore, future studies on gray bat foraging behavior should be centered on collecting more than one year of data per life-stage, in the same location, repeated across areas. Post-lactation foraging studies in Independence County, or lactation foraging studies in Benton County may help resolve the discrepancy in the year effects seen in this study, nullifying habitat variables. However, the unpredictability of weather could still be a factor. Lactation studies in northwest Arkansas should likely be conducted starting during the first week of June, to avoid catching bats already beyond the lactating stage.

My study does not address insect availability in the core-foraging areas directly, with quantitative sampling on species composition or insect load. Future studies could concentrate efforts on insect sampling in core-foraging areas of tracked bats. Samples using light traps, kick seines, or benthic surveys could determine availability in those areas, complementing this study with a more complete understanding. A study centered on aquatic food availability could also determine if feeding preferences are different based on insect types through the three distinct ecoregions in which the colonies within this study foraged.

In addition to these data on gray bat foraging, management decisions could be considered with water quality data conducted at the state or federal level, as these studies are ongoing for other purposes. Data from surveys within the home ranges described may provide information on population fluctuations in maternity colonies. These data would also provide a basis for understanding to why gray bats forage in these locations, and a more specific recovery plan could then be written in light of these findings. Standards protecting aquatic resources could then be proposed and enacted.

5.4 Literature Cited

Brady, J.T., Kunz, T.H., Turtle, M.D., and Wilson, D.E. (1982). "Gray bat recovery plan," U.S. Fish and Wildlife Service, Denver, CO.

Cramer, G.L., Jensen, C.W., and Southgate Jr, D.D. 2001. *Agricultural economics and agribusiness* (No. Ed. 8). John Wiley and Sons.

Drainage Criteria Manual. 2015. Chapter 10- Cave Springs Direct Recharge area water quality protection requirements. City of Rogers, Arkansas. CSK 1-30.

Harvey, M.J. 1976. Homing of gray bats, *Myotis grisescens*, to a hibernaculum. *American Midland Naturalist.* 96: 497–498.

Hoskinson, R.L. 1976. The effect of different pilots on aerial telemetry error. *The Journal of Wildlife Management*.137-139.

Elder, W.H. and Gunier, W.J. 1981. Dynamics of a gray bat population (*Myotis grisescens*) in Missouri. *American Midland Naturalist*. 105: 193–195.

Lacki, M.J., Burford, L.S. and Whitaker, J.O. 1995. Food habits of gray bats in Kentucky. *Journal of Mammalogy*. 76:1256-1259.

LaVal, R.K., Clawson, R.L., LaVal, M.L., and Caire, W. 1977. Foraging behavior and nocturnal activity patterns of Missouri bats, with emphasis on the endangered species *Myotis grisescens* and *Myotis sodalis*. *Journal of Mammalogy*. 58: 592-599.

Lemly, A.D., 1982. Modification of benthic insect communities in polluted streams: combined effects of sedimentation and nutrient enrichment. *Hydrobiologia*. 87: 229-245.

Ludlow, M.E. and Gore, J.A., 2000. Effects of a cave gate on emergence patterns of colonial bats. *Wildlife Society Bulletin*. 191-196.

Martin, K.W., Leslie Jr, D.M., Payton, M.E., Puckette, W.L. and Hensley, S.L., 2003. Internal cave gating for protection of colonies of the endangered gray bat (Myotis grisescens). *Annals of Carnegie Museum*. 51: 143-150.

Mitchell, W.A., and Martin, C.O. 2002. *Cave-and Crevice-Dwelling Bats on USACE Projects: Gray Bat (Myotis grisescens)* (No. ERDC-TN-EMRRP-SI-25). Engineer Research and Development Center, Vicksburg, MS.

Thomas, D.P. and Best, T.L. 2000. Radiotelemetric assessment of movement patterns of the gray bat (*Myotis grisescens*) at Guntersville reservoir, Alabama. *Occasional Papers of the North Carolina Museum of Natural Sciences and the North Carolina Biological Survey*. 12: 27-39.

Tuttle, M.D. 1986. Endangered gray bat benefits from protection. *Bats*. 44: 1-3.

Tuttle, D.M. 1979. Status, causes of decline, and management of endangered gray bats. *The Journal of Wildlife Management.* 43: 1-17.

Tuttle, M.D. 1976(a). Population ecology of the gray bat (*Myotis grisescens*): factors influencing growth and survival of newly volant young. *Ecological Society of America 57*: 587–595.

Tuttle, M.D. 1976(b). Population ecology of the gray bat (*Myotis grisescens*): philopatry, timing, and patterns of movement, weight loss during migration, and seasonal adaptive strategies. *Museum of Natural History, University of Kansas*. Volume 54.

Tuttle, M.D. 1974. Population ecology of the gray bat (*Myotis grisescens*): factors influencing early growth and development. *Occasional Papers of the Museum of Natural History, University of Kansas.* 36: 1-24.

Ward, J.V. and Tockner, K. 2001. Biodiversity: towards a unifying theme for river ecology. *Freshwater Biology*. 46: 807-820.

Appendix A

Appendix A. Capture record and foraging areas (95% FK home range, 50% FK core-foraging, and minimum convex polygon (MCP) in hectares of bats with 15 or more locations that were individually analyzed for foraging and compositional analysis.

Capture Date	Repro. Status	Location	Left Band	Frequency	95% FK	50% FK	MCP	Days Tracked	# Locations
6/15/2014	Lactating	Newark	5002	150213	54,900	14,023	24,246	6	24
6/15/2014	Lactating	Newark	4401	150775	46,113	10,676	13,543	5	20
6/15/2014	Lactating	Newark	4403	150815	32,012	4,838	27,471	6	27
6/15/2014	Lactating	Newark	4406	150936	10,790	1,371	14,162	5	21
6/15/2014	Lactating	Newark	4408	150993	7,213	1,169	4,575	7	15
7/1/2014	Lactating	Bone	4295	150735	126,387	33,368	48,224	8	21
7/1/2014	Lactating	Bone	4280	151143	7,660	1,575	3,679	8	18
7/1/2014	Lactating	Bone	4278	151186	89,901	22,694	21,926	4	15
7/1/2014	Lactating	Bone	4272	151627	24,021	3,908	22,006	6	24
7/1/2014	Lactating	Bone	4269	151667	11,183	2,233	2,890	5	15
7/1/2014	Lactating	Bone	4270	151700	20,273	4,329	12,538	8	26
7/1/2014	Lactating	Bone	4271	151744	6,497	1,191	3,701	7	16
7/1/2014	Lactating	Bone	4274	151788	30,301	5,964	18,154	6	15
7/1/2014	Lactating	Bone	4282	151948	39,866	9,144	23,068	6	17
6/14/2015	Post-lactating	Logan	5689	150994	20,346	4,644	5,058	3	17
6/14/2015	Post-lactating	Logan	5686	151028	5,555	1,440	2,359	4	16
6/14/2015	Post-lactating	Logan	5685	151107	2,834	545	1,156	3	18
6/14/2015	Post-lactating	Logan	5691	151186	14,160	3,682	3,464	4	21
6/14/2015	Post-lactating	Logan	5684	151263	7,935	1,798	3,258	4	16
6/14/2015	Post-lactating	Logan	5682	151308	4,345	693	3,912	4	19
6/14/2015	Post-lactating	Logan	5692	151431	600	171	262	3	26
6/14/2015	Post-lactating	Logan	5679	151709	7,130	1,545	3,106	3	24
6/14/2015	Post-lactating	Logan	5678	151785	2,293	372	2,488	5	18
6/14/2015	Post-lactating	Logan	5698	151832	8,177	2,034	2,527	4	24
6/22/2015	Post-lactating	Cave Springs	15473	150008	3,474	570	997	3	23

6/22/2015	Post-lactating	Cave Springs	15499	150515	3,480	880	1,936	3	31
6/22/2015	Post-lactating	Cave Springs	15500	150554	2,220	386	670	4	24
6/22/2015	Post-lactating	Cave Springs	15459	150713	4,048	699	1,096	4	23
6/22/2015	Post-lactating	Cave Springs	15457	150830	1,669	337	281	4	17
6/22/2015	Post-lactating	Cave Springs	15456	150869	1,793	233	2,071	3	21
6/14/2015	Post-lactating	Crystal	0632	150205	4,857	691	4,013	3	23
6/14/2015	Post-lactating	Crystal	0631	150234	11,807	2,475	4,853	4	17
6/14/2015	Post-lactating	Crystal	4748	150312	2,906	626	639	4	16
6/14/2015	Post-lactating	Crystal	0619	150394	6,264	1,574	3,437	4	35
6/14/2015	Post-lactating	Crystal	4731	150534	5,710	1,314	2,065	3	26
6/14/2015	Post-lactating	Crystal	0614	150573	2,645	489	2,401	4	20
6/14/2015	Post-lactating	Crystal	0613	150614	1,744	256	1,663	4	19
6/14/2015	Post-lactating	Crystal	0611	150734	10,645	2,747	2,878	3	17
6/14/2015	Post-lactating	Crystal	0609	150796	5,706	1,284	3,287	4	23
6/14/2015	Post-lactating	Crystal	0610	150815	12,620	3,410	3,040	2	22
6/14/2015	Post-lactating	Crystal	0608	150855	4,318	1,108	1,714	3	15
6/14/2015	Post-lactating	Crystal	0602	150934	2,876	467	1,202	4	20
								Total	865

Appendix B

Appendix B. Record of all study bats transmittered and had less than 15 locations (70 bats). These bats were not analyzed for foraging areas, but were used in 95% home range, 50% core-foraging area, and minimum convex polygon analysis on the cave level. These were not included in compositional analysis, as the percent habitat used must be addressed using only the bats with enough locations for individual analysis of home range.

Capture Date	Repro. Status	L Wing Damage	Left Band	Frequency	# Locations	Days Tracked
6/15/2014	Lactating	Newark	5018	150227	4	3
6/15/2014	Lactating	Newark	5026	150271	13	4
6/15/2014	Lactating	Newark	5019	150314	6	1
6/15/2014	Lactating	Newark	5015	150348	10	5
6/15/2014	Lactating	Newark	5020	150375	8	5
6/15/2014	Lactating	Newark	5021	150390	10	5
6/15/2014	Lactating	Newark	5022	150415	12	5
6/15/2014	Lactating	Newark	4251	150455	9	4
6/15/2014	Lactating	Newark	4252	150497	2	1
6/15/2014	Lactating	Newark	4253	150534	12	6
6/15/2014	Lactating	Newark	4254	150575	0	0
6/15/2014	Lactating	Newark	4255	150594	2	2
6/15/2014	Lactating	Newark	4256	150615	0	0
6/15/2014	Lactating	Newark	4257	150653	3	1
6/15/2014	Lactating	Newark	4258	150697	9	5
6/15/2014	Lactating	Newark	4402	150795	12	3
6/15/2014	Lactating	Newark	4404	150856	4	3
6/15/2014	Lactating	Newark	4405	150894	5	2
6/15/2014	Lactating	Newark	4407	150975	14	3
6/15/2014	Lactating	Newark	5024	151026	11	5
7/1/2014	Lactating	Bone	4297	151063	13	4
7/1/2014	Lactating	Bone	4298	151107	11	4
7/1/2014	Lactating	Bone	4277	151228	9	4
7/1/2014	Lactating	Bone	4776	151265	11	4

7/1/2014	Lactating	Bone	4285	151310	9	6
7/1/2014	Lactating	Bone	4294	151349	4	3
7/1/2014	Lactating	Bone	4293	151387	4	4
7/1/2014	Lactating	Bone	4300	151428	7	4
7/1/2014	Lactating	Bone	4267	151467	7	4
7/1/2014	Lactating	Bone	4268	151506	12	4
7/1/2014	Lactating	Bone	4299	151550	13	4
7/1/2014	Lactating	Bone	4273	151588	7	3
7/1/2014	Lactating	Bone	4284	151831	11	4
7/1/2014	Lactating	Bone	4283	151867	6	2
7/1/2014	Lactating	Bone	4281	151910	6	3
7/1/2014	Lactating	Bone	4275	151991	9	3
6/14/2015	Post-lactating	Logan	5690	151069	0	0
6/14/2015	Post-lactating	Logan	5673	151229	9	3
6/14/2015	Post-lactating	Logan	5659	151346	0	0
6/14/2015	Post-lactating	Logan	5682	151385	4	2
6/14/2015	Post-lactating	Logan	5681	151475	14	3
6/14/2015	Post-lactating	Logan	5693	151508	1	1
6/14/2015	Post-lactating	Logan	5694	151549	0	0
6/14/2015	Post-lactating	Logan	5680	151589	0	0
6/14/2015	Post-lactating	Logan	5695	151624	0	0
6/14/2015	Post-lactating	Logan	5696	151672	0	0
6/14/2015	Post-lactating	Logan	5697	151746	1	1
6/14/2015	Post-lactating	Logan	5677	151866	8	3
6/14/2015	Post-lactating	Logan	5700	151947	5	2
6/14/2015	Post-lactating	Logan	5676	151991	11	1
6/22/2015	Post-lactating	Cave Springs	15487	150027	6	1
6/22/2015	Post-lactating	Cave Springs	15488	150435	0	0
6/22/2015	Post-lactating	Cave Springs	15497	150473	9	2
6/22/2015	Post-lactating	Cave Springs	15498	150636	0	0
6/22/2015	Post-lactating	Cave Springs	4443	150674	9	1
6/22/2015	Post-lactating	Cave Springs	15458	150756	3	1

6/14/2015	Post-lactating	Crystal	0634	150192	2	1
6/14/2015	Post-lactating	Crystal	0630	150270	1	1
6/14/2015	Post-lactating	Crystal	4747	150354	3	1
6/14/2015	Post-lactating	Crystal	0629	150375	13	3
6/14/2015	Post-lactating	Crystal	0628	150416	11	4
6/14/2015	Post-lactating	Crystal	0617	150452	5	3
6/14/2015	Post-lactating	Crystal	0616	150496	1	1
6/14/2015	Post-lactating	Crystal	4729	150594	4	1
6/14/2015	Post-lactating	Crystal	4703	150653	12	2
6/14/2015	Post-lactating	Crystal	4702	150696	0	0
6/14/2015	Post-lactating	Crystal	4701	150775	4	2
6/14/2015	Post-lactating	Crystal	0607	150895	4	2
6/14/2015	Post-lactating	Crystal	0601	150978	3	1
				Total	428	

Appendix C

Appendix C. The following figures represent the 95% FK home ranges (orange) and 50% core-foraging areas (blue) for each of the 42 individually analyzed bats. The satellite imagery allows for the visual determination of types of water used. All locations have an error of 400 m except bats from Crystal Cave, which have an 800 m error. Bats are identified by the last three numbers of their transmitter frequency and cave location.

