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16. Abstract We conducted a study of the springtime ecology of an isolated North Carolina-Tennessee population of the Virginia big-eared bat (<i>Corynorhinus townsendii virginianus</i>), a federally endangered species. With limited data on the whereabouts of this population during the maternity season, we could not adequately predict the impacts of transportation improvement projects (TIPs) such as the proposed widening of NC 105 (R-2566), which is ~3.3 km from the population's hibernacula on Grandfather Mountain, NC. The three objectives of our study were: 1) document seasonal movements and assess foraging habitat selection, 2) locate and describe springtime roosts and assess landscape-scale selection of roosting habitat, and 3) describe winter bat activity at the population's main hibernaculum. We radio-tagged 44 adult bats (42 female, 2 male), located 35 roost sites (25 rock and 10 building roosts), and delineated foraging home range polygons for 10 bats. We found the first known maternity roost sites for this species in NC, including a primary maternity roost on private land 14.4 km north-northwest from the hibernacula (≥ 359 bats used this roost), and we found the first known roosts for Tennessee. Bats moved across NC 105, NC 194, and other roads while commuting the short distance to the primary maternity roost, but generally did not cross major roads during nighttime foraging bouts. Bats moved relatively short distances between the hibernacula and springtime roost sites (0.1-24.1 km), but covered a relatively large area while foraging (~330 ha on average) mainly over forested lands. Most bats used a primary maternity roost and ≥ 1 secondary roosts; primary roosts were larger, with cooler and more stable temperatures. We detected winter bat activity at the hibernaculum, even on very cold days, and suggest further surveys to monitor the hibernating population. It is essential that the NC population of Virginia big-eared bats is able to cross NC 105 and NC 194 as they commute between their winter and summer habitats, but we do not have sufficient data to adequately predict how Virginia big-eared bats will respond to widening or increased traffic. Widening NC 105 could have a negative effect on this Virginia big-eared bat population if these bats are vulnerable to collisions or the barrier effect of a larger road, or if road development and associated projects degrades the foraging and roosting habitats of this population. We make recommendations for potential approaches to R-2566 that might minimize impacts to Virginia big-eared bats, as well as suggestions for future research that could lead to the development of safer crossing points over roads for this and other bat species.			
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**ECOLOGY OF VIRGINIA BIG-EARED BATS
IN NORTH CAROLINA AND TENNESSEE**

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TABLE OF CONTENTS

INTRODUCTION	1
METHODS	3
STUDY AREA	3
BAT CAPTURE	3
MOVEMENT AND FORAGING ECOLOGY	5
ROOSTING ECOLOGY	11
WINTER ACOUSTIC MONITORING	15
RESULTS	17
CAPTURED BATS	17
MOVEMENT AND FORAGING ECOLOGY	17
ROOSTING ECOLOGY	26
WINTER ACOUSTIC MONITORING	39
DISCUSSION	41
BAT CAPTURE	41
MOVEMENT AND FORAGING ECOLOGY	41
ROOSTING ECOLOGY	44
WINTER ACOUSTIC MONITORING	46
RECOMMENDATIONS	46
REFERENCES	49

LIST OF TABLES

Table 1. Names, locations, and antennae directions of telemetry towers in 2013 and 2014.	5
Table 2. Landscape variables measured for 31 secondary springtime roost sites used by Virginia big-eared bats in 2013 and 2014 in North Carolina and Tennessee and 31 associated random points.....	12
Table 3. Trail camera deployment record at two entrances of a primary maternity roost of Virginia big-eared bats in Watauga County, North Carolina, 2013 and 2014.....	14
Table 4. Names and locations of telemetry towers, with Virginia big-eared bats detected in 2013 and 2014.....	18
Table 5. Foraging range sizes and foraging distances for 10 Virginia big-eared bats tracked for 3–9 nights each in April and May 2013 and 2014 in North Carolina and Tennessee.	22
Table 6. Characteristics of foraging points for 10 Virginia big-eared bats tracked for 3–9 nights each in April and May 2013 and 2014 in North Carolina and Tennessee. We present the mean and range (in parentheses) for each bat and weighted means and ranges for all bats at the bottom of the table.....	23
Table 7. Distances from Virginia big-eared bat roosts to nearest NC DOT TIP, primary or secondary road, and all streets.	28
Table 8. Roost-scale variables (mean \pm 1 SE) for primary and secondary roosts used by Virginia big-eared bats in North Carolina and Tennessee, March–June 2013 and 2014.....	29
Table 9. Number of estimable parameters (K), Akaike’s information criterion for small sample sizes (AICc), difference between AICc value and model with lowest AICc value (Δ AICc), and Akaike’s weight (w_i) for A) a full model set (eight models) and B) a reduced model set (seven models) used to predict springtime (March to June) roost site selection by Virginia big-eared bats in North Carolina and Tennessee.....	31
Table 10. Model-averaged parameter estimates and standard errors (SE) for variables used in seven models describing springtime (March to June) roost site selection by Virginia big-eared bats in North Carolina and Tennessee.	32
Table 11. Principal component loadings for each variable measured at springtime roost sites used by Virginia big-eared bats in North Carolina and Tennessee, March–June 2013 and 2014.	34
Table 12. Organisms detected by camera traps at the entrance of Virginia big-eared bat Roost 7 in western North Carolina.	36

LIST OF FIGURES

Figure 1. Virginia big-eared bat study site in northwestern North Carolina and eastern Tennessee.	4
Figure 2. Telemetry tower locations in 2013 and 2014. Virginia big-eared bats were radio-tagged at the main hibernaculum on the east side of Grandfather Mountain; towers recorded their movements between 20 March–20 May 2013 (white) and 18 March–28 May 2014 (black).....	6
Figure 3. Telemetry tower setup with two 9-element yagi antenna and datalogging receiver at the base.	6
Figure 4. Examples of reception ranges for two telemetry tower antennae. Reception ranges are 95% minimum convex polygons created by mapping the detections of test transmitters that were walked or driven around the telemetry towers.....	7
Figure 5. Radio-telemetry driving transect driven to listen for signals from transmitters applied to Virginia big-eared bats at the hibernaculum on Grandfather Mountain, North Carolina from 19–25 March 2014.	8
Figure 6. Bat detector acoustic microphone setups for A) SM2+ Bat at cave entrance gate, B) SM2+ with PVC hood weatherproofing at cave entrance gate, C) RL1 Anabat at cave entrance gate, and D) SD2 Anabat microphone at outer cave entrance. Detectors and microphones were deployed to record winter Virginia big-eared bat activity (Winter 2012–2013 and Winter 2013–2014) at Black Rock Cliffs Cave on Grandfather Mountain in North Carolina.	16
Figure 7. Telemetry tower locations in 2014 and the <i>all-bats-composite polygons</i> that contain the most probable areas of detection for all 10 bats detected by towers (see Appendix B2 for data on individual bats). Probable bat detection is based on antennae reception polygons and high-power (signal >171) bat detections (see Methods). Virginia big-eared bats were radio-tagged at the main hibernaculum; these five towers recorded their movements from 18 March to 28 May 2014.	20
Figure 8. Radio-telemetry driving transect driven to listen for signals from transmitters applied to Virginia big-eared bats at the hibernaculum on Grandfather Mountain, North Carolina from 19–25 March 2014.	21
Figure 10. A) Landscape-level foraging habitat use and B) home range-level foraging habitat use for 10 adult female Virginia big-eared bats tracked in North Carolina and Tennessee from March–June 2013 and 2014.	25
Figure 11. Virginia big-eared bat roost locations found from March to June 2013 and 2014, in northwestern North Carolina and eastern Tennessee. The primary maternity roost near Beech Mountain and the hibernaculum on Grandfather Mountain both served as primary roosts during this period (housing 30–359 bats each). All other roosts were secondary, containing 1–9 bats on any given day.	27

Figure 12. A) Results of PCA size/cover, which compared 21 natural rock roosts used by Virginia big-eared bats based on structural, light, and vegetation cover variables..... 33

Figure 13. Inside temperatures (bold line = median, lower and upper whiskers = minimum and maximum temperatures, respectively) measured with HOBO Pro Series RH Temperature Data Loggers (Onset Computer Corporation, Bourne, Massachusetts) every 30–120 minutes for eight natural rock (P1, S2, S4, S5, P7, S11, S15, S26) and two barn (S18, S22) roosts of Virginia big-eared bats in North Carolina. 35

Figure 14. Camera detections per camera hour of common (> 100 total observations) non-threatening animals for each month at the entrance to Virginia big-eared bat Roost 7 in western North Carolina. 37

Figure 15. Camera detections per camera hour of common (> 50 total observations) potential bat predators for each month at the entrance to Virginia big-eared bat Roost 7 in western North Carolina. Months are indicated by numbers (1=Jan, 2=Feb, and so forth)..... 38

Figure 16. Camera detections of potential bat predators by hour for the months of April–September at Virginia big-eared bat Roost 7 in western North Carolina. 39

Figure 17. Bat calls (markers) detected and average daily temperatures (lines) recorded from 30 November 2012–24 March 2013 (A) and 9 November 2013–30 March 2014 (B) at the primary hibernaculum (BRCC) of Virginia big-eared bats on Grandfather Mountain, North Carolina. ... 40

INTRODUCTION

Background.—The Virginia big-eared bat (*Corynorhinus townsendii virginianus*) is a federally endangered subspecies of the Townsend’s big-eared bat complex (*Corynorhinus townsendii*), which is distributed across much of North America. As of 2008, Virginia big-eared bats were known to occur only in isolated populations in Kentucky, North Carolina, Virginia, and West Virginia (USFWS 2008). Winter counts suggest the hibernating population was ~11,600 bats in the seven major (>200 bats) known hibernacula, while 13 significant (>200 bats) maternity roosts in Kentucky, Virginia, and West Virginia harbored ~7,600 Virginia big-eared bats (200–1100 individuals in each roost; USFWS 2008). This cave-dependent bat uses limestone caves (Barbour and Davis 1969) and mines (Gates and Johnson 2006; Johnson et al. 2005, 2006) as winter hibernacula and summer maternity roosts. In spring, pregnant female Virginia big-eared bats migrate from winter hibernacula to maternity sites, where they give birth and raise young. In West Virginia, Virginia big-eared bats move 32 km between winter caves and summer maternity sites (USFWS 2008). Across the species’ range, known maternity sites are caves, cliffs, and rock ledges in oak-hickory and beech-maple-hemlock forests (Barbour and Davis 1969). Virginia big-eared bats are thought to feed primarily on moths, which they may glean from vegetation or hawk from the air (Kunz and Martin 1982). In West Virginia, these bats forage in woodlands and fields (USFWS 2008), while in Kentucky old fields are favored foraging habitat (Burford and Lacki 1995). Many of the moth species eaten by this bat in Kentucky are dependent on forest plants for larval development (Burford and Lacki 1998).

Threats to Virginia big-eared bats.—Though the overall Virginia big-eared bat population appears to be stable or increasing, we are challenged with protecting the species due to a lack of knowledge about its habits and the serious potential for population-level declines due to habitat loss, disturbance at hibernacula and maternity sites, and other anthropogenic effects, plus a new threat—white-nose syndrome. As summer and winter caves have been protected with land acquisitions and cave gates, populations of Virginia big-eared bats have increased across the eastern range (USFWS 2008). However, we do not know the whereabouts of most of the known population during the summer maternity season, nor has there been sufficient work to identify habitat requirements. Furthermore, this species is highly susceptible to disturbance due to the apparent restriction of the population to only a small number of caves and mines across the four states where the species occurs (USFWS 2008). Loss of critical roosting and foraging habitat remains an issue for populations of Virginia big-eared bats, as urbanization and land-use changes may alter or destroy caves, mines, or buildings that serve as roosts. However, this cave-obligate species may face a greater threat from *Pseudogymnoascus destructans*, the fungus that is the causal agent for white-nose syndrome. This disease has killed millions of hibernating bats in the eastern U.S., though Virginia big-eared bat populations remain unaffected thus far (Turner et al. 2011).

Justification for North Carolina Study.—Like many bat species, Virginia big-eared bats show long-term fidelity to both winter and maternity roosts, so long-term protection of active colony sites is considered critical for recovery of the species (USFWS 2008). A better understanding of foraging ecology is also critical to the species’ recovery. Unfortunately, we know almost nothing about the roosting or foraging habits, or movement paths of Virginia big-eared bats in western North Carolina. In 1981, Virginia big-eared bats were discovered in a hibernaculum, Black Rock

Cliffs Cave (BRCC), on Grandfather Mountain in Avery County (Clark and Lee 1987; McGrath and Marsh 1997). Since that time, biologists have determined that two hibernacula in North Carolina house ~400 Virginia big-eared bats in winter; this is about 3% of the overall hibernating population (USFWS 2008). However, no maternity sites have been identified in western North Carolina (Clark and Lee 1987, McGrath and Marsh 1997). Based on information from the other states where Virginia big-eared bats occur (USFWS 2008), this species is likely to use at least two major maternity sites in western North Carolina (McGrath and Marsh 1997). We also do not know how far bats travel between winter and summer sites in western North Carolina. In 1994–1996, during nighttime radio telemetry surveys in this area, McGrath and Marsh (1997) obtained signals from two female Virginia big-eared bats 9–19 km north of the primary hibernacula. Field crews lost the transmitter signals for these bats and maternity roosts were not identified; McGrath and Marsh (1997) surmised that Virginia big-eared bats may move significant distances between their winter and summer sites in this region.

Roads may pose a threat to North Carolina population of Virginia big-eared bats, but there are no data on how this population interacts with roads in its landscape. The North Carolina Department of Transportation (NC DOT) has various transportation improvement program (TIP) projects scheduled in Avery, Caldwell and Watauga counties within close proximity to known locations for Virginia big-eared bats; the most notable project is R-2566, the proposed widening of NC 105 (~3.3 km or 2 miles from BRCC). With very limited data on the distribution, roosting, and foraging ecology of Virginia big-eared bats in western North Carolina, it is almost impossible to anticipate how NC DOT highway and bridge projects will affect this endangered bat. Therefore, we conducted a two-year study of the winter and springtime ecology of the Virginia big-eared bat in the R-2566 project area in northwestern North Carolina.

Objectives.—Our overall objective was to study the winter and springtime ecology of Virginia big-eared bats in northwestern North Carolina. We developed specific goals in three areas:

1) Document seasonal movements and assess foraging habitat selection

We aimed to identify routes for seasonal movements away from BRCC, to determine if and where bats cross NC 105, and to identify the locations, sizes, and characteristics of springtime foraging areas.

2) Locate and describe springtime roosts, and assess landscape-scale selection of roosting habitat

We aimed to locate and describe fine-scale characteristics of maternity roosts, and to identify factors that might affect landscape-scale roost habitat selection. We used camera traps to assess the potential for interactions between Virginia big-eared bats and other animals at maternity roosts.

3) Describe winter bat activity at the main Virginia big-eared bat hibernaculum

We aimed to measure variation in winter bat acoustic activity at the primary Virginia big-eared bat hibernaculum in North Carolina.

METHODS

STUDY AREA

This study took place in the Grandfather Mountain area of the Blue Ridge Mountains, which included parts of northwestern North Carolina and eastern Tennessee, extending from the Pisgah National Forest and Blue Ridge Parkway lands on the southeast side of Grandfather Mountain northwest to the Watauga and Elk Rivers in Tennessee (Figure 1). The study area included some state and federal lands, but mostly (~85%) privately owned lands in Avery, Caldwell and Watauga counties in North Carolina, and Carter and Johnson counties in Tennessee (Figure 1). Elevation ranged from approximately 470 m to 1,818 m above sea level. Grandfather Mountain housed the only known hibernacula for Virginia big-eared bats in North Carolina, Black Rock Cliffs Cave (BRCC; 1,422 m) and Mystery Hole Cave (1,400 m). Grandfather Mountain is part of the Grandfather Window Formation, consisting mostly of metamorphosed rock; westward, in Tennessee, the underlying geology changes to sedimentary rock (Bryant and Reed 1967). In mid-April 2013, while radio tracking bats tagged at BRCC, we discovered the first known primary maternity roost for this bat population near the base of Beech Mountain 14.4 km north-northwest of BRCC; subsequently, we used this roost location to help define the study area and to determine best placement of telemetry towers to assess seasonal movement patterns in 2014. Landcover was mainly cool temperate forest (~75%) interspersed with agriculture (~9%) and other developed land (~10%). Other landcover present included southern floodplain and riparian communities, southern Appalachian grass and shrub balds, and temperate cliff, scree and rock vegetation landcover. Major forest types included southern and central Appalachian oak and hardwood forests, cove forests, and conifer/pine forests (Schafale 2012). During the periods of the study, March through June 2013 and 2014, temperatures on Grandfather Mountain ranged from -14.6 to 23.0 °C (State Climate Office of North Carolina 2014), with surrounding low-lying areas typically 6 to 11 °C warmer (Grandfather Mountain 2010).

Several TIP projects were located within the study area (Figure 1). R-2566 (NC 105) bisected the study area from northeast to southwest and was located ~3.3 km from BRCC and ~10.1 km from the primary maternity roost (discovered during this project, see Study Area section) near Beech Mountain. R-2710 (NC 194), which was located ~9 km from BRCC and ~5.6 km from the primary maternity roost, partially bisected the study area from northeast to southwest. R-2811 (NC-184) was located ~3.4 km from BRCC and ~6 km from the primary maternity roost. R-5016 (US 321) was on the northern edge of the study area, ~17 km north of BRCC and ~4 km from the primary maternity roost. R-2520 was 17.9 km southwest of BRCC and 26.7 km southwest the primary maternity roost. R-2595 and R-2596 were located 9.9 km and 18.0 southwest of BRCC, respectively, and 20.1 km and 27.2 km south of the primary maternity roost, respectively. There were also several bridges (B-3608, B-3818, B-4053, B-4315, B-4316, B-4318, B-4668, B-4669, B-4670, B-4707, and B-5118) within the study area.

BAT CAPTURE

From March to May 2013 and 2014, we captured adult Virginia big-eared bats by carefully removing them from walls or ceilings at BRCC and at five additional springtime roost sites in North Carolina. We placed bats into cloth holding bags until they were measured and radio-

transmitted. For each bat, we recorded sex, age, mass, forearm length, and white-nose syndrome wing damage score as per Reichard and Kunz (2009) (Appendix A1). We did not band or mark any bats. Female bats that weighed ≥ 8.4 g and that appeared to be in good health were radio-tagged with standard beeper transmitters (PicoPip Ag379; Lotek Wireless, Inc., Newmarket, Ontario; henceforth, beeper tags) or digitally encoded radio transmitters (NTQB-2; Lotek Wireless, Inc.; henceforth, coded tags) weighing ≤ 0.4 g ($\leq 4.8\%$ of body weight). We placed transmitters on 19 female bats in 2013 (10 standard beeper tags and nine coded tags) and on 23 female and two male bats in 2014 (15 standard beeper tags and 10 digitally encoded tags). We released all bats at the capture site. When handling bats or entering known roost sites, we followed the guidelines of the American Society of Mammalogists for the use of wild mammals in research (Sikes et al. 2011; ISU IACUC protocol 510249-2), and national white-nose syndrome decontamination protocols (USFWS 2012) to reduce the potential for transmitting or spreading white nose syndrome. Fieldwork was conducted under permits held by J. O'Keefe: USFWS federal recovery permit TE206872, North Carolina permit ES261, Tennessee permit 3148, and National Park Service Permit BLRI-2014-SCI-0001.

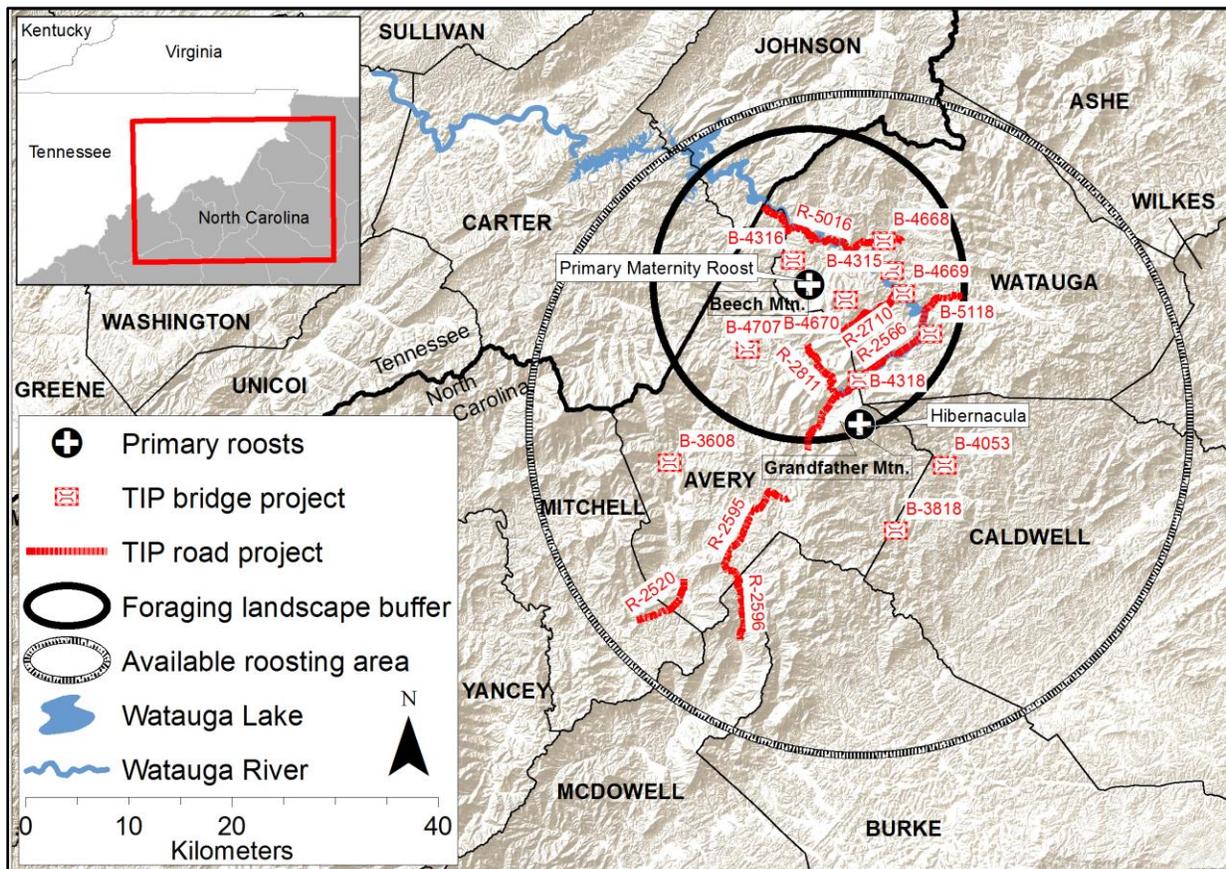


Figure 1. Virginia big-eared bat study site in northwestern North Carolina and eastern Tennessee. To make the foraging landscape buffer, we buffered the primary maternity roost used by the population with the maximum roost switching distance recorded during the study (15.1 km). We defined the landscape available for roosting as all land within a 32.0 km buffer around the hibernaculum, which was equal to the greatest distance moved by any of the bats tracked from the hibernaculum (24.1 km) plus the mean maximum roost switching distance for radio-tagged bats (7.9 km).TIPs displayed are those within the project study area.