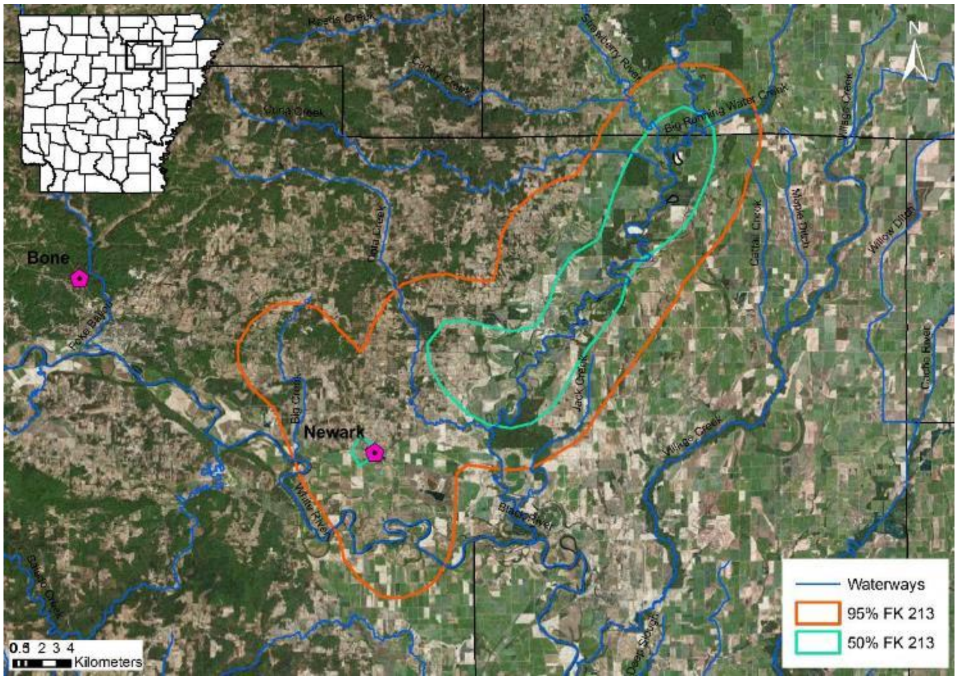


Figure C-1. Lactaing female 213 from Newark storm drain with a 95% FK of 54,900 ha and a 50% FK of 14,023 ha (15 June – 30 June 2014).

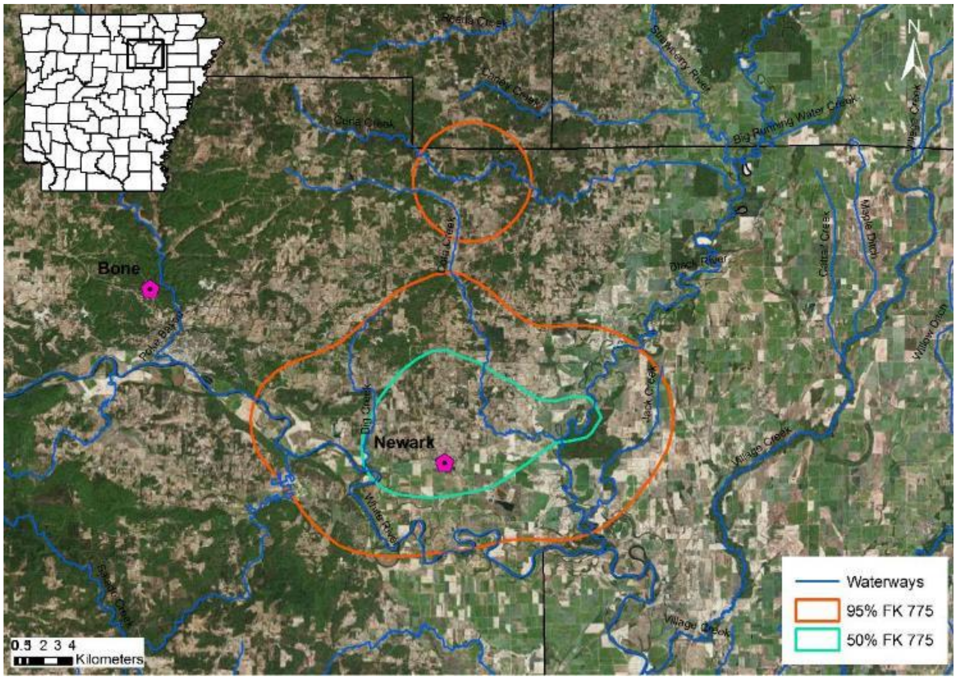


Figure C-2. Lactaing female 775 from Newark storm drain with a 95% FK of 46,113ha and a 50% FK of 10,676 ha (15 June – 30 June 2014).

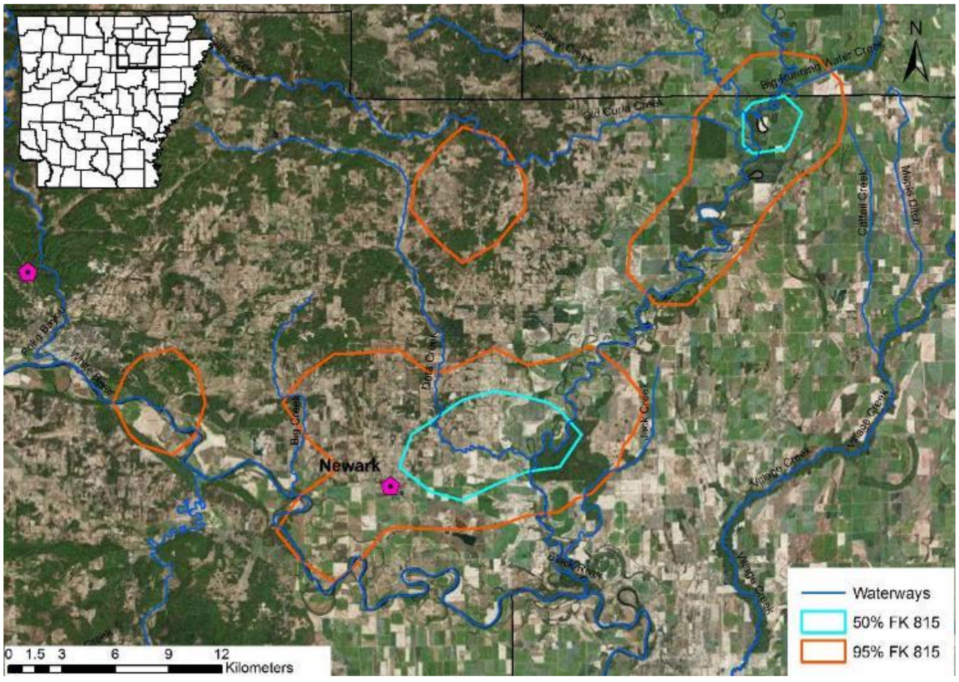


Figure C-3. Lactaing female 815 from Newark storm drain with a 95% FK of 32,012 ha and a 50% FK of 4,838 ha (15 June – 30 June 2014).

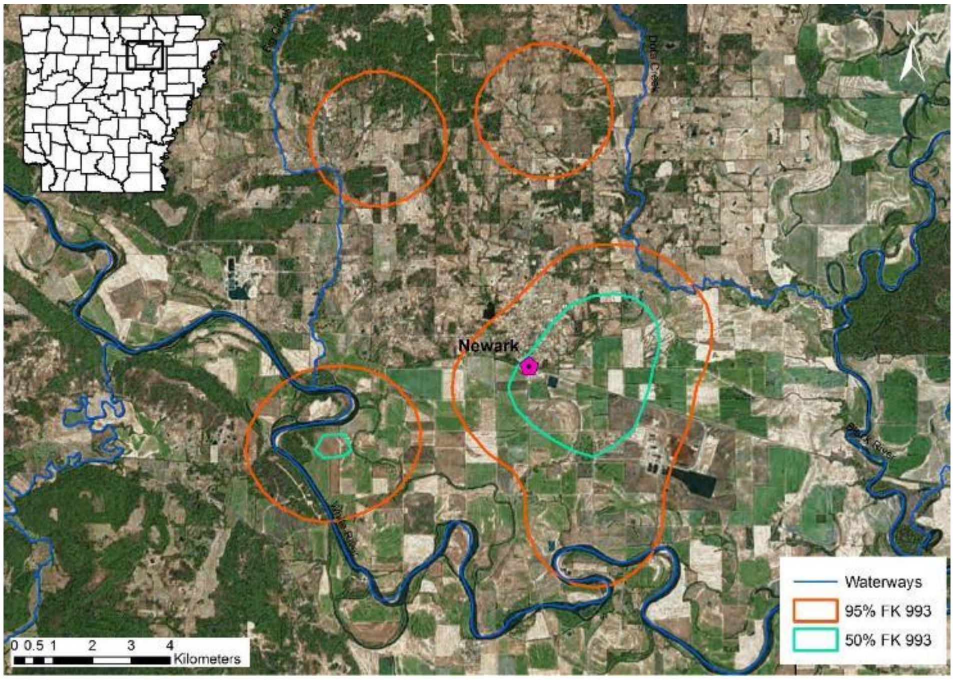


Figure C-4. Lactaing female 993 from Newark storm drain with a 95% FK of 7,213 ha and a 50% FK of 1,169 ha (15 June – 30 June 2014).

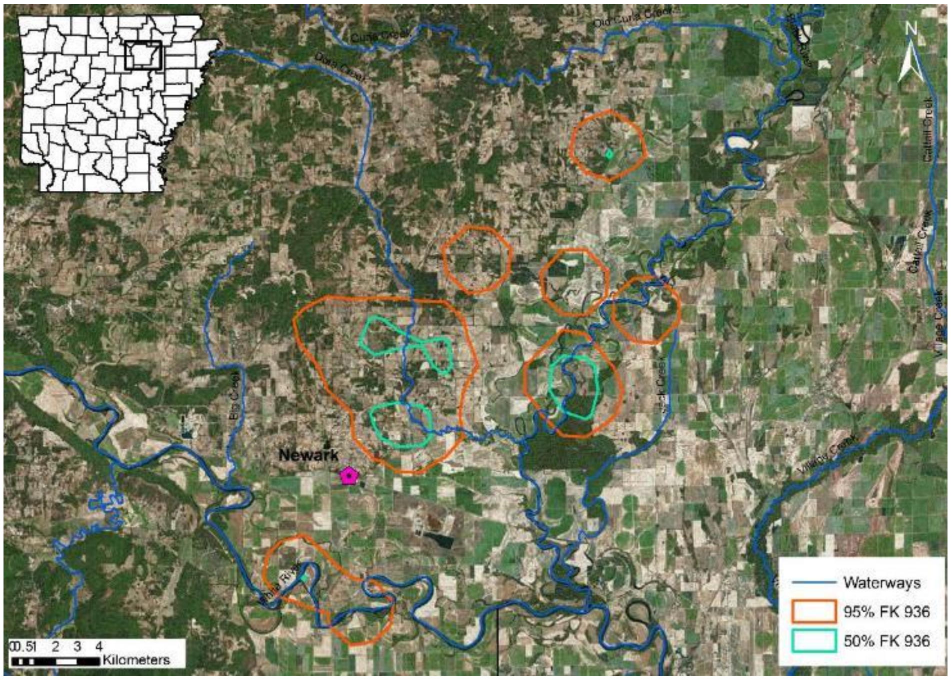


Figure C-5. Lactaing female 936 from Newark storm drain with a 95% FK of 10,790 ha and a 50% FK of 1,371 ha (15 June – 30 June 2014).

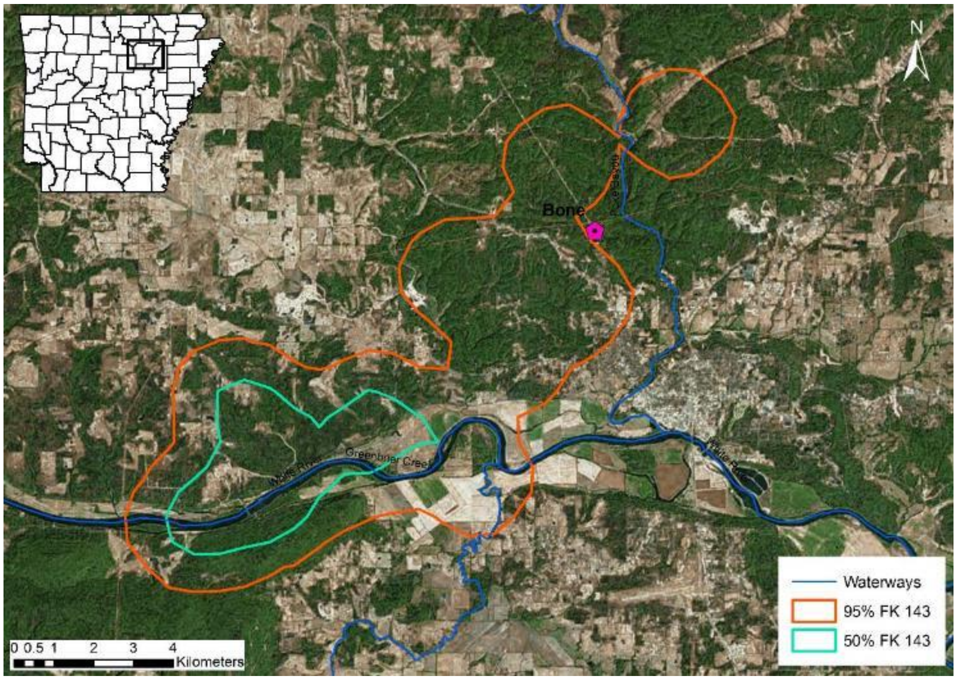


Figure C-6. Lactaing female 143 from Bone Cave with a 95% FK of 7,660 ha and a 50% FK of 1,575 ha (15 June – 30 June 2014).