MOVEMENT AND FORAGING ECOLOGY

Telemetry towers.—In both 2013 and 2014, we deployed telemetry towers with datalogging receivers to listen for bats carrying coded tags (Table 1; Figure 2). Each fixed telemetry tower consisted of a SRX-DL1 datalogging telemetry receiver (Lotek Wireless, Inc., Newmarket, Ontario) powered by a 12V battery, two 9-element Yagi antennae, and one antenna mast (Figure 3). The dataloggers allowed for simultaneous monitoring of up to 10 coded tags, which had the same frequency but digitally-encoded unique IDs that could be separated by the DL1 datalogger. Coded tags transmitted a signal every 5 seconds. When analyzing data from the datalogging receivers, we considered signals to be detections if they were at 5-second intervals, there were ≥ 2 detections within one minute, and ≥ 3 detections within one hour; if there were two signals at a 5-second interval within one minute but no other signals within an hour's time, we did not consider this a detection.

In 2013, we positioned a tower at Grandfather Golf and Country Club (GFGCC) maintenance building approximately 2.9 km west-southwest of BRCC, near NC Highway 105 and two additional telemetry towers approximately 0.8 km west and 0.3 km northeast of BRCC (Linn and Stack Rock; Figure 2). These towers were deployed to give us more information about bat movements in the vicinity of Grandfather Mountain; subsequently, we discovered that most bats were making a seasonal movement across NC 105 to a primary maternity roost on Beech Mountain.

In 2014, we positioned four fixed telemetry towers with antennae pointed approximately northeast and southwest, along NC 105, a major road that bisects the primary hibernation and maternity areas on the landscape (Figures 1 and 2). Surveying this corridor allowed us to determine the point at which bats crossed the highway during springtime. We spaced telemetry towers about 1.0 ± 0.1 km (range 0.7–1.2 km) apart. We deployed a fifth tower, which was the southernmost tower (labeled Linville Tower in Figure 2), on 24 March 2014, after three bats had already moved from the hibernaculum. This tower held two 5-element Yagi antennae and, thus, may have had a lower detection rate than the other towers.

Table 1. Names, locations, and antennae directions of telemetry towers in 2013 and 2014. Virginia big-eared bats were radio-tagged at the main hibernaculum on Grandfather Mountain in North Carolina between 19 March–13 April 2013 and 19–25 March 2014.

Tower name	Location (NAD 83 UTM)	Antennae azimuth	Date deployed	Date retrieved
GFGCC	17S 0423715 3995053	225, 320	3/20/2013	5/23/2013
Linn (Cove)	17S 0426741 3994936	74, 166	4/10/2013	5/20/2013
Stack Rock	17S 0425801 3994520	140, 231	4/11/2013	5/20/2013
Ennis	17S 0426593 3999215	57, 220	3/18/2014	5/9/2014
Barker	17S 0425844 3998391	50, 216	3/18/2014	5/28/2014
Profile	17S 0424989 3997580	66, 253	3/18/2014	5/28/2014
TNC	17S 0424402 3997241	55, 220	3/18/2014	5/28/2014
Linville	17S 0423559 3996358	46, 207	3/24/2014	5/28/2014

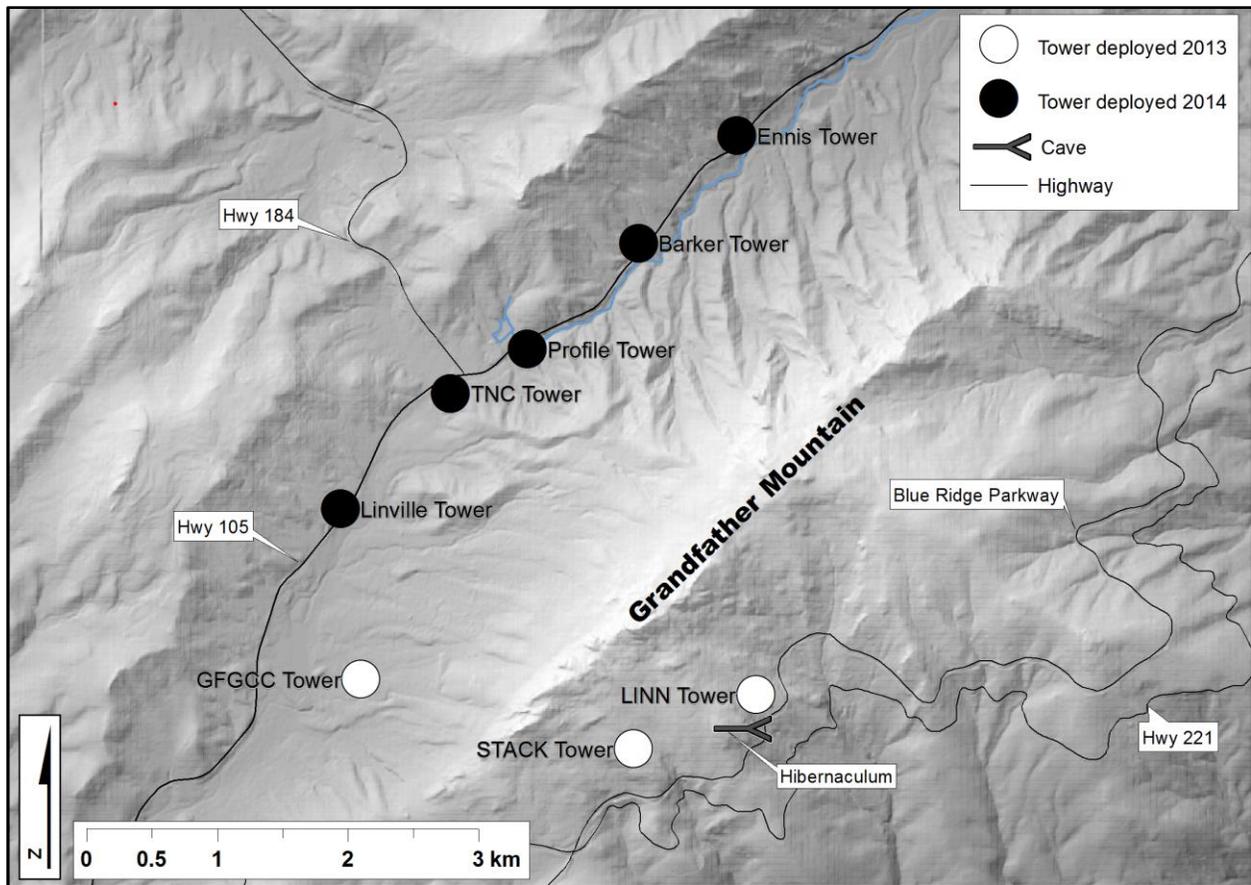


Figure 2. Telemetry tower locations in 2013 and 2014. Virginia big-eared bats were radio-tagged at the main hibernaculum on the east side of Grandfather Mountain; towers recorded their movements between 20 March–20 May 2013 (white) and 18 March–28 May 2014 (black).



Figure 3. Telemetry tower setup with two 9-element yagi antenna and datalogging receiver at the base.

For 2014 towers only, we created reception range polygons for each tower's antennae to allow us to make inferences about locations for bats detected by towers (see example map, Figure 4). We tested each antenna's reception by driving or walking with test transmitters up to 13.1 km away from towers. However, we were not able to cover all terrain within 13.1 km of each tower due to time and property access issues. For testing tower reception, we considered signals to be detections of the test transmitter if there were two detections at 5-second intervals within five minutes. In 2014, the farthest distance that any of the telemetry towers picked up test transmitters was 3.1 km away. However, there were many locations within 3.1 km where test transmitters were not detected. We then mapped the reception range of each antenna by making a 95% minimum convex polygon (MCP, Figure 4) for all of the locations where the test transmitter was detected by that antenna. To a degree, reception ranges of the antennae are reflective of where we tested. However, we attempted to cover as many areas as possible (time and property access permitting) that would give a good range of the reception capabilities of each antenna.

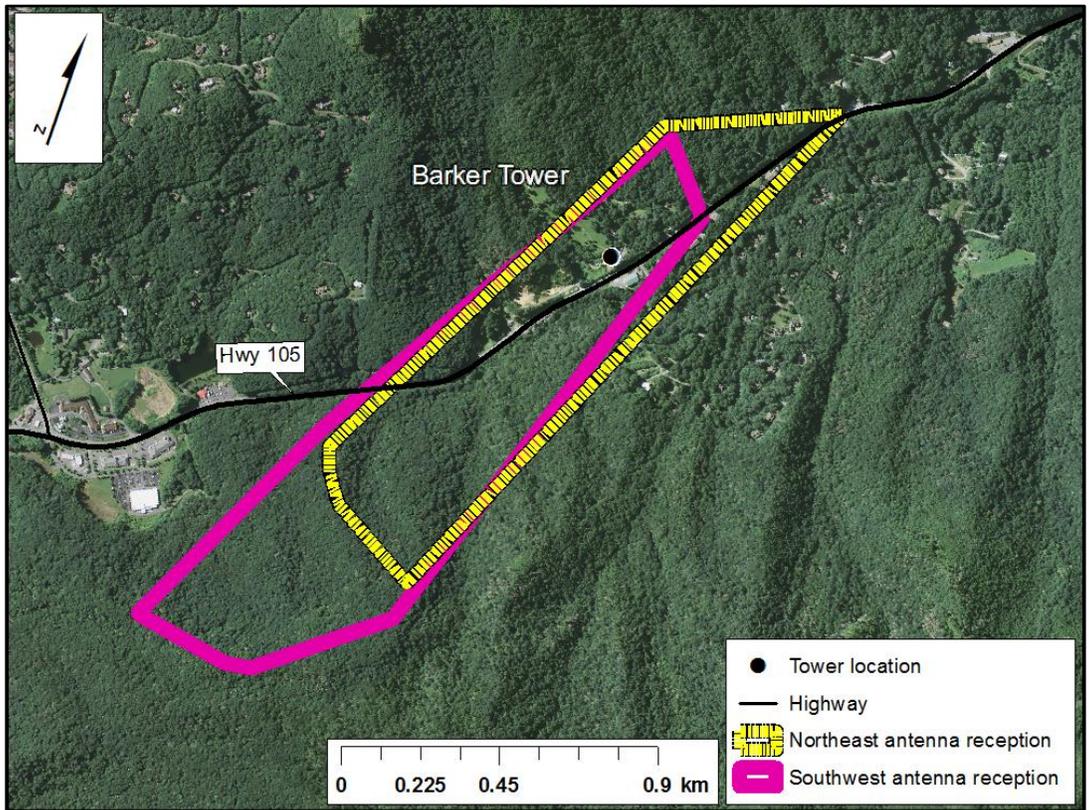


Figure 4. Examples of reception ranges for two telemetry tower antennae. Reception ranges are 95% minimum convex polygons created by mapping the detections of test transmitters that were walked or driven around the telemetry towers.

In 2014, we used reception ranges for each tower's antennae to infer where bats might be crossing NC 105 as they moved from hibernacula to the primary maternity roost near Beech Mountain. We aimed to roughly estimate where the bats were flying while being detected by the telemetry towers. To do this, we first selected only the bat detections for which the power was ≥ 171 (the power of signal strength can range from 1–255). We predicted that detections of high strength (171–255) were more likely to be areas where bats crossed the highway because the signal strength is higher the closer the transmitter is to the receiver.

Next, we grouped these detections into 30-second blocks and determined which towers and antennae picked up the bats during each period. For each 30-second block, we created a *composite polygon* that represented the intersection of the reception ranges of the relevant antennae for that period (see Appendix B1 for examples of detections). We then overlaid these composite polygons for the entire time period that we were detecting high-power signals (ranging from 8–59 minutes for bats that clearly crossed the road). We considered the intersection of the composite polygons as the most likely area where each bat crossed NC 105 (described as *greatest reception overlap polygons* on our maps, see Appendix B1). We overlaid the greatest reception overlap polygons for each bat to define an *all-bats-composite polygon* for all 10 bats that represents the most probable area(s) where bats crossed NC 105.

Driving.—From 24 March to 30 April, we conducted 48 driving transects (44 km or 27 miles; Figure 5) along NC 105 with a datalogging receiver and either a 3- or 5-element Yagi antenna mounted ≤ 1 m above the vehicle, forward and parallel to the road. We drove pre-dawn and post-dusk transects between the times of 03:02–06:10 and 19:58–23:04 EDT, respectively, and alternated the beginning direction (north or south) driven each day or night. The length of the transect was driven in both directions (north and south) during each survey. We drove ≤ 48 km/h (30 mph) while the receiver scanned continuously for bats radio-tagged with coded tags. We mapped transmitter detections from driving transects (Appendix B2). As with the tower detections, we included detections that were at 5-second intervals with ≥ 2 detections within one minute but also ≥ 3 detections within one hour.

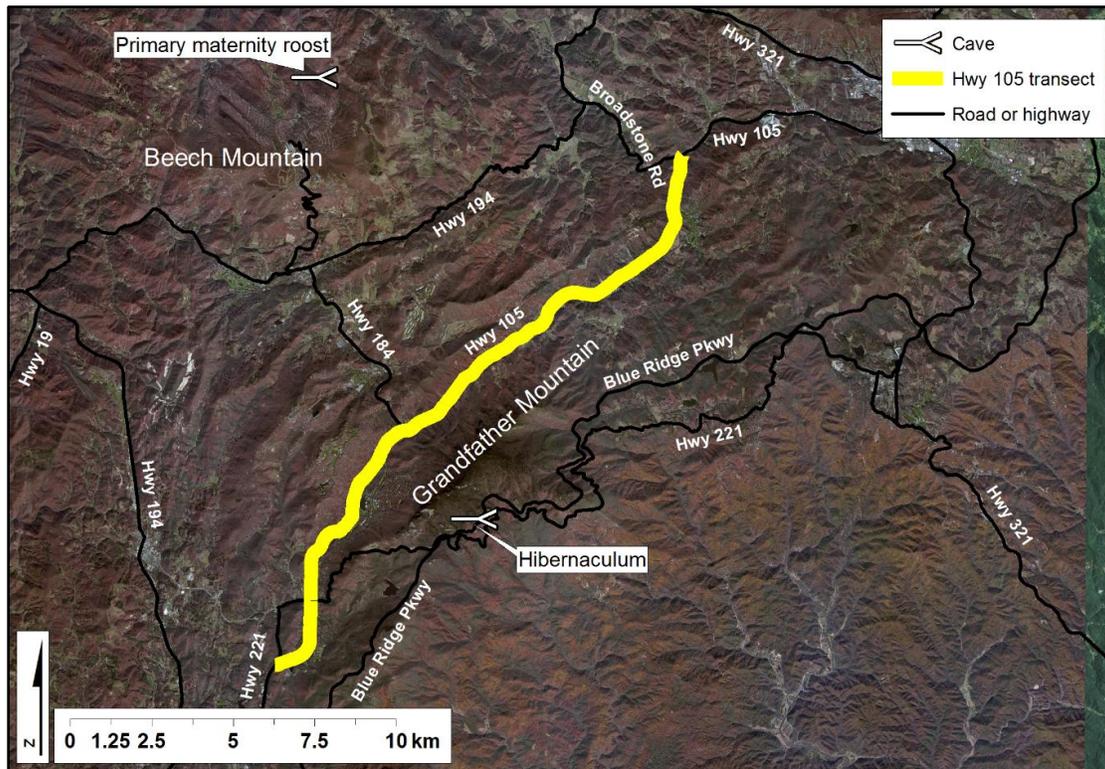


Figure 5. Radio-telemetry driving transect driven to listen for signals from transmitters applied to Virginia big-eared bats at the hibernaculum on Grandfather Mountain, North Carolina from 19–25 March 2014. The driving transect followed NC Highway 105 for most of its length and NC State Road 1545 at its southern end.

Foraging telemetry.—To identify foraging areas, we followed 2–3 bats per night. While searching for bats at night, we traveled > 2,467 km (1,533 miles) for > 72 hours of driving time. From immediately after emergence time (around 20:45 EDT) until as late as 3:00, we recorded a series of simultaneous multi-azimuth (2–6) triangulations/biangulations at 5–6 minute intervals to obtain location estimates for foraging bats. We stationed personnel at various points on the landscape around a focal bat’s foraging area, with each person recording an azimuth or bearing for the focal bat at set time intervals. Azimuths were recorded on a 5-minute cycle when a single bat was being tracked or a 3-minute cycle when multiple bats were being tracked; thus, when tracking two bats, personnel recorded azimuths for each bat every six minutes. We converted foraging telemetry triangulations/biangulations to point location estimates using the program Locate III, Version 3.34 (Nams 2006). When estimating point locations, we excluded biangulations that were < 20 degrees different, and triangulations or biangulations with lines that did not cross.

We calculated telemetry error using a beacon testing method at 13 locations where foraging telemetry was conducted during the study. For each known location, we conducted multiple triangulations or biangulations of the test transmitter position. We then measured the distances from point location estimates to known transmitter locations using the measure tool in ArcMap (ESRI 2012). We estimated the error of telemetry points to be 148.3 ± 24.6 m (range 11.2–668.0 m; n = 40 triangulations/biangulations used to estimate telemetry error).

Foraging habitat selection analysis.—We used the Geospatial Modeling Environment (GME), Version 0.7.2.1 (Beyer 2012) and Adehabitat package, Version 1.8.15 (Calenge 2015a) in the program R, Version 3.12 (R Core Team 2014) to calculate four foraging home range estimates for each bat: minimum convex polygons (95% and 100% MCPs) and fixed kernel density estimates (90% and 95% KDEs). We used MCPs to enable us to compare our results with previous studies done on Virginia big-eared bats (Clark et al. 1993, Adam et al. 1994, Wethington et al. 1996). We used KDEs because they provide a more accurate estimate of the utilization distribution (UD) of animals, taking into account the density of locations (Seaman and Powell 1996). A UD represents the probability of finding an animal of interest at any particular location at any given time (Powell and Mitchell 2012). For KDEs, we used cross-validation (CVh) smoothing parameters, because this method works better than more commonly used smoothing parameters (e.g., least-squared cross-validation) when samples consist of < 50 locations per individual (Horne and Garton 2006). We also report elevation, slope, and distances to water, transportation improvement projects, and roads for bats with foraging locations.

We assessed foraging habitat use via a resource utilization function (RUF; Marzluff et al. 2004). RUFs make use of UD, which provide continuous probability measures of an animal’s space use (Marzluff et al. 2004). As opposed to using point locations as sample points, RUFs reflect the probability of resource use more accurately (Marzluff et al. 2004) and should give a better measure of habitat use by bats, fast-moving volant animals, which are difficult to pin-point while foraging. The UD, which uses a continuous plane rather than point locations, should compensate for sampling error when estimating resource use (Marzluff et al. 2004). We estimated the UD for each bat using fixed 95% KDEs with CVh smoothing parameters in the GME program.

To measure landscape-scale habitat selection and within-foraging-range habitat selection, we identified available landcover categories and then used a weighted compositional analysis (Aebischer et al. 1993, Millspaugh et al. 2006) to assess selection of these landcover types at two levels for each bat—landscape-level and home range-level. We reclassified 30 m × 30 m cell GAP landcover data (2001 Southeast Gap Analysis Project; Davidson 2001) and named streams or water bodies on 24K maps (NC DENR Division of Water Quality 2012) into four general landcover types using ArcMap: 1) natural riparian vegetation and water; 2) upland forest, shrub, herb, rock vegetation and rock; 3) developed/urban; and 4) agriculture (Appendix B3). We restricted our analysis to four general habitat types to avoid zero values in our data (i.e., zero use or availability of specific habitat types). To define the foraging area available at the landscape-level, we buffered the primary maternity roost used by the population with the maximum roost switching distance recorded during the study (15.1 km; Figure 1). We calculated landcover availability within the two foraging areas (landscape: 15.1 km buffer around maternity roost; home-range: each bat's 95% KDE) by counting the number of 30 m cells of each landcover type and dividing this by the total number of cells within the available area. To calculate relative use of each of the four landcover types for each bat, we used the Zonal Statistics Tool in ArcMap to sum the volume of the UD for each bat's 95% KDE by landcover type, then divided the summed density values by the total of the summed density values to obtain proportion of use of each landcover type. Using the AdehabitatHS package, Version 0.3.13 (Calenge 2015b) in program R, we tested the significance of overall habitat selection with Wilks' lambda statistic and built a habitat ranking matrix, comparing the mean difference between the used and available log ratios (Aebischer et al. 1993). We assumed that all landcover types in the study area were available to all bats because they have the ability to fly over land-based obstacles.

Movement analysis.—In 2014, for 10 bats with consecutive day data, we calculated the average movement distance from the hibernaculum to bats' first springtime roosts. We also calculated movement distances between the hibernaculum and the first springtime roosts for 11 bats with non-consecutive day roost data. For the foraging locations of 10 focal bats, we calculated mean elevation, slope, slope direction, distance to nearest water, distance to nearest TIP project, distance to nearest primary and secondary road, and distance to nearest street. We measured distances from all foraging points used by Virginia big-eared bats to the nearest TIP project, primary and secondary road, and street. We used shapefiles named TIPRoads.shp and TIPBridges2009_2015.shp, given to us by NCDOT, for TIP project locations. We used a TIGER/Line primary and secondary roads shapefile for primary and secondary road locations. Primary roads generally included divided, limited access highways under federal and state management. Secondary roads were main arteries with one or more lanes of traffic in each direction. Streets were local neighborhood roads, rural roads, city streets, vehicular trails (4-wheel drive), ramps, service drives, walkways, stairways, alleys, and private roads, but also included primary and secondary roads. To calculate distance to the nearest street, we used a NCDOT Integrated Statewide Road Network (ISRN) shapefile layer (ISRN_v2_Nov2007) and a TIGER/Line All Roads shapefile which includes primary roads, secondary roads, local neighborhood roads, rural roads, city streets, vehicular trails (4-wheel drive), ramps, service drives, walkways, stairways, alleys, and private roads.

ROOSTING ECOLOGY

Homing telemetry.—We used radio telemetry receivers (R410 model; Advanced Telemetry Systems, Isanti, Minnesota) and 3- or 5-element Yagi antennae to track bats to day time roosts. We searched for each bat for the expected transmitter battery life, as feasible (33 days for coded tags and 56 days for beeper tags). Mean track time for beeper tags was 27 ± 3 days (range 1–51 days) and 34 ± 2 days (range 10–49 days) for coded transmitters. During daytime searches, we drove $> 8,367$ km (5,199 miles) of roads in North Carolina and Tennessee for > 788 hours.

Upon finding a roost, we entered the roost once to confirm the radio-tagged bat's location, and on one additional occasion (when we suspected the bat was not in the roost) to measure internal roost characteristics. When feasible, we conducted ≥ 1 emergence count or visual survey on roosts that might have held >1 bat. We considered roosts “primary” if ≥ 30 bats used them on more than one occasion (as defined for tree-roosting bats, *Myotis sodalis*; Callahan et al. 1997) and “secondary” if fewer bats used them. Because of the remoteness of two roosts (BRCC and Roost 2), and property access issues at Roost 7, datalogging telemetry receivers and 3- or 5-element Yagi antennae were placed near roosts to monitor radio-tagged bat activity for short periods of time (3–21 days). The dataloggers allowed for simultaneous monitoring of up to 10 coded tags in each year.