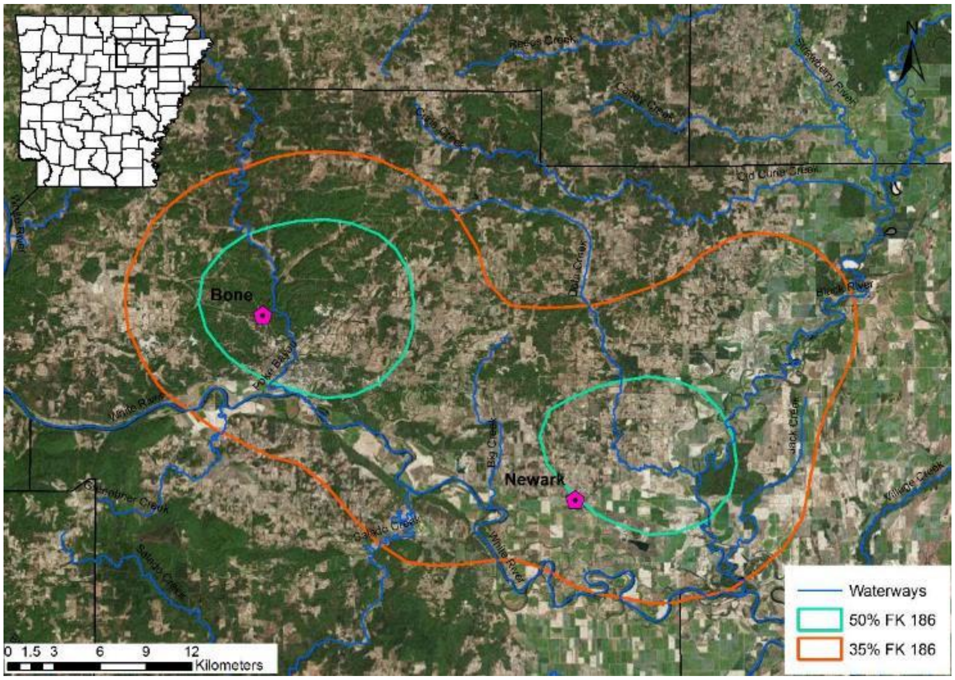


Figure C-7. Lactaing female 186 from Bone Cave with a 95% FK of 89,901 ha and a 50% FK of 22,694 ha (1 July – 15 July 2014).

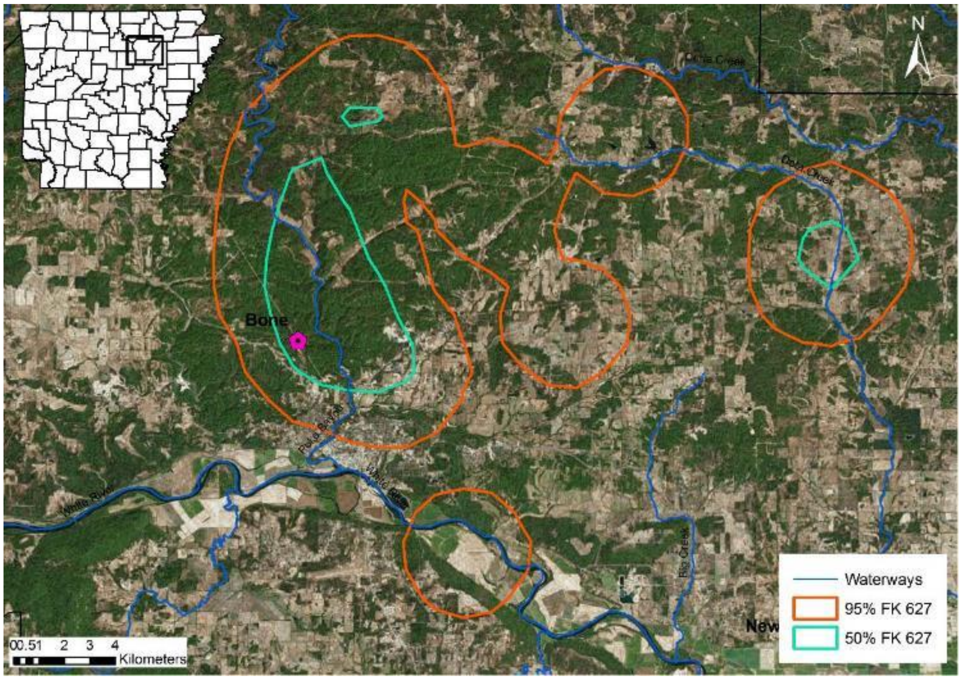


Figure C-8. Lactaing female 627 from Bone Cave with a 95% FK of 24,021 ha and a 50% FK of 3,908 ha (1 July – 15 July 2014).

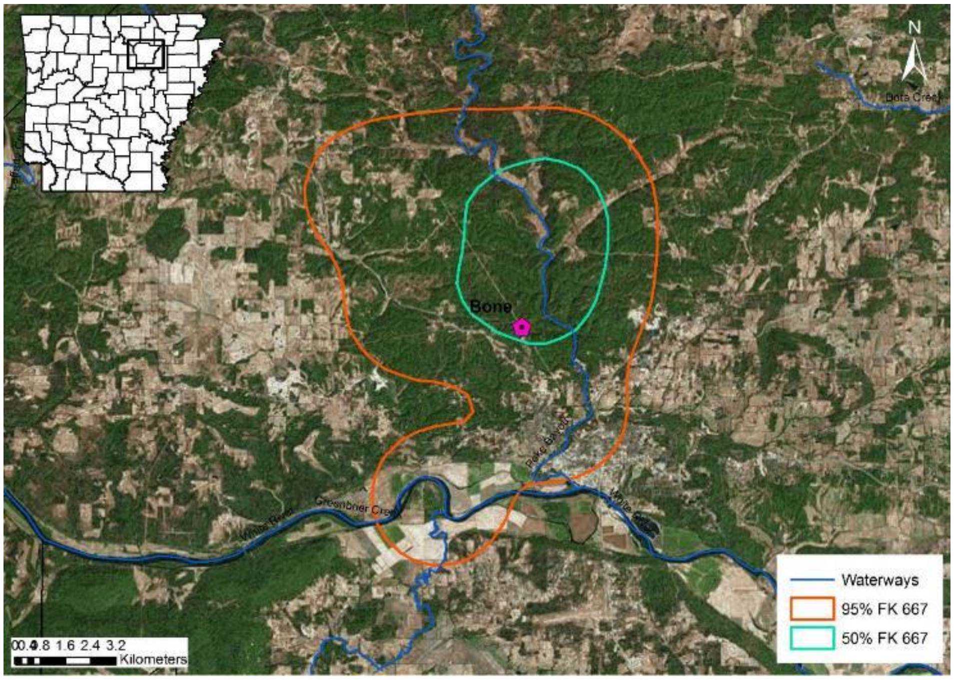


Figure C-9. Lactaing female 667 from Bone Cave with a 95% FK of 11,183 ha and a 50% FK of 2,233 ha (1 July – 15 July 2014).

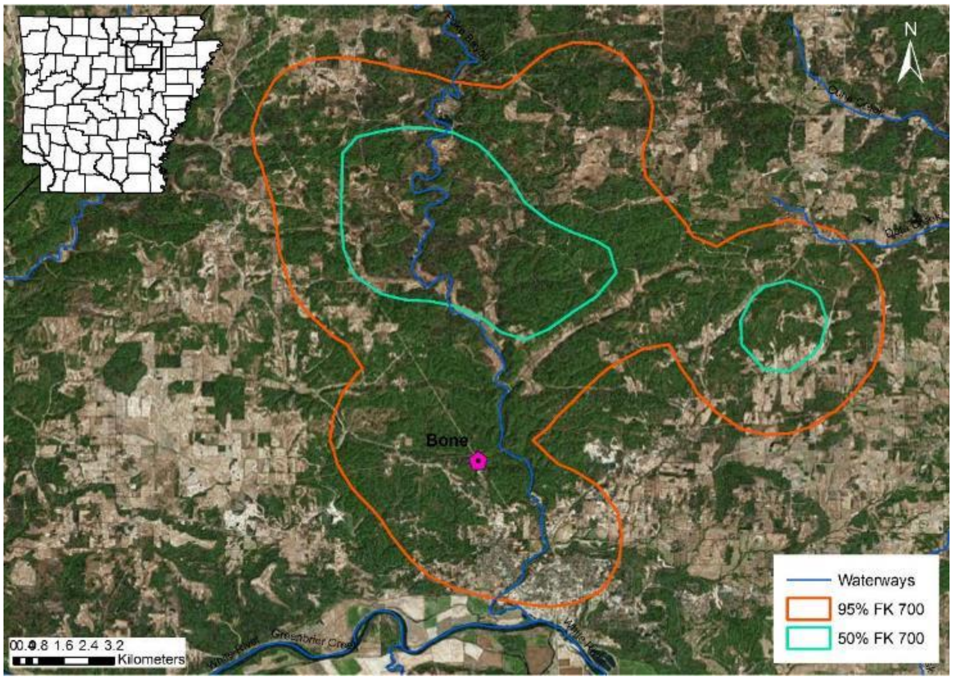


Figure C-10. Lactaing female 700 from Bone Cave with a 95% FK of 20,273 ha and a 50% FK of 4,329 ha (1 July – 15 July 2014).

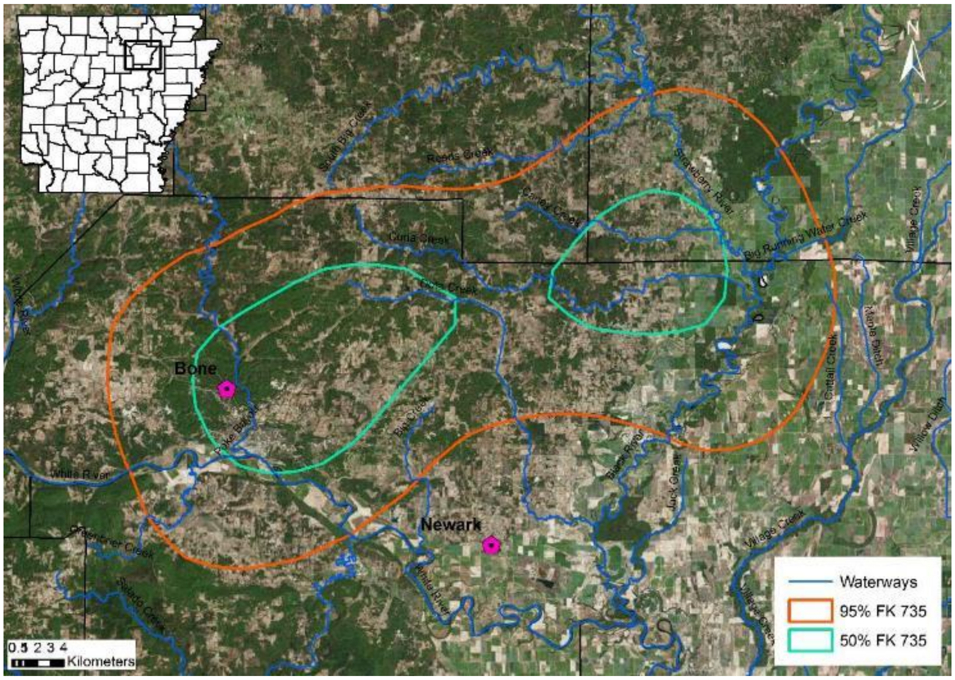


Figure C-11. Lactaing female 735 from Bone Cave with a 95% FK of 126,387 ha and a 50% FK of 33,368 ha (1 July – 15 July 2014).

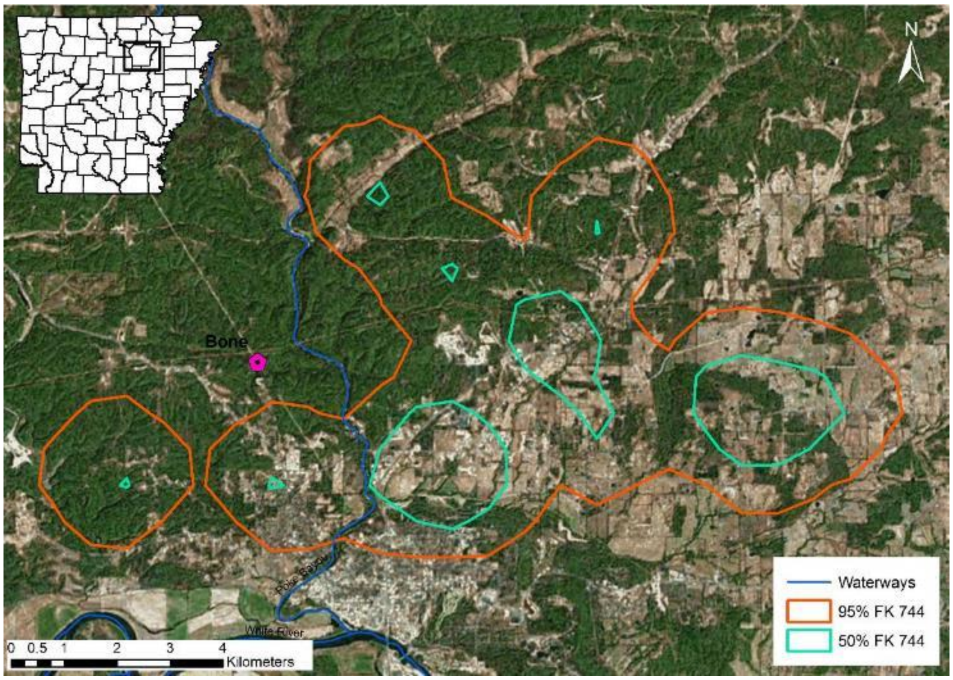


Figure C-12. Lactaing female 744 from Bone Cave with a 95% FK of 6,497 ha and a 50% FK of 1,191 ha (1 July – 15 July 2014).

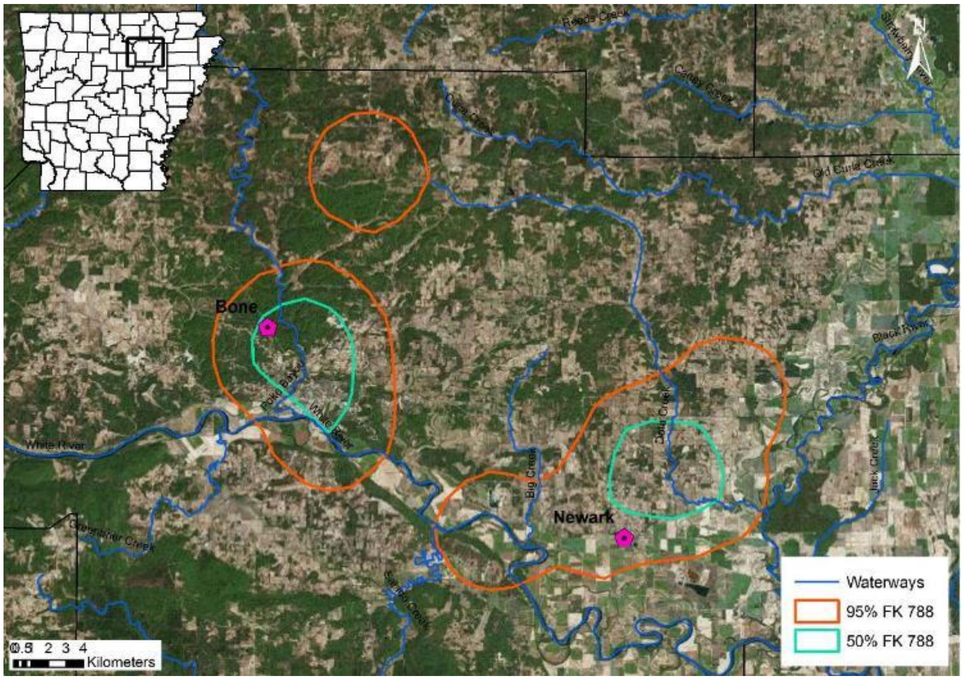


Figure C-13. Lactaing female 788 from Bone Cave with a 95% FK of 30,301 ha and a 50% FK of 5,964 ha (1 July – 15 July 2014).

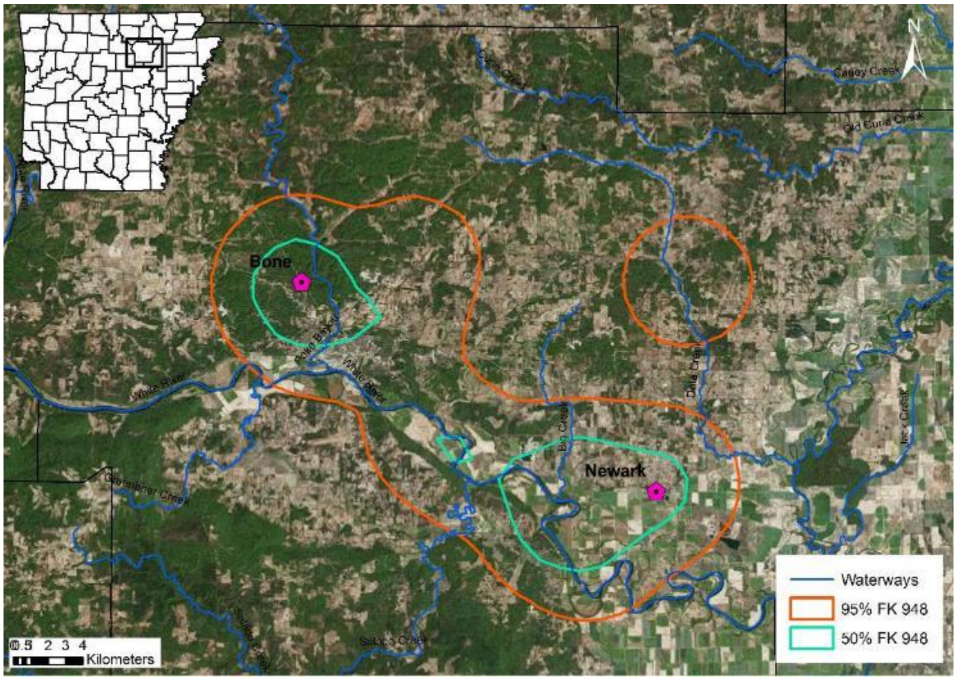


Figure C-14. Lactaing female 948 from Bone Cave with a 95% FK of 39,866 ha and a 50% FK of 9,144 ha (1 July – 15 July 2014).

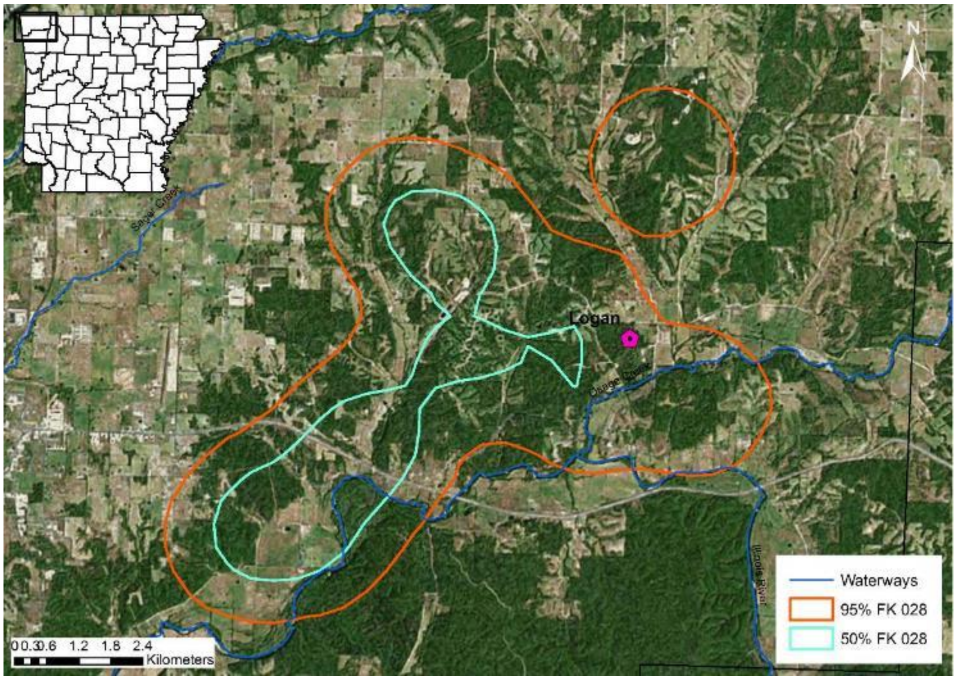


Figure C-15. Post-lactaing female 028 from Logan Cave with a 95% FK of 5,555 ha and a 50% FK of 1,440 ha (15 June – 30 June 2015).

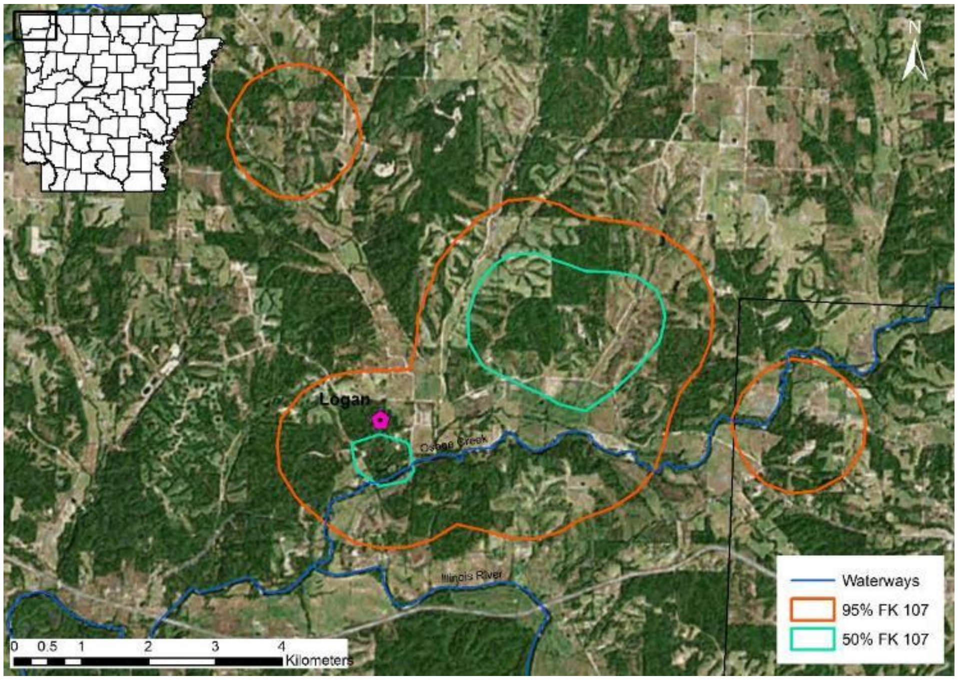


Figure C-16. Post-lactaing female 107 from Logan Cave with a 95% FK of 2,834 ha and a 50% FK of 545 ha (15 June – 30 June 2015).

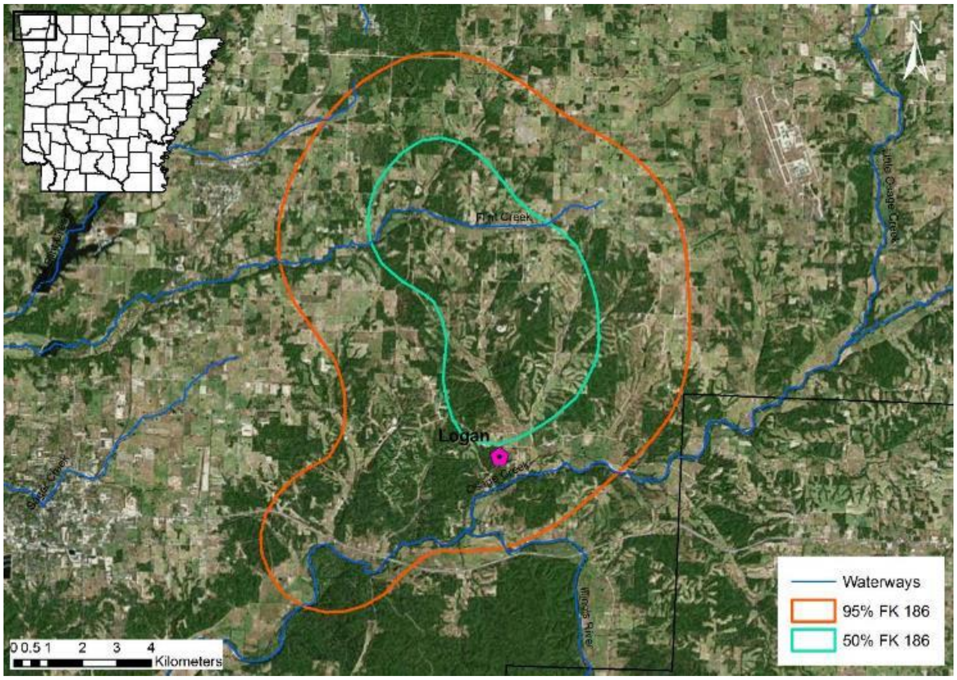


Figure C-17. Post-lactaing female 186 from Logan Cave with a 95% FK of 14,160 ha and a 50% FK of 3,682 ha (15 June – 30 June 2015).

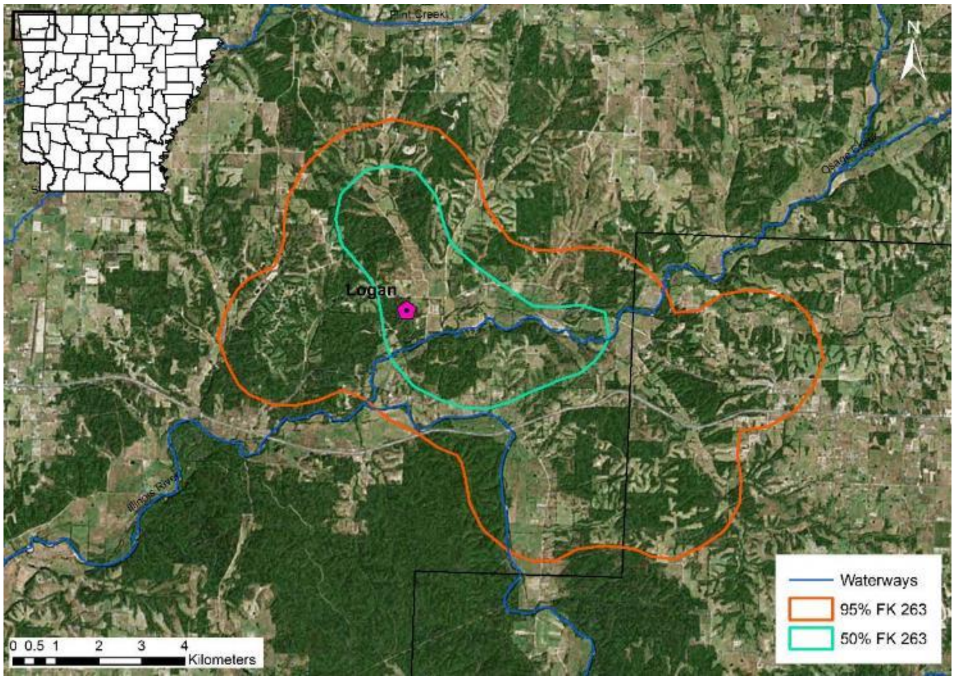


Figure C-18. Post-lactaing female 263 from Logan Cave with a 95% FK of 7,935 ha and a 50% FK of 1,798 ha (15 June – 30 June 2015).