Roost selection.— In order to assess large-scale roost habitat selection by Virginia big-eared bats, we used ArcMap 10.1 (ESRI 2012, Redlands, CA) and 2001 Southeast Gap Analysis Project landcover raster data (Davidson 2001; Appendix C1) to measure 12 landscape variables (Table 2) for 62 focal locations, which included 31 secondary roost locations and 31 random locations. One random location was plotted on the available landscape for each secondary roost site using the Create Random Points tool in ArcMap; random points were not matched to any particular roost location. We defined the landscape available for roosting as all land within a 32.0 km buffer around BRCC, which was equal to the greatest distance moved by any of the bats tracked from the hibernaculum (24.1 km) plus the mean maximum roost switching distance for radio-tagged bats (7.9 km; Figure 1). We measured elevation at each focal point using 3-m resolution digital elevation models (DEMs; USDA/NRCS 2014). We obtained slope and aspect from DEMs using the Slope and Aspect tools in ArcMap, respectively. To use aspect in models, we transformed the hillside aspect of each focal point to northness values by taking the cosine of aspect; hence, -1 indicates a south aspect and 1 indicates a north aspect (Roberts 1986). We measured distances from all roosts used by Virginia big-eared bats to the nearest TIP project, primary and secondary road, and street. We used shapefiles named TIPRoads.shp and TIPBridges2009_2015.shp, given to us by NCDOT, for TIP project locations. We used a TIGER/Line primary and secondary roads shapefile for primary and secondary road locations. Primary roads generally included divided, limited access highways under federal and state management. Secondary roads were main arteries with one or more lanes of traffic in each direction. Streets were local neighborhood roads, rural roads, city streets, vehicular trails (4-wheel drive), ramps, service drives, walkways, stairways, alleys, and private roads, but also included primary and secondary roads. To calculate distance to the nearest street, we used a NCDOT Integrated Statewide Road Network (ISRN) shapefile layer (ISRN_v2_Nov2007) and a TIGER/Line All Roads shapefile which includes primary roads, secondary roads, local neighborhood roads, rural roads, city streets, vehicular trails (4-wheel drive), ramps, service drives, walkways, stairways, alleys, and private roads.

We used the Line Density tool in ArcMap to calculate stream densities (km/km^2) within a 4.7 km radius of each focal point and road densities (km/km^2) within a 7.9 km radius of each focal point, as these are the known mean maximum foraging and mean maximum roost switching distances for this population, respectively (see Foraging and Roosting Ecology sections in Results). We calculated distance from each focal point to rock-vegetation and rock (Appendix C1) by first converting the landcover raster to a shape file, then using the Near tool to measure distance to the nearest polygon of the cover type in ArcMap. We measured the percent forest cover within 4.7 km of each focal point, but we omitted forest patches < 20 ha from this calculation because 20 ha is the minimum patch size tolerated by some bat species (de Jong 1995).

Table 2. Landscape variables measured for 31 secondary springtime roost sites used by Virginia big-eared bats in 2013 and 2014 in North Carolina and Tennessee and 31 associated random points. Landcover types were taken from 2001 Southeast Gap Analysis Project data (Davidson 2001).

Variable	Definition
North and south aspect	Hillside north and south aspect of roost
Elevation	Elevation (m) of roost
Density of streams	Density (km/km^2) of streams within mean max foraging distance (4.7 km)
Density of streets	Density (km/km^2) of streets within mean max roost switching distance (7.9 km)
Distance to primary roosts	Distance (m) to primary maternity roosts (BRCC and Roost 7)
Distance to developed	Distance (m) to developed/disturbed landcover
Distance to riparian	Distance (m) to riparian vegetation landcover
Distance to streets	Distance (m) to streets
Distance to rock vegetation	Distance (m) to rock vegetation/ rock landcover
Distance to water	Distance (m) to major streams
Percent developed	Percent developed/disturbed landcover within mean max roost switching distance (7.9 km)
Percent forest	Percent forest landcover within mean max foraging distance (4.7 km)

We also made measurements at a finer scale, which we term the roost level. We took measurements of outcrop area ($L \times H$), and percent outcrop vegetative cover, defining outcrops as rock surfaces with little (< 2.5 cm depth) or no visible soil. Percent outcrop vegetative cover was an estimate to the nearest 25% of the proportion of the roost outcrop that was covered with vegetation (e.g., small trees, herbs, and moss or lichen). We recorded the presence or absence of a cave within 50 m. We classified roosts by structure type (cave, rock shelter or overhang, uninhabited house, barn, building porch deck, or tree). We further classified cave roosts into three types: fracture caves, breakdown caves, and boulder caves. Fracture caves (Twidale and Romani 2005) likely formed by weathering along sheeting planes, with cracks forming along joints/fractures, or by other large rock movements. Breakdown caves may have formed by breakdown of the ceiling similar to the formation of breakdown chambers inside of karst caves, whereas boulder caves were formed by spaces left between fallen boulders (Osborne et al. 2013).

Rock shelters or overhangs were characterized by having an entrance that was wider than the structure was deep and lacking a “dark zone”, or area of complete darkness (Osborne et al. 2013). We recorded and measured the number of entrances, entrance dimensions ($L \times H$), and entrance solar exposure (nearest 25%) for each roost. Due to the ruggedness of the terrain and thick vegetative cover, it is possible that we failed to detect every entrance for some roosts. In the interior of roosts, we measured the number of rooms, room dimensions ($L \times W \times H$), level of light (lux) inside the roost using a digital luxmeter (LX1010B; Dr. Meter, California), and airflow (m/s) and temperature using an Alnor AVM440 air velocity meter (TSI, Inc., Shoreview, Minnesota).

Roost temperatures.—From 1–26 May, we recorded internal temperatures in 10 roosts (eight natural rock roosts and two barns) using temperature dataloggers (HOBO Pro Series RH Temperature Data Logger; Onset Computer Corporation, Bourne, Massachusetts); we monitored temperatures in nine roosts (seven natural rock roosts, two barns) in May 2014 and, we used temperature data recorded in BRCC in May 2008 (provided by North Carolina Wildlife Resources Commission). We set dataloggers to record temperature every 30 minutes, 24 hours per day; BRCC temperature data were recorded every 120 minutes, 24 hours per day. For natural roosts, we housed each logger (~ 10 cm in diameter) inside a perforated plastic jar (~20 cm tall and 10 cm wide) for weather-proofing, and we placed the jar ~ 2 m from where the bats were known to roost or thought to be roosting. We did not weatherproof loggers used inside building roosts.

Roost trailcam setup.—From 12 May 2013 to 21 November 2014, we recorded animal activity at the primary maternity roost (Roost 7). We set trail cameras (Wildgame Innovations IR4 or Bushnell Trophy Cam) to record either still photographs or 1-minute videos at both entrances to the cave 24 hours per day (Table 3). We positioned the trail cameras 1–1.5 m above the ground and 2–5 m from entrances.

Table 3. Trail camera deployment record at two entrances of a primary maternity roost of Virginia big-eared bats in Watauga County, North Carolina, 2013 and 2014.

Camera model	Start date	End date	Entrance	Record type	Hours active	Number of wildlife photos/videos
WI IR4 ¹	5/12/2013	5/21/2013	1	photo	230.5	11
WI IR4	5/27/2013	6/23/2013	1	video	669	13
WI IR4	6/29/2013	12/5/2013	1	photo	3811	59
BT Cam ²	11/8/2013	9/24/2015	1	photo	16434	1460
Entrance 1 total					21144.5	1543
WI IR4	5/21/2013	8/15/2013	2	photo	2064	23
WI IR4	3/16/2014	5/11/2014	2	video	1357	70
BT Cam	6/27/2014	1/14/2015	2	video	4833	285
Entrance 2 total					8254	378

¹Wildgame Innovations IR4

²Bushnell Trophy Cam

Roost analysis.—We conducted all statistical analyses using the programming language R, Version 3.12 (R Core Team 2014) or the program PAST, Version 3.04 (Hammer et al. 2001). For reported variables, we present mean \pm 1 standard error (SE). To identify coarse-scale landscape characteristics that may be important for Virginia big-eared bat springtime roost preferences, we used GIS and an information theoretic approach to compare secondary roosts to random points on the landscape available for roosting. In R, we formed eight different predictive logistic regression models (Appendix C2) using the data from 12 variables (Table 2) measured at each random point and secondary roost location. Prior to building the candidate model set, we conducted a Spearman’s rank test on all possible pairs of variables to test for correlation; only two variables were highly correlated, street density and distance to developed landcover (Spearman’s $r = 0.71$); thus, we discarded the street density variable to avoid over parameterizing the model. The remaining 11 variables in the models were not highly correlated (Spearman’s $r \leq 0.58$). Models included between 1 and 3 variables and tested hypotheses related to optimal temperatures on the landscape and proximity to foraging resources, primary maternity roosts, anthropogenic structures, disturbance, and rock habitat. We considered full and reduced (post-hoc) model sets. We calculated Akaike’s Information Criterion for small samples sizes (AICc) and weights (w_i) for each model; we used AICc values to select the most parsimonious model and to predict variable importance. To account for model selection uncertainty, we averaged parameters from models in the confidence set (those models for which w_i was within 10% of w_i for the highest weighted model).

To assess roost selection at a finer scale, we conducted two separate principal components analyses (PCAs); $PCA_{\text{size/cover}}$ included nine variables measured at 21 natural rock roosts (excluding any temperature variables) and PCA_{temp} included 11 variables measured at eight natural rock roosts (including two temperature variables). $PCA_{\text{size/cover}}$ included the number of entrances, number of rooms, sum of entrance area, sum of room area, airflow, lux, outcrop dimensions, outcrop vegetation cover, and outcrop solar exposure. We did not include any

temperature variables in this PCA because we did not have adequate temperature data for all 21 roosts. We omitted one cave roost (Roost 9) from the PCA_{size/cover} analysis because we were not able to fit inside the entrance and, thus, could not measure interior characteristics. PCA_{temp} included all of the above variables plus two temperature variables (mean temperature and temperature range inside each roost for the period 1–26 May). We used temperature data from dataloggers placed inside seven natural rock roosts in May 2014 and from a datalogger set in BRCC in May 2008 (we attempted to measure BRCC temperatures in 2014, but our datalogger was stolen). We assumed that temperatures inside BRCC in 2008 were similar to 2014, though in 2008 the datalogger was set in a part of the cave that was ~ 2° C cooler than the point where the bats roosted in summer. For both PCA_{size/cover} and PCA_{temp}, we reduced the roost-scale variables to two principal components using the FactoMineR package (Version 1.28; Husson et al. 2014, Lê et al. 2008) in R. We chose to retain only two factors in each PCA in order to provide clear and simple results (Tabachnick and Fidell 2007). The resultant components are representations of the variance-covariance structure of the original variables.

We conducted additional statistical tests to assess variation in temperature means and stability in a subset of roosts (eight natural rock roosts and two barns) in which we measured interior temperatures between 1–26 May 2014 (or 2008 for BRCC). We used an ANOVA with a Welch correction for non-homogeneity and a post-hoc Tukey test to compare temperature means between each of the primary maternity roosts (BRCC and Roost 7) and the eight secondary roosts in this subsample. We used a Levene’s test for homogeneity of variance based on medians to compare temperature variability between each of the primary maternity roosts and the eight secondary roosts.

Roost trailcam analysis.—We viewed each recording and identified any animals that we observed visiting the primary maternity roost to the lowest taxonomic ranking possible. We identified the most commonly observed animals, and created plots to show observations/camera effort across months for the most commonly detected non-threatening animals (common if >100 observations total) and potential predators (common if > 50 observations). For four potential predators, we developed hourly activity plots to assess how their activity overlapped with the months when bats were most likely active at the maternity roost (April to September).

WINTER ACOUSTIC MONITORING

Detector Setup.—From 30 November 2012 to 24 March 2013, we deployed a Wildlife Acoustics SM2+ Bat detector (henceforth, SM2; Wildlife Acoustics, Inc., USA) at the entrance gate to BRCC (Figures 6A and 6B). For the SM2, we ran a 30 m microphone cable to a SMX-US omnidirectional microphone housed in a PVC hood ~2 m from the ground near the cave gate (Figures 6A and 6B). From 9 November 2013 to 30 March 2014, we deployed a RL1 Anabat (henceforth, RL1 Anabat; Titley Scientific, Inc., USA) at the gate of BRCC (Figure 6C) and a SD2 Anabat (henceforth, SD2 Anabat; Titley Scientific, Inc., USA) at the outside of the main entrance to BRCC (Figure 6D). The RL1 Anabat is self-contained with a sealed microphone. For the SD2 Anabat, we ran a 10 m microphone cable to a directional microphone housed in a PVC elbow ~1 m from the ground and oriented towards the outer cave entrance (~10 m from the gate; Figure 6D). The SM2 and RL1 Anabat recorded zero crossing with a division ratio of 8. The SD2 Anabat recorded zero crossing with a division ratio of 16. We set all acoustic data loggers to record 24 hours per day.