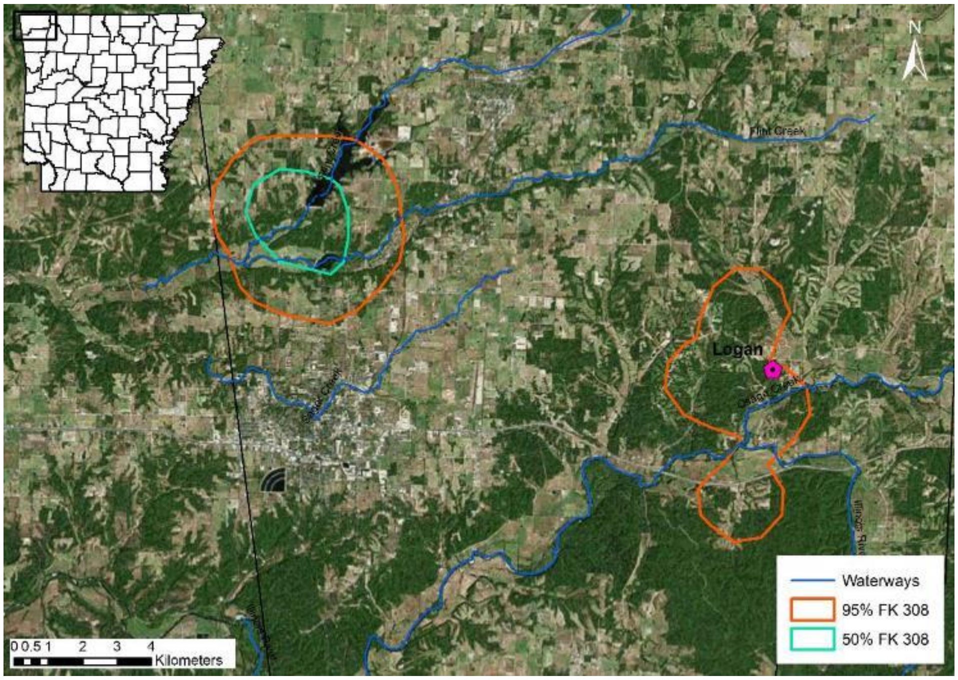


Figure C-19. Post-lactaing female 308 from Logan Cave with a 95% FK of 4,345 ha and a 50% FK of 693 ha (15 June – 30 June 2015).

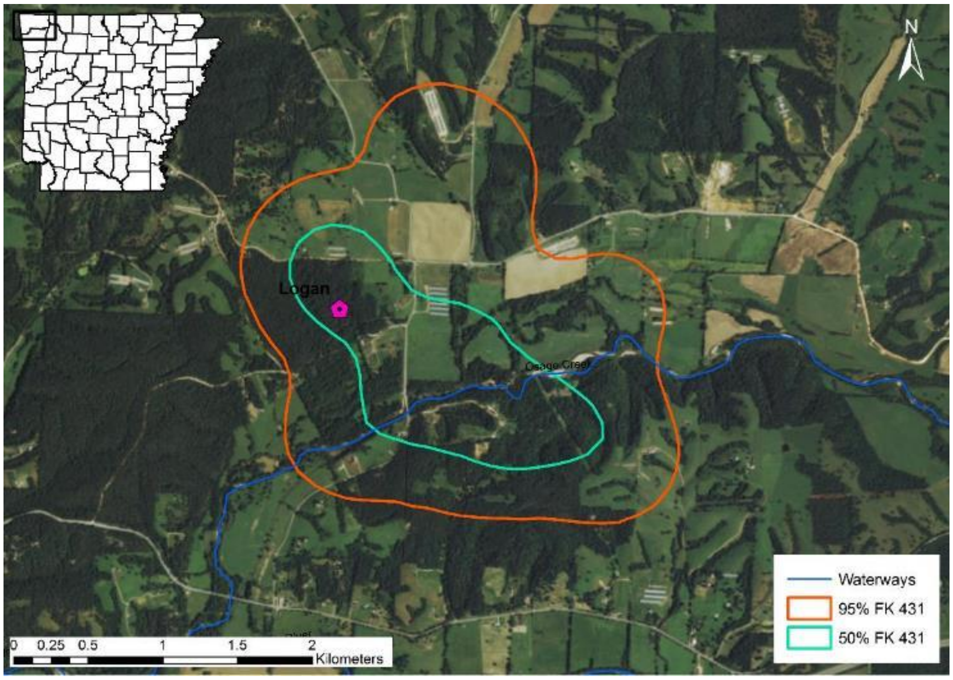


Figure C-20. Post-lactaing female 431 from Logan Cave with a 95% FK of 600 ha and a 50% FK of 171 ha (15 June – 30 June 2015).

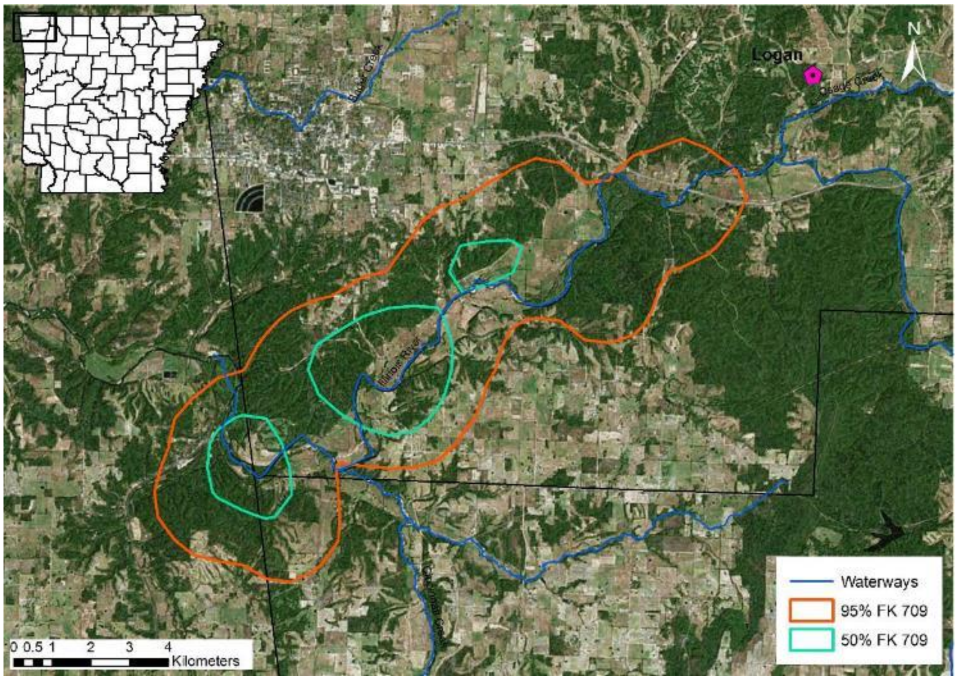


Figure C-21. Post-lactaing female 709 from Logan Cave with a 95% FK of 7,130 ha and a 50% FK of 1,545 ha (15 June – 30 June 2015).

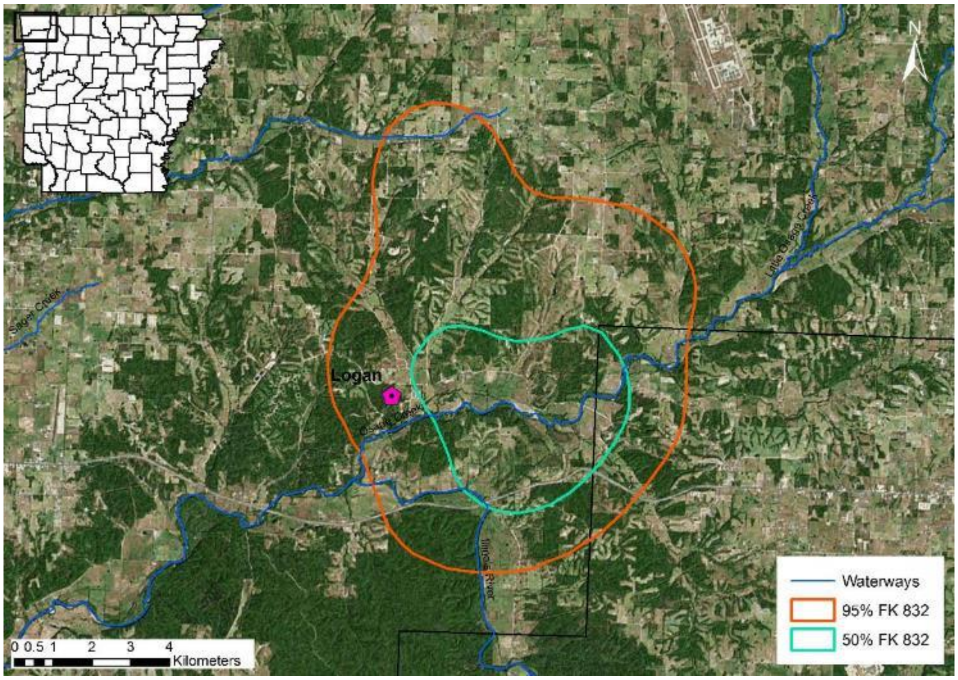


Figure C-22. Post-lactaing female 832 from Logan Cave with a 95% FK of 8,177 ha and a 50% FK of 2,034 ha (15 June – 30 June 2015).

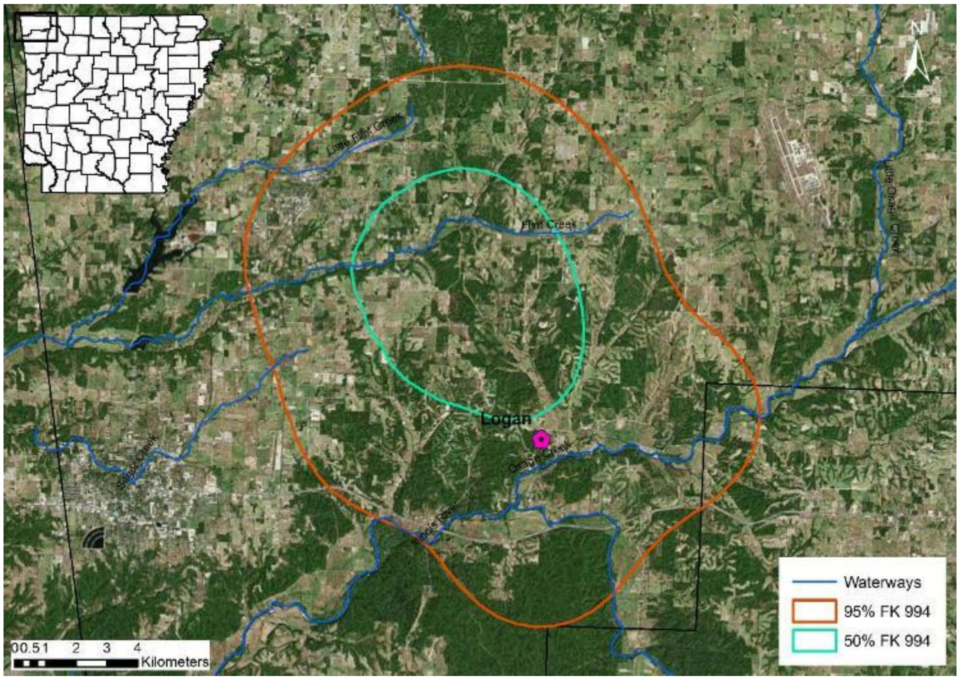


Figure C-23. Post-lactaing female 994 from Logan Cave with a 95% FK of 20,346 ha and a 50% FK of 4,644 ha (15 June – 30 June 2015).

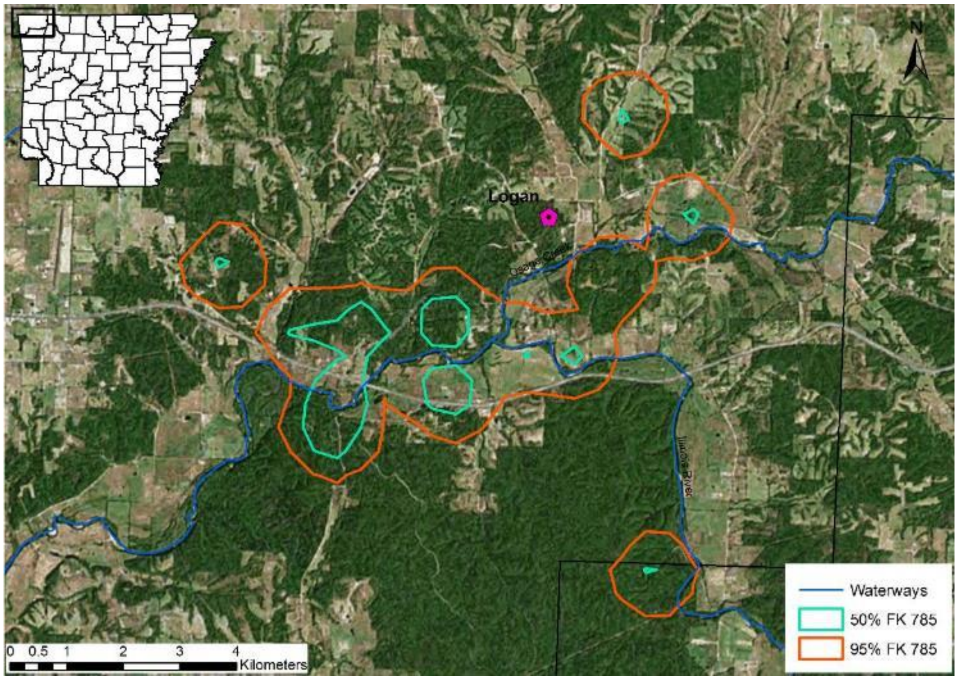


Figure C-24. Post-lactaing female 785 from Logan Cave with a 95% FK of 2,293 ha and a 50% FK of 372 ha (15 June – 30 June 2015).

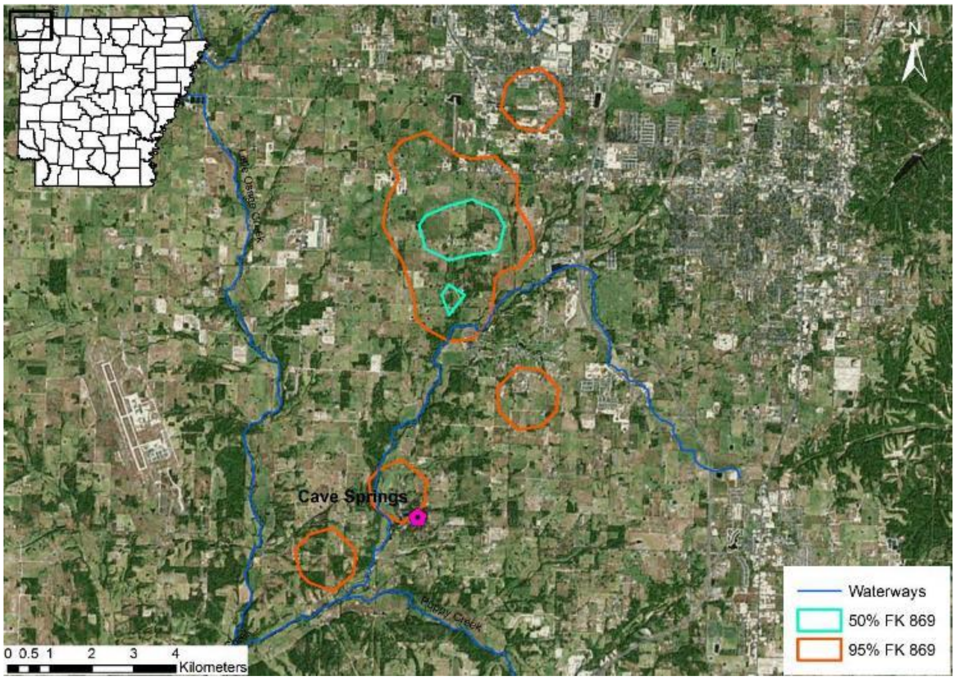


Figure C-25. Post-lactaing female 869 from Cave Springs Cave with a 95% FK of 1,793 ha and a 50% FK of 233 ha (22 June – 2 July 2015).

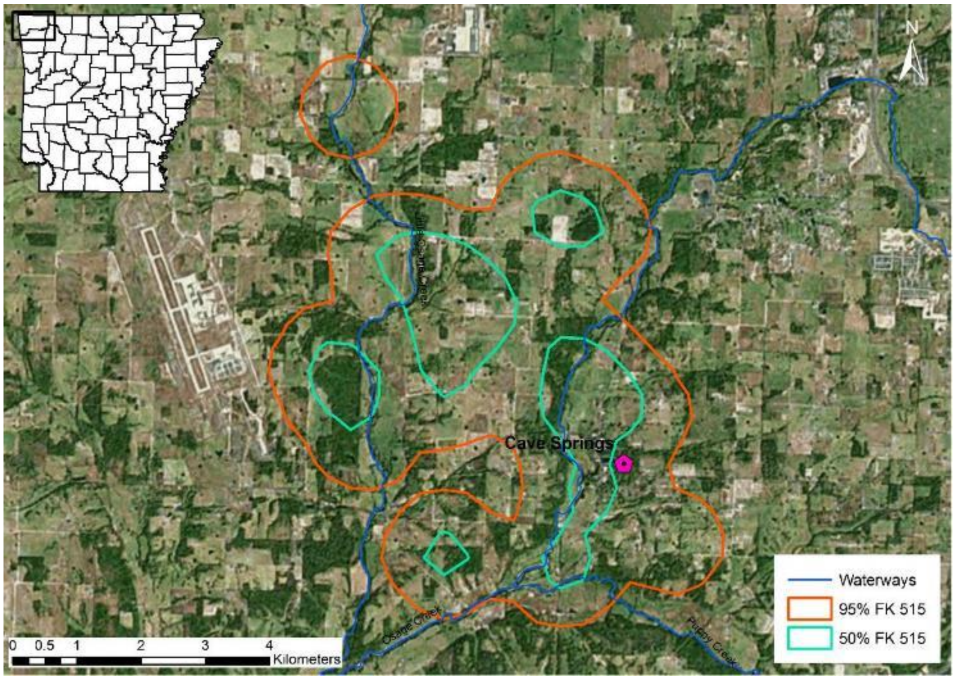


Figure C-26. Post-lactaing female 515 from Cave Springs Cave with a 95% FK of 3,480 ha and a 50% FK of 880 ha (22 June – 2 July 2015).

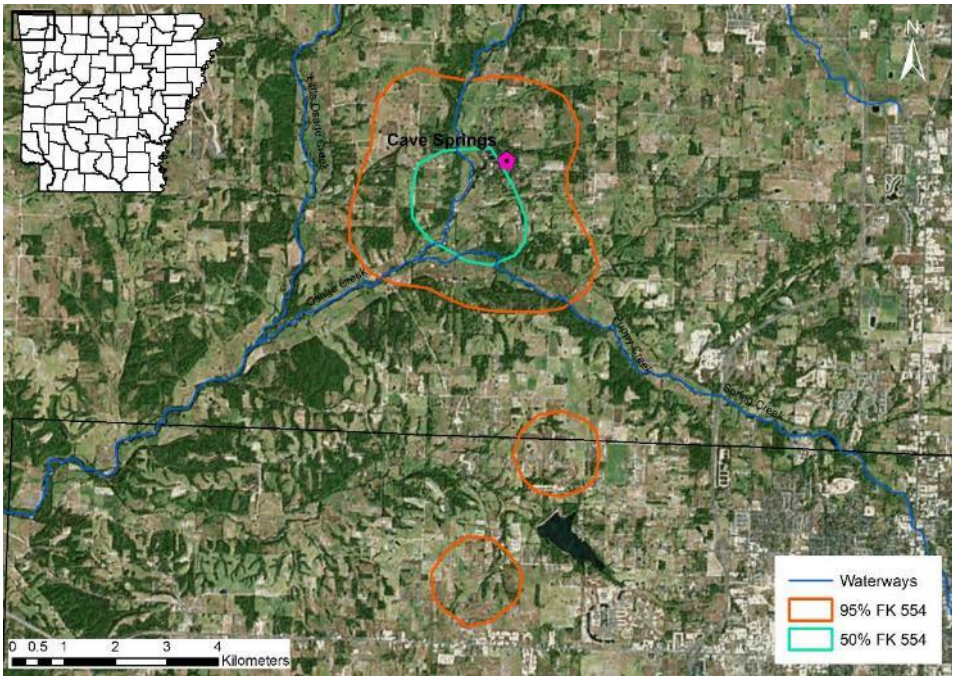


Figure C-27. Post-lactaing female 554 from Cave Springs with a 95% FK of 2,220 ha and a 50% FK of 386 ha (22 June – 2 July 2015).

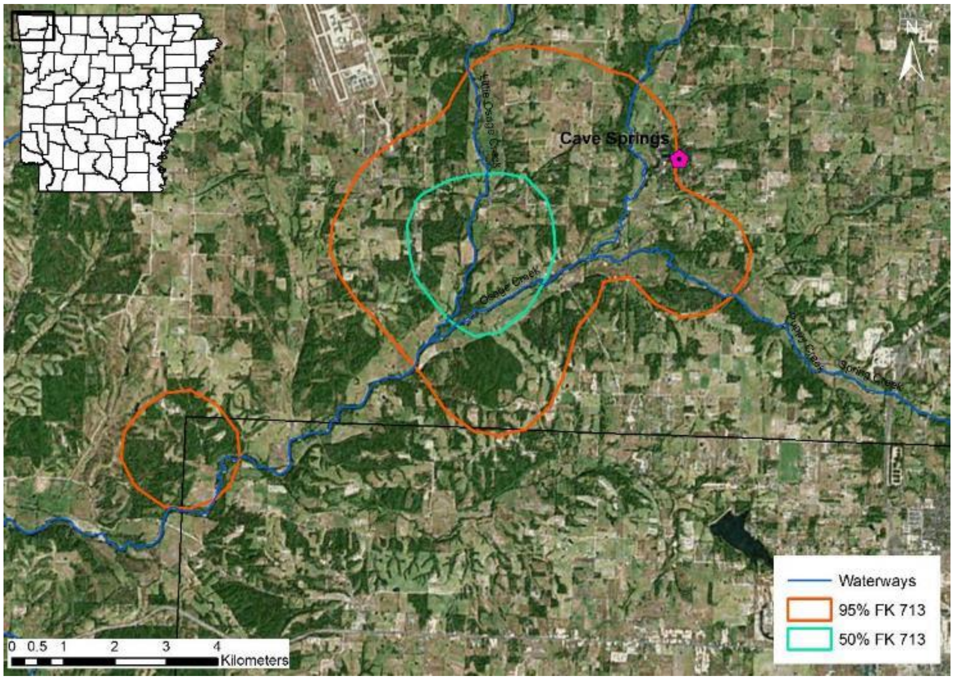


Figure C-28. Post-lactaing female 713 from Cave Springs Cave with a 95% FK of 4,048 ha and a 50% FK of 699 ha (22 June – 2 July 2015).

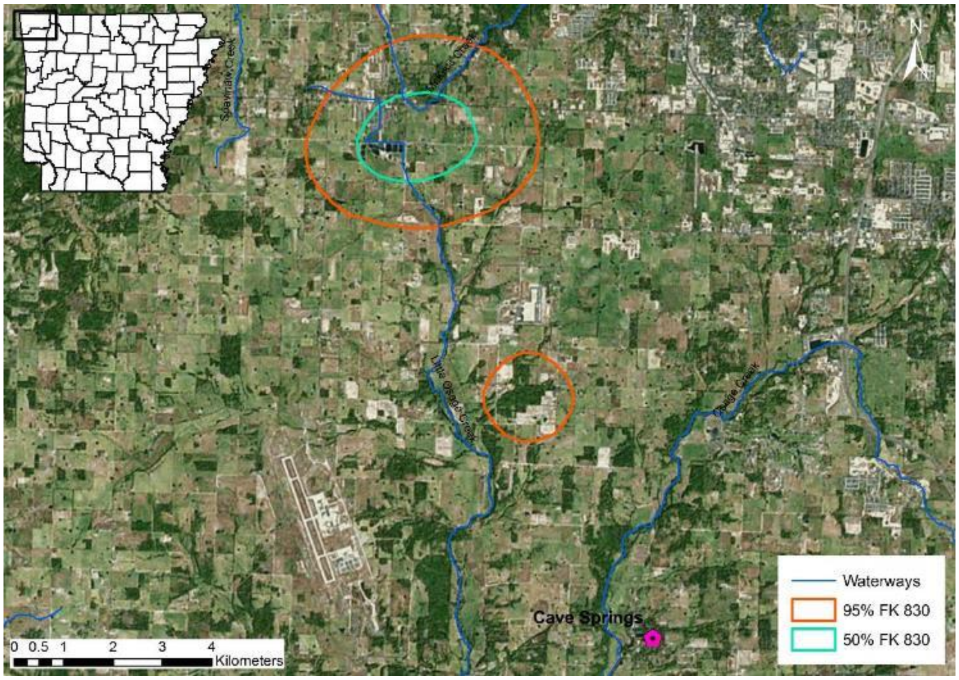


Figure C-29. Post-lactaing female 830 from Cave Springs Cave with a 95% FK of 1,669 ha and a 50% FK of 337 ha (22 June – 2 July 2015).

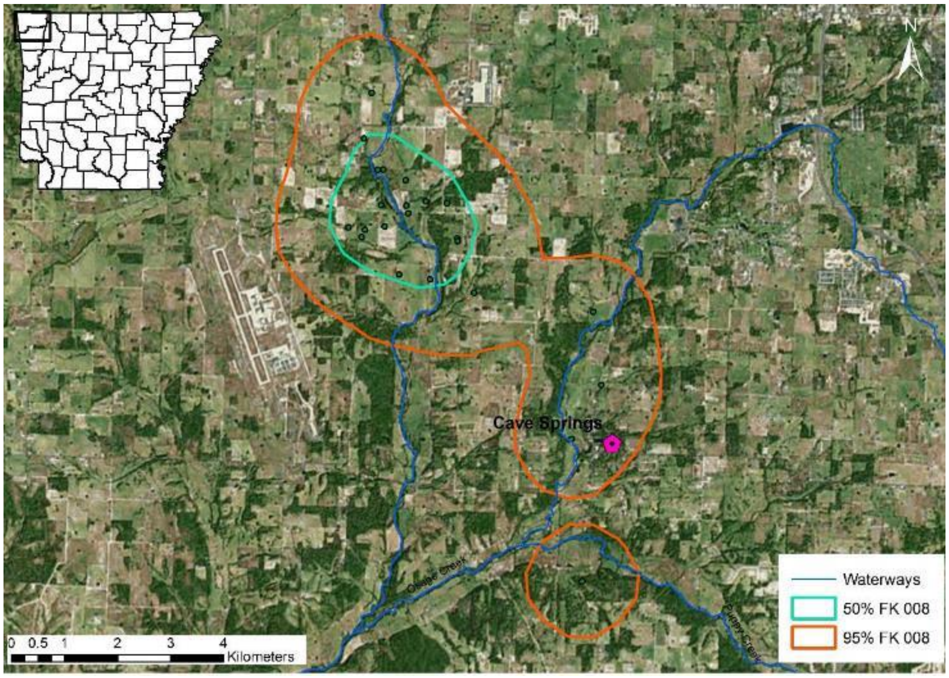


Figure C-30. Post-lactaing female 008 from Cave Springs Cave with a 95% FK of 3,474 ha and a 50% FK of 570 ha (22 June – 2 July 2015).