Acoustic Analysis.—Using AnalookW, we considered an acoustic file a bat call if there were ≥ 3 consecutive echolocation pulses within 0.5 seconds. We only considered pulses that were ≥ 2.5 kHz in bandwidth and between 20–100 kHz (see Appendix E1 for sample Virginia big-eared bat call) and did not apply any other filter parameters in the analysis. We only observed two other bats (both *Myotis leibii*) in BRCC in 2013 and 2014, so we assumed that Virginia big-eared bats made all calls. For bat activity data from 9 November 2013 to 30 March 2014, we overlaid activity graphs with temperature data obtained from either the Grandfather Mountain weather station or a HOBO data logger placed outside of the entrance at BRCC.

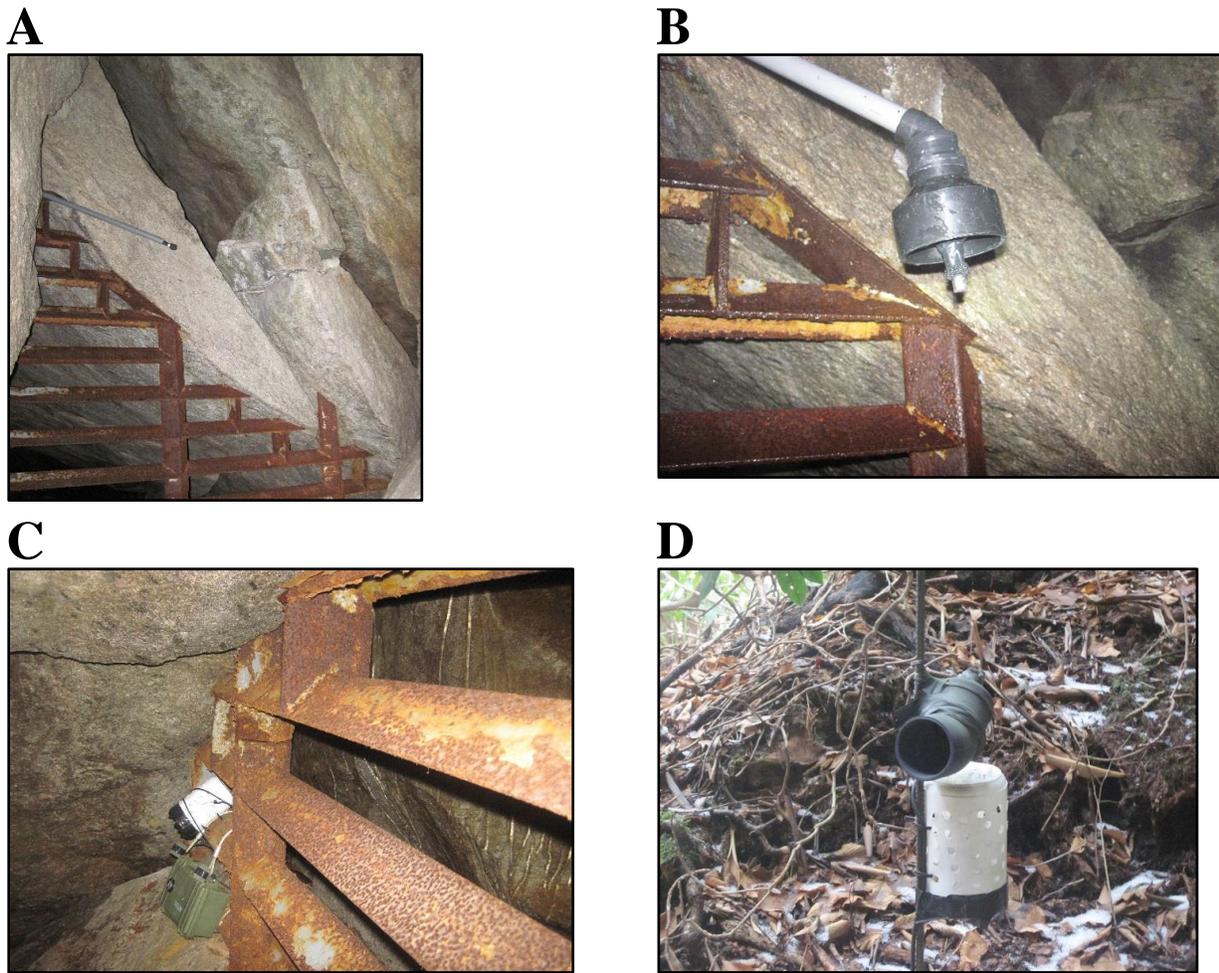


Figure 6. Bat detector acoustic microphone setups for A) SM2+ Bat at cave entrance gate, B) SM2+ with PVC hood weatherproofing at cave entrance gate, C) RL1 Anabat at cave entrance gate, and D) SD2 Anabat microphone at outer cave entrance. Detectors and microphones were deployed to record winter Virginia big-eared bat activity (Winter 2012–2013 and Winter 2013–2014) at Black Rock Cliffs Cave on Grandfather Mountain in North Carolina.

RESULTS

CAPTURED BATS

From March to May 2013 and 2014, we captured and radio-tagged 42 adult female and two adult male Virginia big-eared bats at BRCC and at five additional roost sites in North Carolina (see Appendix A1). Bats weighed 10.2 ± 0.2 g and had white-nose syndrome wing damage scores of 0 or 1, with physical damage (i.e., ≥ 0.5 mm holes or trailing edge tears) observed on 20 bats.

MOVEMENT AND FORAGING ECOLOGY

Departure from BRCC.—We used data only from 2014 to assess seasonal movements between the primary hibernaculum and the primary maternity roost, as we did not learn the location of the latter roost until part way through Spring 2013 when we first tracked bats to this roost. In 2014, 10 of 21 female bats radio-tagged at BRCC moved 14.4–15.1 km north-northwest from the hibernaculum on Grandfather Mountain to the primary maternity roost or to another nearby roost (Roost 5) during a single night's flight. We relocated 11 of the 21 bats radio-tagged at BRCC 2–15 days after they left the hibernaculum at roosts (including the primary maternity roost) that were 12.0 ± 1.4 km (range 0.3–14.9 km) from the hibernaculum. Of these 11 bats, nine eventually used the primary maternity roost. These bats arrived at the primary maternity roost 2–25 days (mean 10.8 ± 2.8 days) after we radio-tagged them at the hibernaculum. Bats departed BRCC between 19 March and 27 April 2014 (mean date was 31 March 2014) and arrived at the primary maternity roost between 22 March and 30 April 2014 (mean date was 6 April 2014). The longest single-night movement observed was on 19 March for a bat that moved 15.1 km from the hibernaculum to a roost site near the primary maternity roost. Some bats used roosts in between the hibernaculum and the primary maternity roost or roosted in unknown locations. In 2013 and 2014, nine bats used a roost at a higher elevation on Grandfather Mountain (near Attic Window) before moving towards the primary maternity roost; bats appeared to be “staging” near the top of the mountain, but we were unable to determine the bats' exact location(s) due to adverse weather conditions or ice/snow cover. We believe these bats were “staging” because they used this area for roosting for 1–9 days before they moved towards and eventually roosted at the primary maternity roost. Despite regular telemetry searches, we only located two roosts south of the hibernaculum.

Telemetry towers.—In 2013, when we erected telemetry towers near BRCC and at Grandfather Golf and Country Club on the other side of Grandfather Mountain, three bats were detected (Table 4; Appendix D1). One of these bats (COTO 151.500-016) was detected by the towers near BRCC as it day-roosted on seven days and as it foraged on 19 nights in April and May (Appendix D1).

In 2014, when we erected telemetry towers along NC 105, all five towers detected bats with coded tags moving from the hibernaculum to the primary maternity roost or other roosts (Table 4; Appendix B2). Bat detections and reception ranges of telemetry towers indicate bats may have crossed NC 105 anywhere between the Linville tower and 5 km northeast on NC 105 (Appendix B2). Based on high-power signals for bats that clearly moved towards Beech Mountain in one night, crossing NC 105 occurred in 8–12 minutes for 4 bats, 29–38 minutes for 2 bats, and 56–59 minutes for 2 bats. Areas with the greatest reception overlap for all 10 bats were between the TNC tower and slightly northeast of the Barker tower (all-bats-composite polygon, Figure 7).

Table 4. Names and locations of telemetry towers, with Virginia big-eared bats detected in 2013 and 2014. Virginia big-eared bats were radio-tagged at the main hibernaculum on Grandfather Mountain in North Carolina between 19 March–13 April 2013 and 19–25 March 2014 .

Tower name	Location (NAD 83 UTM)	Bats detected (151.500-xxx)
GFGCC	17S 0423715 3995053	012, 013, 016
Linn Cove	17S 0426741 3994936	015, 016
Stack Rock	17S 0425801 3994520	016
Ennis	17S 0426593 3999215	020, 021, 022, 023, 024, 025, 026, 027, 028, 029
Barker	17S 0425844 3998391	020, 021, 022, 023, 024, 025, 026, 027, 028, 029
Profile	17S 0424989 3997580	020, 021, 022, 023, 024, 025, 026, 027, 028
TNC	17S 0424402 3997241	020, 021, 022, 023, 024, 025, 026, 027, 028
Linville	17S 0423559 3996358	020, 022, 027, 028

On the night of 31 March 2014 at 20:41 EDT, we triangulated a bat’s position (tag 151.453 at NAD 83 17S 0424468, 3996206) near Big Grassy Creek (~1.1 km directly south of Linville Gap or the NC 105/NC 184 junction on the west side of Grandfather Mountain). This bat was radio-tagged at BRCC on 31 March and was in Roost 7 the next day. A second bat (151.524), tagged on 16 April 2014 at BRCC, was detected that same night via radio-telemetry as it crossed over NC 105 near the Green Ridge Branch of the Watauga River (near the Ennis Tower). The bat was carrying a standard beeper transmitter so the towers did not detect its signal; however, we identified the crossing point based on signal strength and direction. Later that night we heard this bat’s signal in the Pigeon Roost Road and Horse Bottom Ridge areas ~4 km north of NC 105. The following day the bat was roosting near the Watauga River (~0.2 km south of NC 105) in the vicinity of NAD 83 17S 0427156, 3999516. However, we were unable to access the property to find its exact location. There were several buildings in the area where a bat could have easily roosted. The next day this bat was roosting ~1.2 km north of this location across NC 105. It appears that this bat crossed NC 105 twice in one night (16 April) and then again on the next night (17 April).

Driving.—During 48 driving transects on NC 105, we drove 2,116 km (1,315 miles) for a total of 58 hours and 26 minutes (mean trip time = 73 minutes). We detected two radio-tagged bats during five driving transects (Figure 8). On 1 April, while driving south along NC 105 near the Avery/Watauga County line, we recorded bat 151.500-020 from 21:54–21:58 (Figure 8; Appendix B3). This bat was also recorded, at various times on the same night from 21:13–22:04, by the five telemetry towers located along NC 105. On four occasions, we recorded bat 151.500-027 while driving on SR-1545 (Figure 8; Appendix B3). On 2 April, from 21:15–21:16 we recorded signals near Linville Golf Club 0.2–0.7 km northeast of Lake Kawahna, south of Linville, NC. On 4 April, 12 April, and 30 April, in the same area, we recorded signals from this bat from 21:52–21:56 and 21:26–21:30 and 21:28–21:29 respectively. The bat was likely foraging in this area, but because we were driving along SR-1545, we only picked up the signals for short periods of time before we moved on. Bat 151.500-027 was also picked up by the five telemetry towers on the nights of 2 April and 3 April (Table 4).