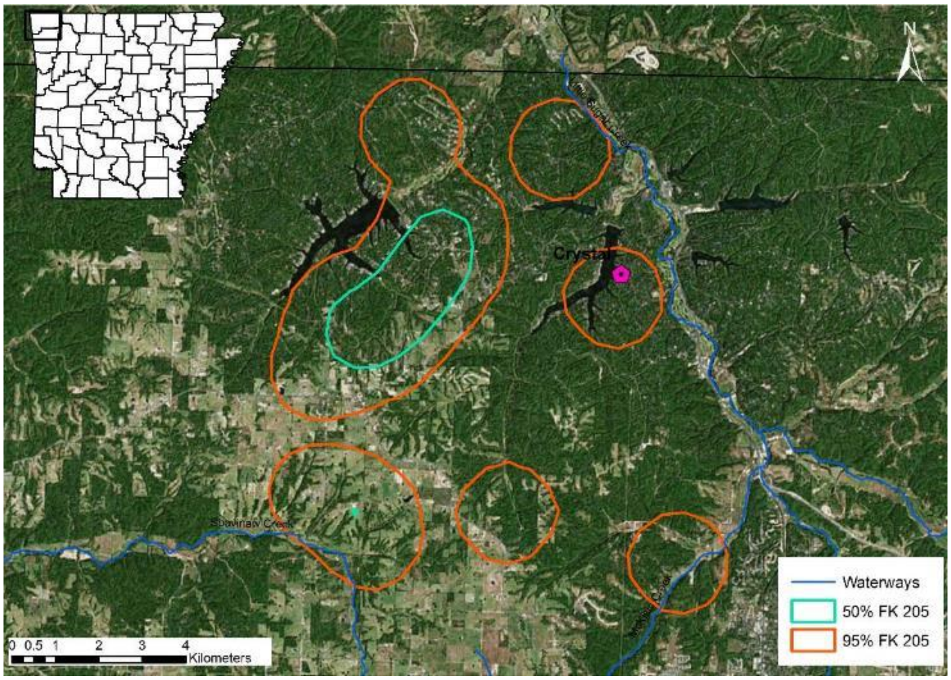


Figure C-31. Post-lactaing female 205 from Crystal Cave with a 95% FK of 4,857 ha and a 50% FK of 691 ha (1 July – 15 July 2015).

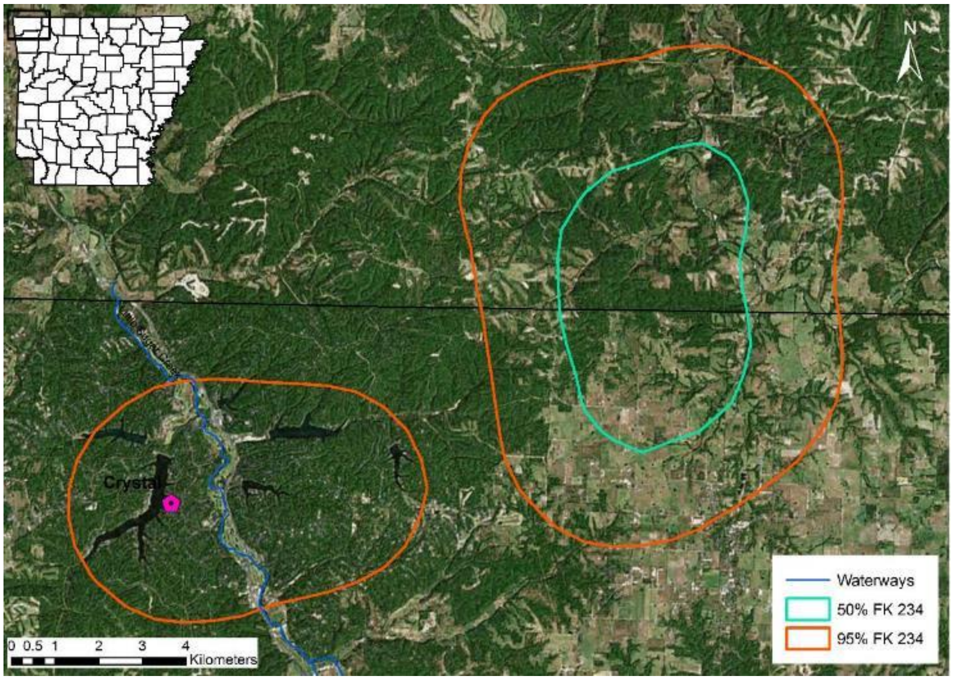


Figure C-32. Post-lactaing female 234 from Crystal Cave with a 95% FK of 11,807 ha and a 50% FK of 2,475 ha (1 July – 15 July 2015).

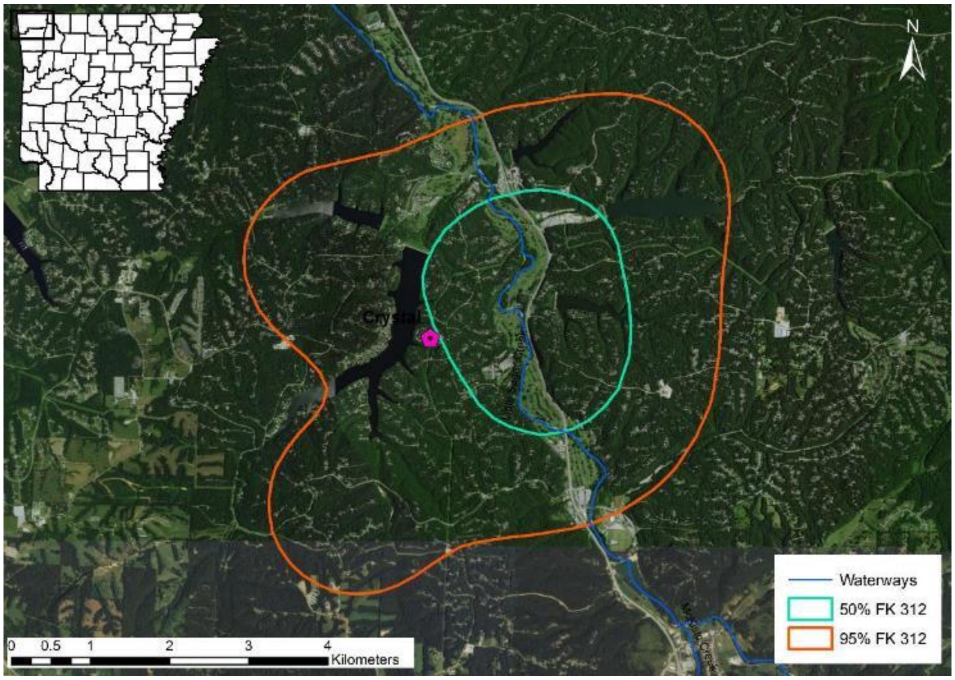


Figure C-33. Post-lactaing female 312 from Crystal Cave with a 95% FK of 2,906 ha and a 50% FK of 626 ha (1 July – 15 July 2015).

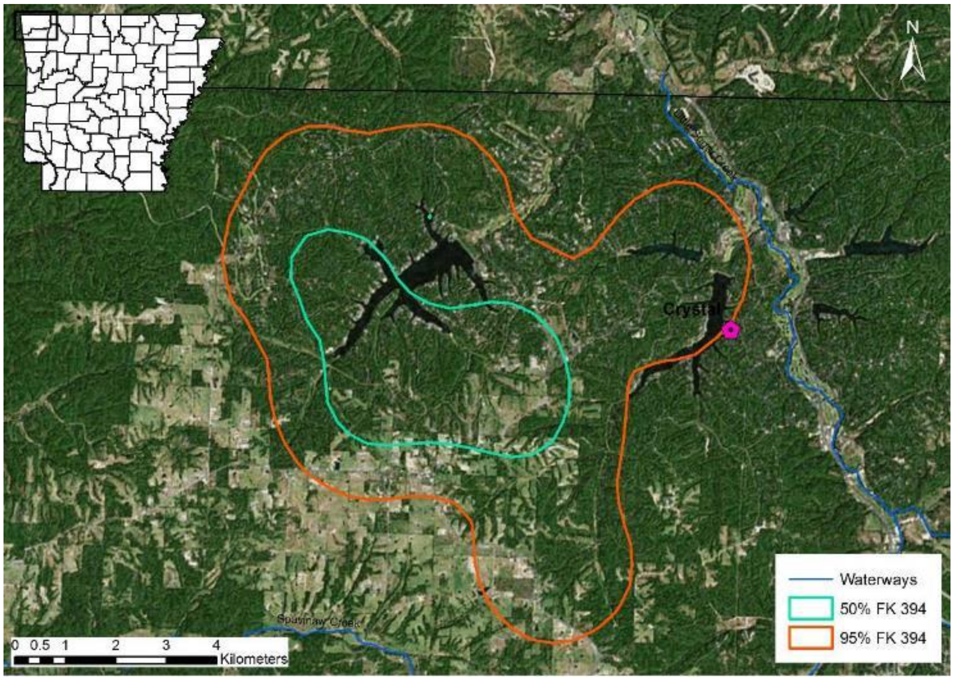


Figure C-34. Post-lactaing female 394 from Crystal Cave with a 95% FK of 6,264 ha and a 50% FK of 1,574 ha (1 July – 15 July 2015).

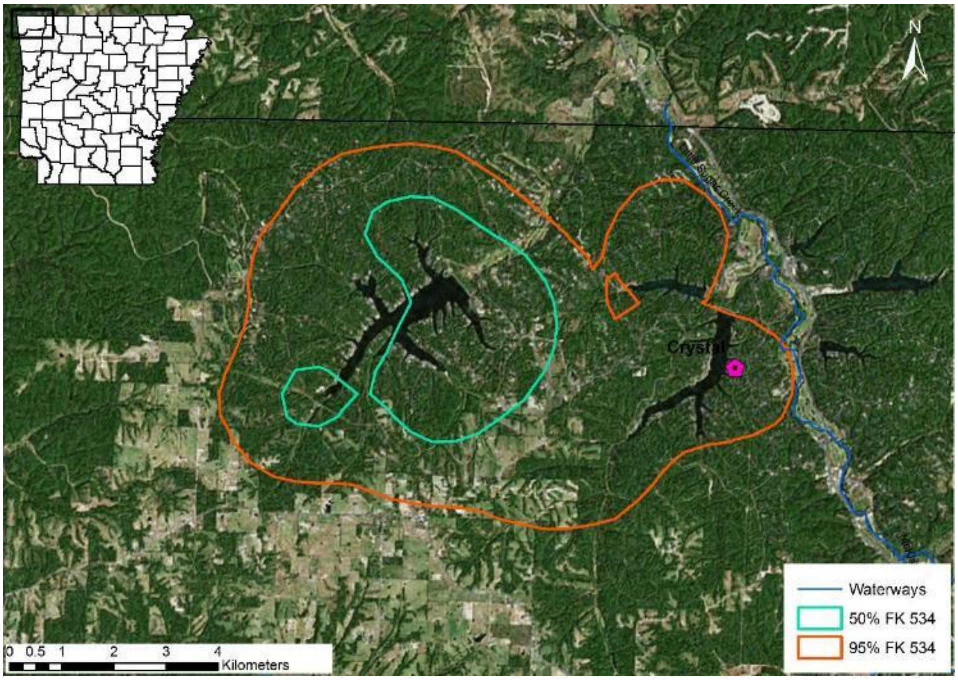


Figure C-35. Post-lactaing female 534 from Crystal Cave with a 95% FK of 5,710 ha and a 50% FK of 1,314 ha (1 July – 15 July 2015).

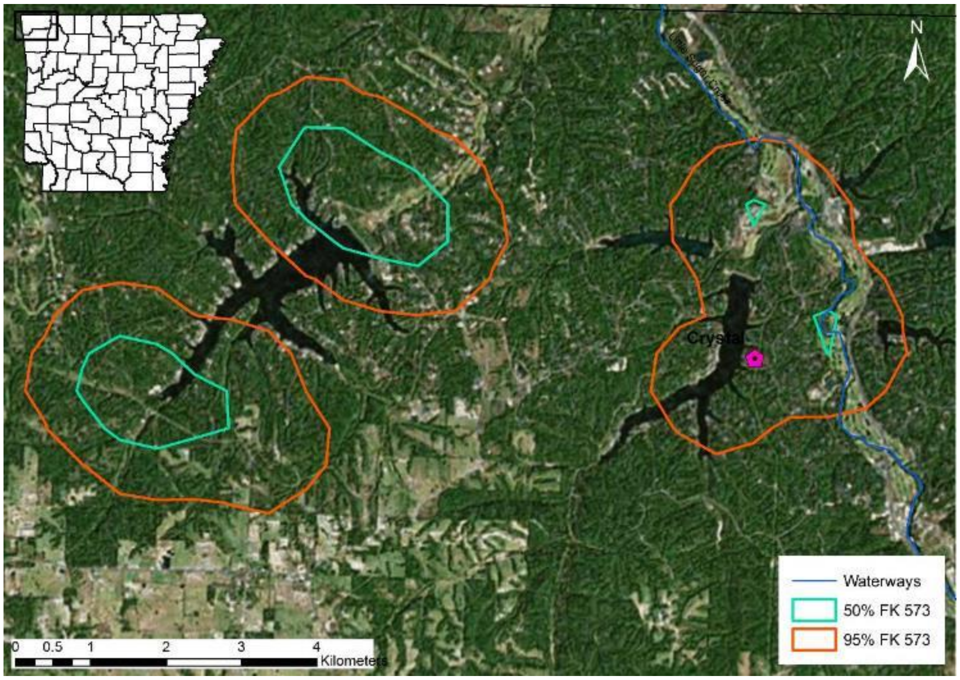


Figure C-36. Post-lactaing female 573 from Crystal Cave with a 95% FK of 2,645 ha and a 50% FK of 489 ha (1 July – 15 July 2015).