Foraging.—We collected 579 foraging location estimates for 16 bats (mean 36 ± 7 location estimates/per bat) and obtained a sufficient number (≥ 29) of locations to make foraging ranges for 10 focal bats (five in each year, Tables 5 and 6; Figure 9; see Appendix D for individual ranges). We conducted foraging telemetry from 2 April–26 May (2013 and 2014), tracking all focal bats 3–9 nights each. Foraging range sizes for focal bats were 472.7 ± 133.8 ha (range 74.7–1527.6 ha) for 90% fixed KDEs and 650.3 ± 188.3 ha (range 92.8–2140.4 ha) for 95% fixed KDEs (Table 5). MCP foraging ranges were smaller: 95% MCPs for focal bats were 331.2 ± 111.6 ha (59.6–1048.8 ha) and 100% MCPs were 633.6 ± 202.6 ha (118.6–2185.1 ha; Table 5). Focal bats foraged an average of 2.4 ± 0.7 km (range 0.6–6.3 km) from daytime roosts and as far away as 4.7 ± 0.8 km (range 1.8–8.1 km). On occasion, focal bats returned to the primary maternity roost while foraging or used other roosts as night roosts. We tracked bats back to the primary roost and two other night roosts 1–4 hours after emergence, and found dropped transmitters underneath two rock overhangs not used as day roosts. Foraging locations were relatively close to streets (mean distance = 162 m), but were typically much further from TIPS (mean distance = 2.4 km) and primary or secondary roads (mean distance = 1.8 km; Table 6). Note that primary roads were generally divided, limited access highways under federal and state management and secondary roads were main arteries with one or more lanes of traffic in each direction. Bats foraged near US 321 (TIP R-5016) on several occasions, sometimes as close as ~25 m to the highway. TIP projects nearest to foraging locations were R-2566, R-2710, R-2811, R-5016, B-4315, B-4316, B-4668, and B-4670.

We did not detect foraging habitat selection at either the landscape (Wilks' Lambda = 0.663, $p = 0.343$) or home range level (Wilks' Lambda = 0.675, $p = 0.417$). Landscape level was defined as the area within a 15.1 km buffer around the primary maternity roost, whereas home range level was defined as each bat's 95% KDE (see Foraging habitat selection analysis in Methods). All 10 bats used the four landcover types in close proportion to their availability at the landscape and foraging home range scales (Figure 10). Bats used upland forest and rock vegetation (mean probability of use was 76% for both scales combined) more than riparian vegetation/water (7%), developed (9%), and agriculture (9%). However, the ranking of relative use of any of the habitat types over others was not significant at either the landscape or home range scales. Further, individual bats did not show specialization for any particular habitat types.

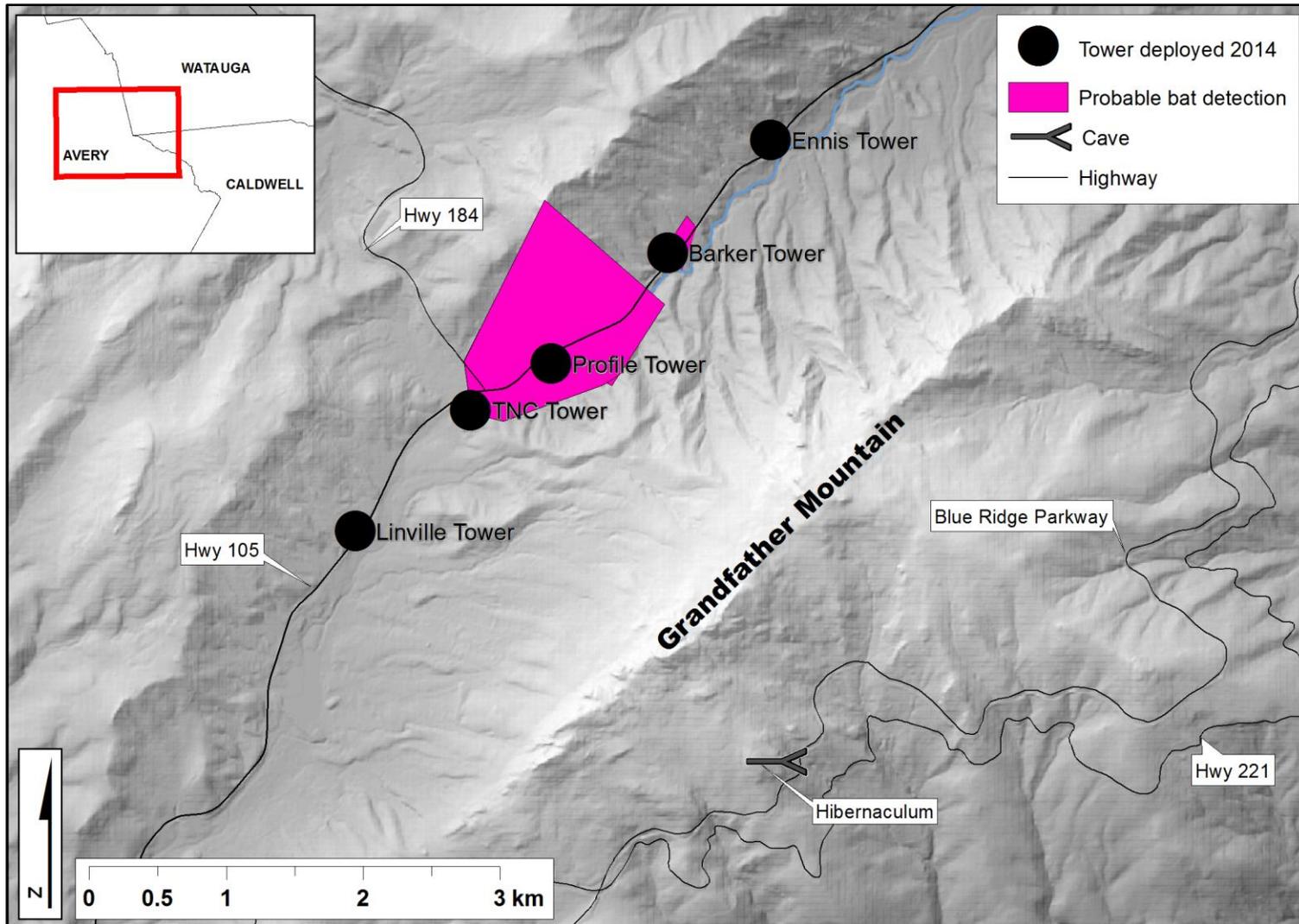


Figure 7. Telemetry tower locations in 2014 and the *all-bats-composite polygons* that contain the most probable areas of detection for all 10 bats detected by towers (see Appendix B2 for data on individual bats). Probable bat detection is based on antennae reception polygons and high-power (signal >171) bat detections (see Methods). Virginia big-eared bats were radio-tagged at the main hibernaculum; these five towers recorded their movements from 18 March to 28 May 2014.

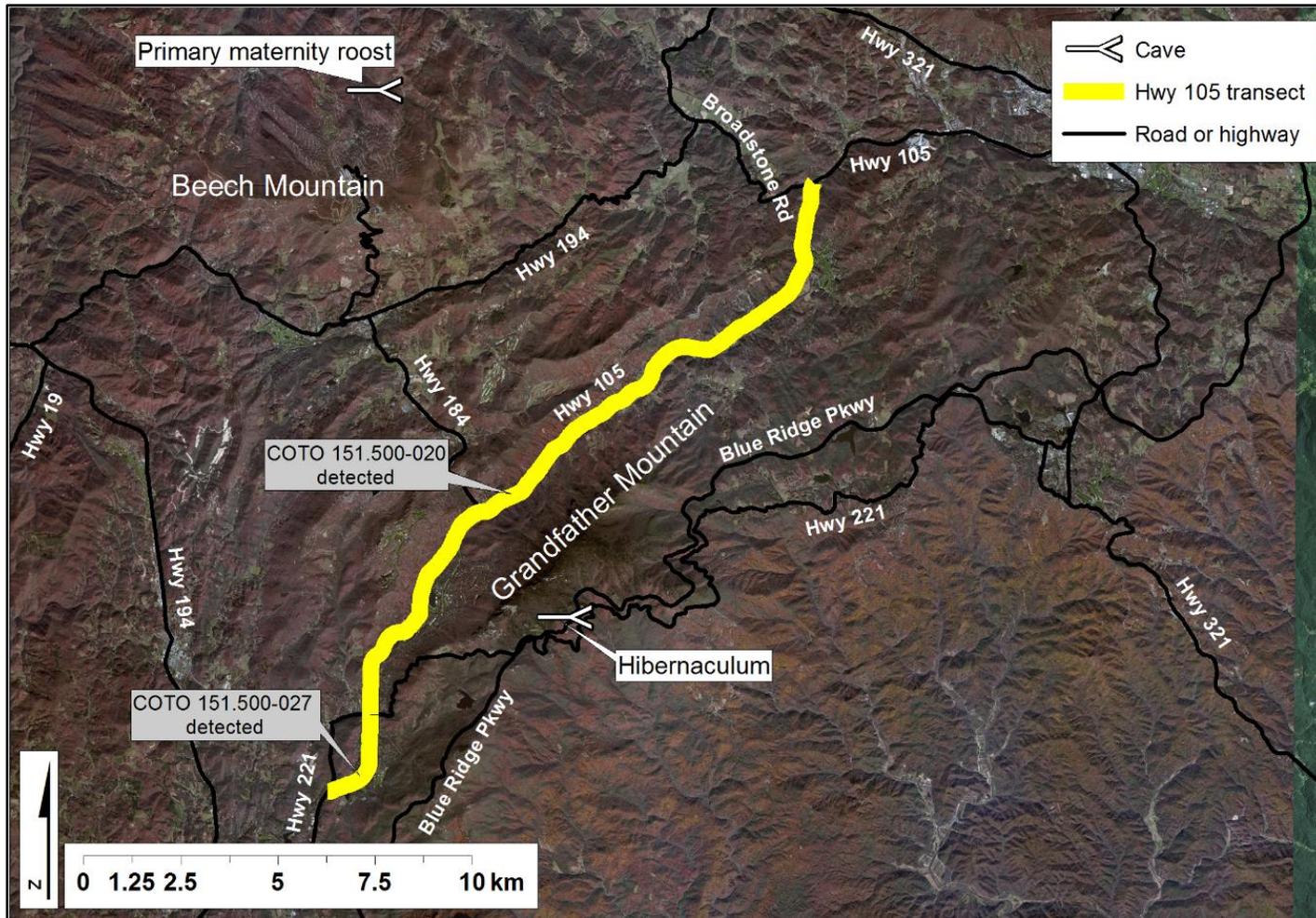


Figure 8. Radio-telemetry driving transect driven to listen for signals from transmitters applied to Virginia big-eared bats at the hibernaculum on Grandfather Mountain, North Carolina from 19–25 March 2014. The driving transect follows NC Highway 105 for most of its length and NC State Road 1545 at its southern end. Areas where bats were detected during driving transects are indicated by callouts.

Table 5. Foraging range sizes and foraging distances for 10 Virginia big-eared bats tracked for 3–9 nights each in April and May 2013 and 2014 in North Carolina and Tennessee. We dropped point location estimates with high potential for error and used residual point location estimates to calculate minimum convex polygons (MCPs) and kernel density estimates (KDEs) for each bat.

Transmitter frequency	Nights of telemetry	Number of residual locations ¹	90% KDE				Foraging distance from daytime roosts	
			95% MCP (ha)	100% MCP (ha)	(ha)	95% KDE (ha)	Mean (km)	Maximum (km)
306	3	29	112.3	461.5	279.1	368.2	3.0	4.0
388	9	51	879.2	1192.7	710.8	917.5	4.5	7.0
398	6	41	341.7	587.6	631.3	941.0	6.3	8.0
416	8	86	1048.8	2185.1	1527.6	2140.4	1.9	8.1
453	7	90	89.7	159.5	148.6	204.9	0.6	1.8
466	7	38	223.9	294.6	415.4	519.6	0.9	2.3
466B	5	36	59.6	118.6	443.3	600.0	5.3	6.1
496	7	48	369.2	807.6	74.7	92.8	0.6	2.0
500-013	3	45	101	134.4	175.7	220.1	0.6	2.0
507	4	43	86.6	394.2	320.3	498.9	3.5	5.3
Total sample								
mean ± SE	5.9 ± 0.7	50.7 ± 6.5	331.2 ± 111.6	633.6 ± 202.6	472.7 ± 133.8	650.3 ± 188.3	2.7 ± 0.7	4.7 ± 0.8
Sample								
range	3–9	29–90	59.6–1048.8	118.6–2185.1	74.7–1527.6	92.8–2140.4	0.6–6.3	1.8–8.1

¹ Biangulations that were < 20 degrees different and triangulations or biangulations with lines that did not cross were excluded, leaving only residual locations for analysis.