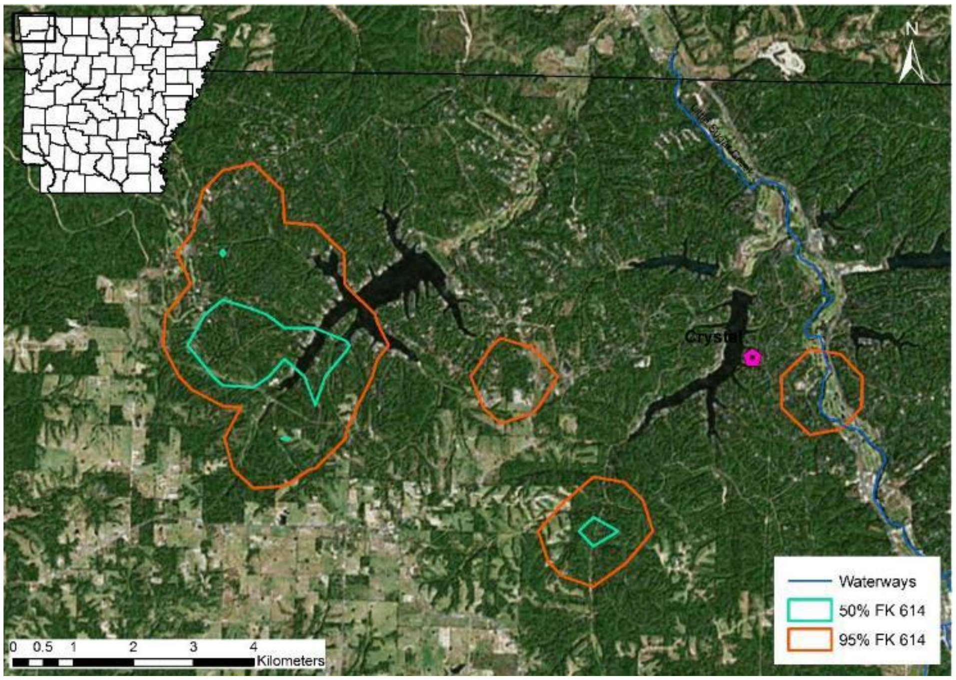


Figure C-37. Post-lactaing female 614 from Crystal Cave with a 95% FK of 1,744 ha and a 50% FK of 256 ha (1 July – 15 July 2015).

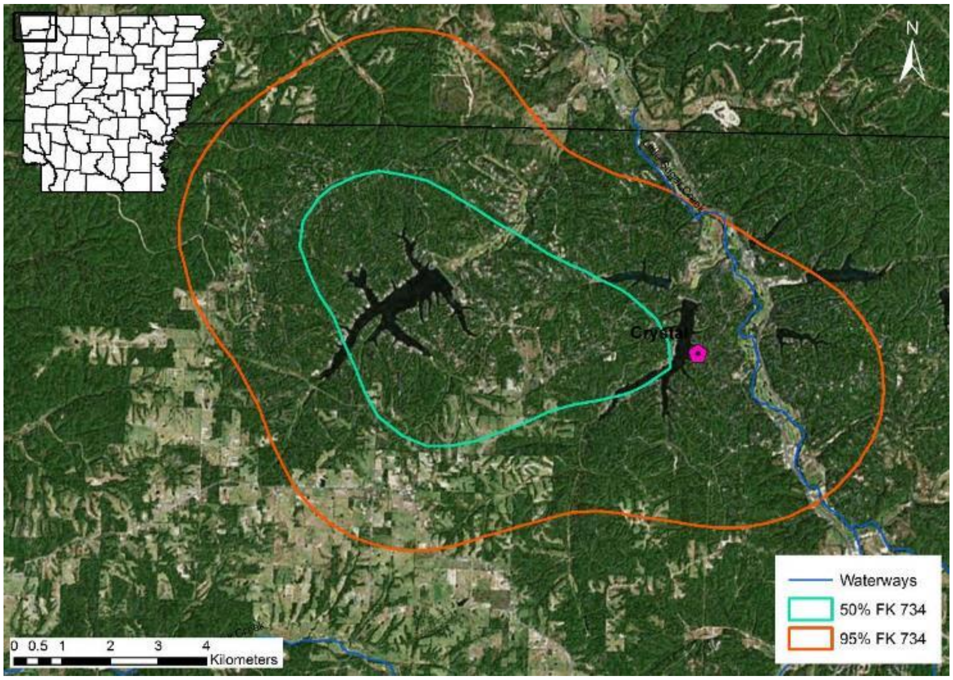


Figure C-38. Post-lactaing female 734 from Crystal Cave with a 95% FK of 10,645 ha and a 50% FK of 2,747 ha (1 July – 15 July 2015).

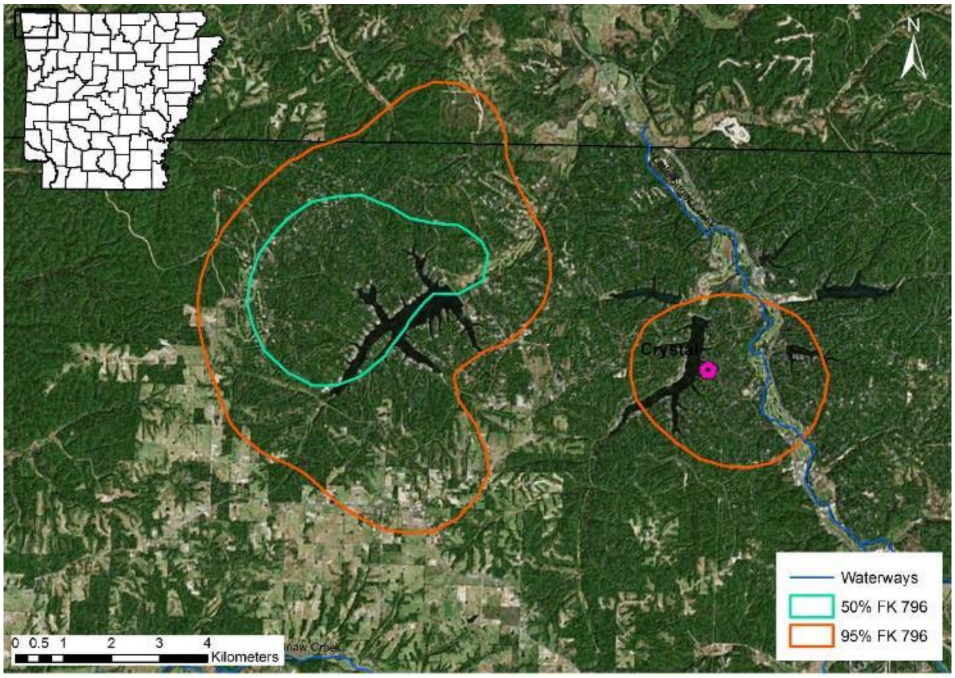


Figure C-39. Post-lactaing female 796 from Crystal Cave with a 95% FK of 5,706 ha and a 50% FK of 1,284 ha (1 July – 15 July 2015).

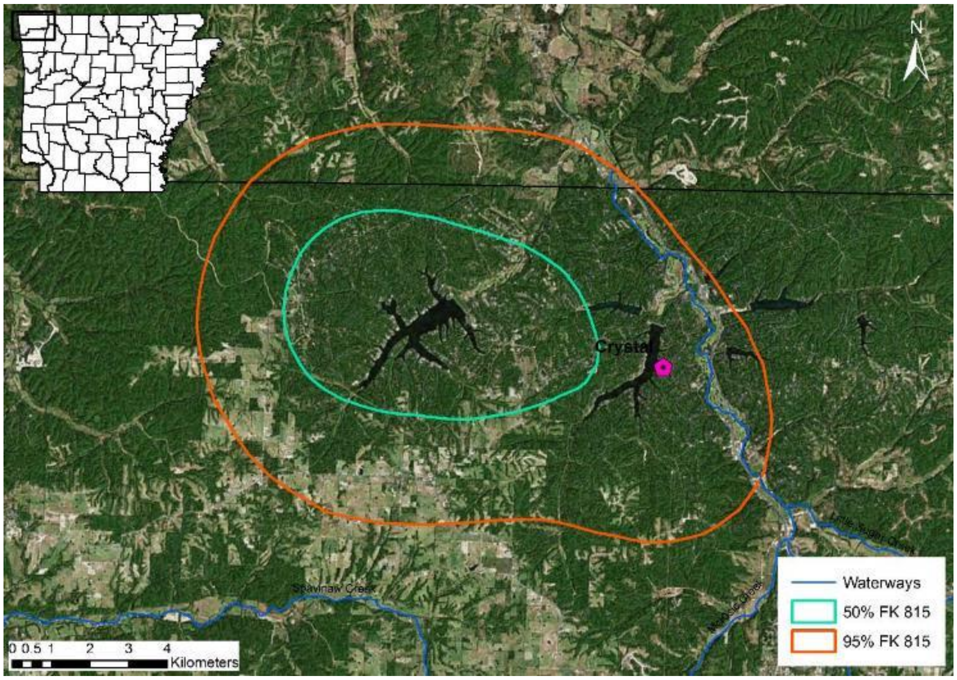


Figure C-40. Post-lactaing female 815 from Crystal Cave with a 95% FK of 12,620 ha and a 50% FK of 3,410 ha (1 July – 15 July 2015).

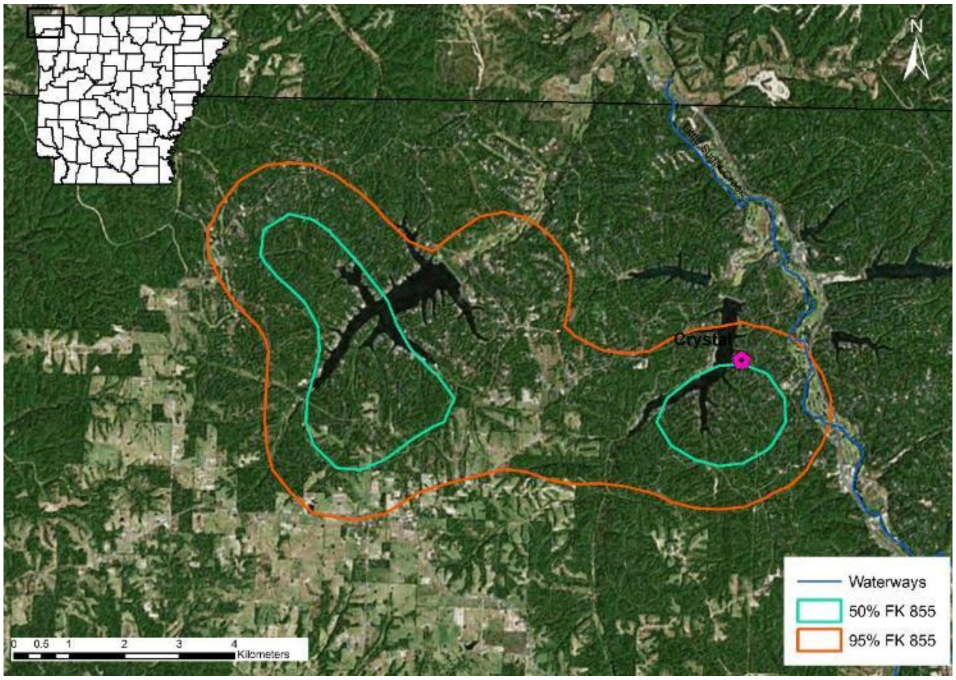


Figure C-41. Post-lactaing female 855 from Crystal Cave with a 95% FK of 4,318 ha and a 50% FK of 1,108 ha (1 July – 15 July 2015).

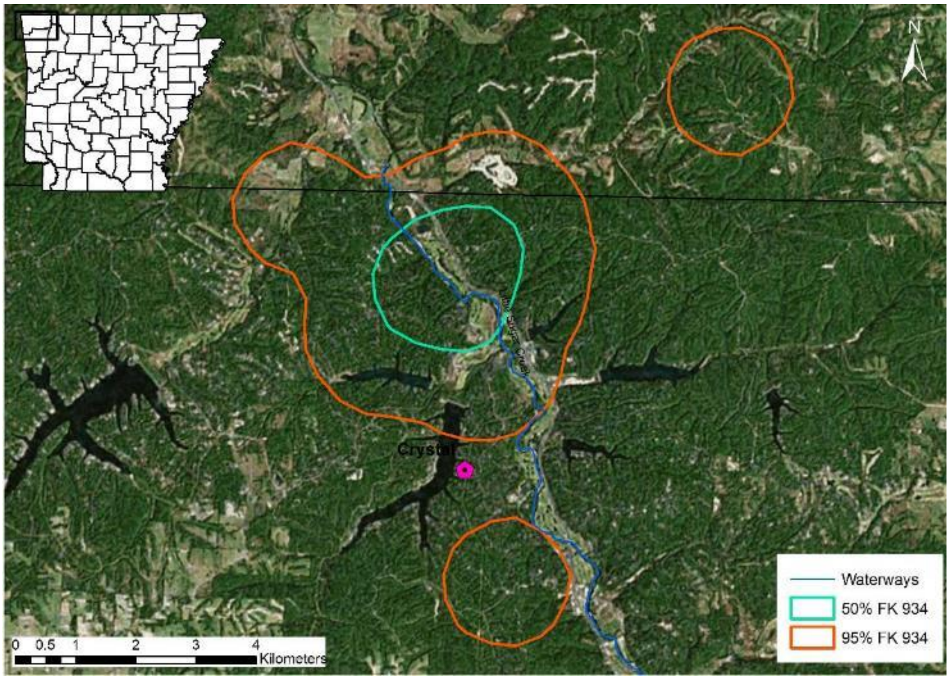


Figure C-42. Post-lactaing female 934 from Crystal Cave with a 95% FK of 2,876 ha and a 50% FK of 467 ha (1 July – 15 July 2015).