Table 6. Characteristics of foraging points for 10 Virginia big-eared bats tracked for 3–9 nights each in April and May 2013 and 2014 in North Carolina and Tennessee. We present the mean and range (in parentheses) for each bat and weighted means and ranges for all bats at the bottom of the table.

Transmitter frequency	Mean elevation (m)	Mean slope (degrees)	Mean slope direction (degrees)	Mean distance to water (m)	Mean distance to nearest TIP (m) [†]	Mean distance to nearest primary or secondary road (m)	Mean distance to nearest streets (m)*
306	932 (827–1249)	17 (7–30)	129 (9–357)	247 (2–878)	1412 (421–2112)	1497 (418–3364)	124 (18–276)
388	928 (803–1318)	14 (2–27)	158 (10–351)	369 (10–906)	1811 (118–3108)	1585 (122–3160)	133 (7–408)
398	856 (796–1136)	16 (0–27)	215 (9–343)	222 (6–2983)	1808 (510–2963)	1581 (506–2963)	89 (1–456)
416	1225 (798–1435)	13 (4–37)	189 (0–353)	276 (13–1303)	2514 (278–3367)	1399 (149–2341)	133 (1–363)
453	1239 (1123–1371)	15 (3–29)	174 (4–359)	174 (3–532)	3003 (829–3355)	1763 (832–2119)	140 (0–383)
466	1196 (991–1402)	16 (1–34)	159 (1–356)	160 (7–670)	2429 (456–3213)	2023 (1395–2833)	174 (13–384)
466B	864 (755–1037)	17 (2–29)	192 (16–359)	451 (3–1310)	439 (45–1378)	470 (49–2458)	240 (6–561)
496	1259 (1117–1373)	17 (6–31)	272 (0–360)	587 (43–940)	1956 (1179–3125)	1957 (1184–2895)	328 (51–669)
500-013	759 (647–958)	21 (2–41)	215 (1–348)	192 (2–623)	5703 (4356–6262)	2648 (1818–3196)	210 (9–522)
507	1211 (1145–1393)	15 (3–26)	221 (6–345)	124 (2–422)	925 (500–2975)	2641 (1804–2973)	81 (2–384)
Mean	1084	15.7	192.7	274	2352	1752	162
Range	647–1435	0–41	0–360	2–1310	45–6262	49–3364	0–669

[†]TIP = TIP projects nearest to foraging locations were R-2520, R-2566, R-2595, R-2596, R-2710, R-2811, R-5016, B-3608, B-3818, B-4053, B-4315, B-4316, B-4668, B-4669, B-4670, and R-4707

*Includes primary and secondary roads in TIGER/Line roads shapefile

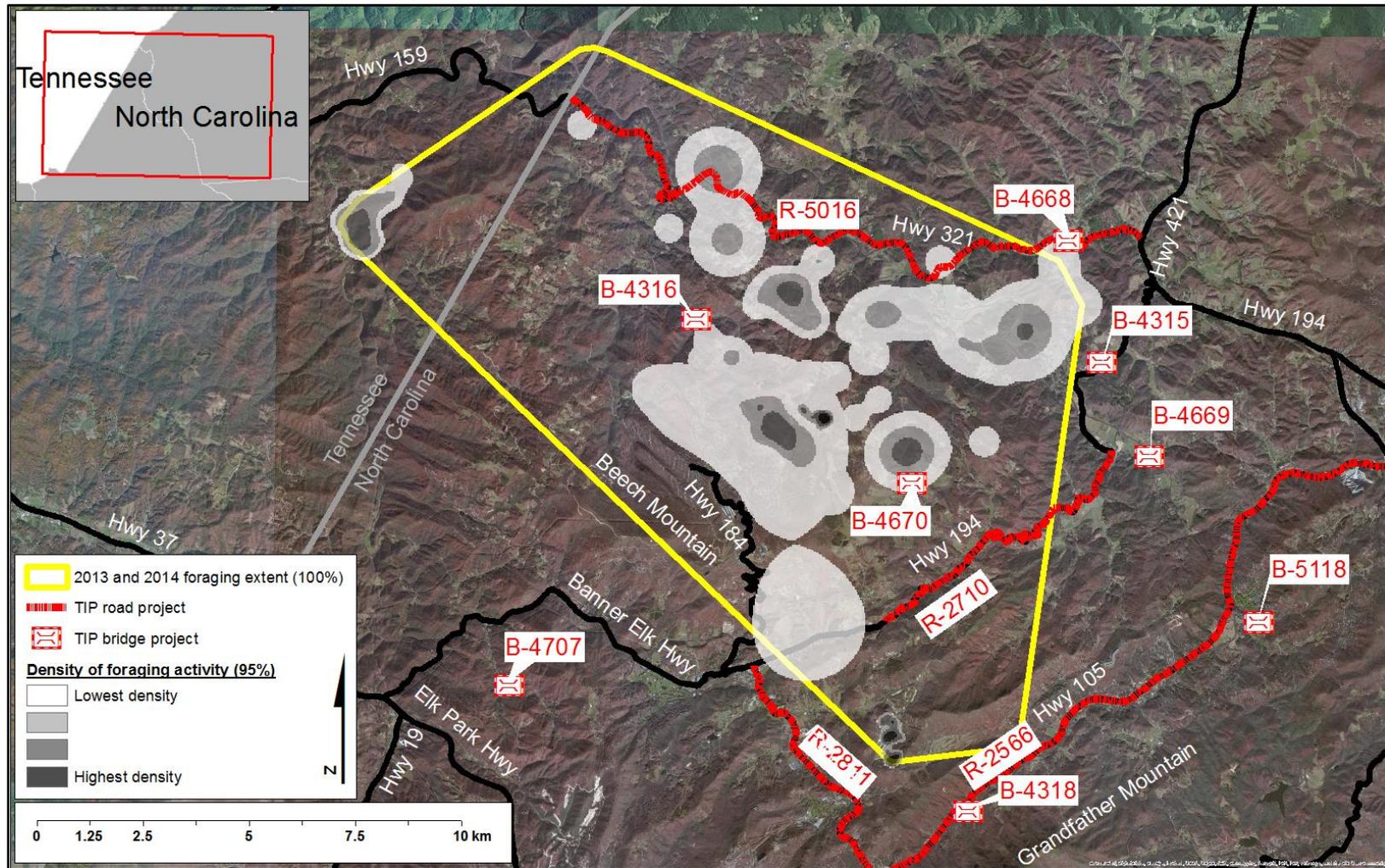
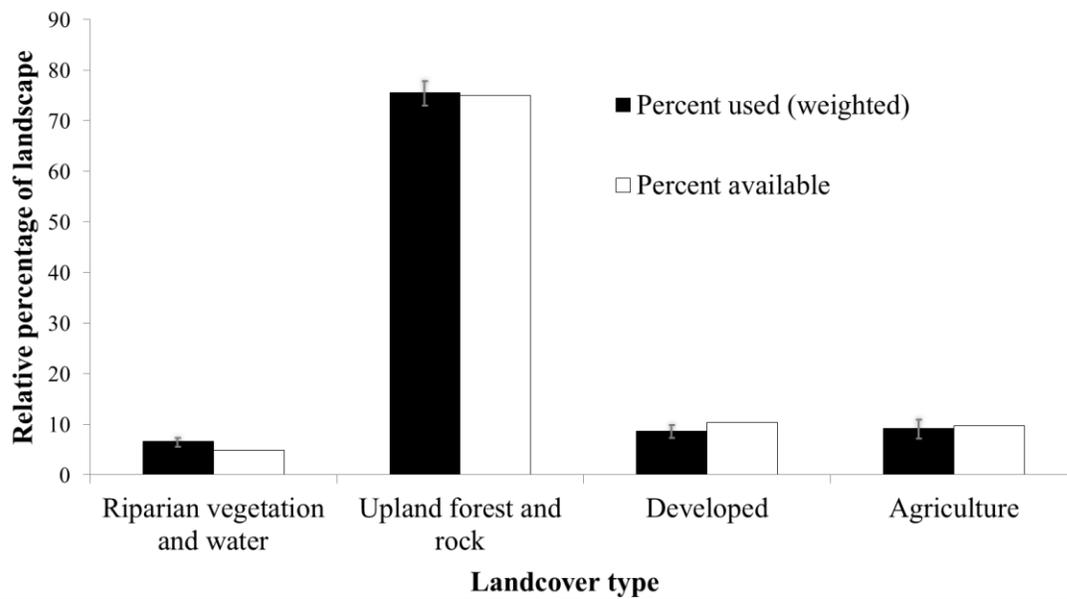


Figure 9. Foraging extent and density of foraging activity for female Virginia big-eared bats tracked in North Carolina and Tennessee from April–May 2013 and 2014. The foraging extent 100% minimum convex polygon contains all of the 579 foraging locations for 16 bats we tracked. The foraging density raster was made by combining 95% foraging kernel density estimate (KDE) rasters of 10 focal bats with sufficient data to generate a KDE. TIPs displayed are those near or overlapping foraging areas.

A.



B.

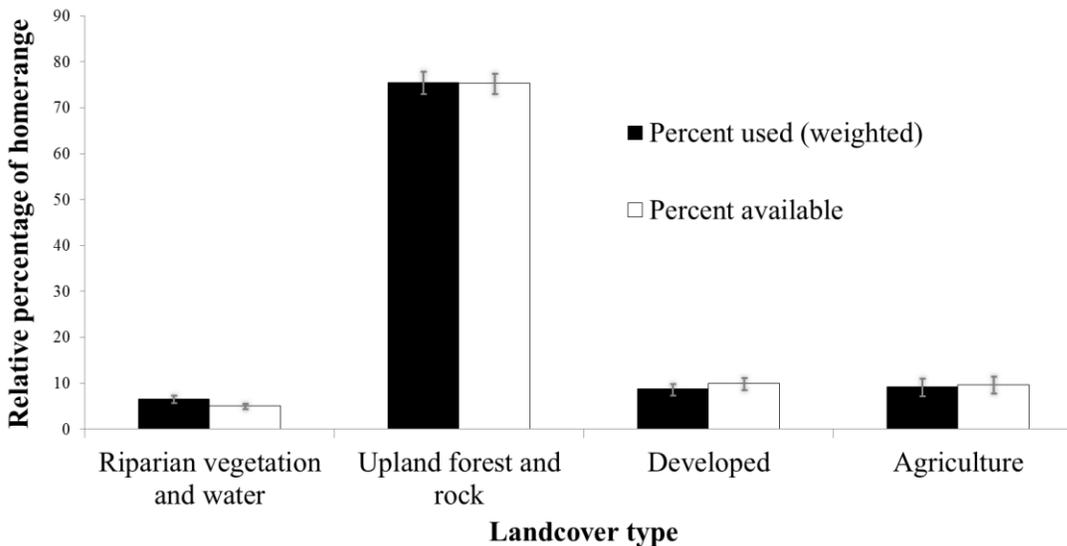


Figure 10. A) Landscape-level foraging habitat use and B) home range-level foraging habitat use for 10 adult female Virginia big-eared bats tracked in North Carolina and Tennessee from March–June 2013 and 2014. Black bars show mean weighted percent and white bars show percent availability of four landcover types on the landscape (A), which was defined as the area within a 15.1 km buffer around the primary maternity roost, and within bats’ 95% kernel density estimate home ranges (B).

ROOSTING ECOLOGY

Roost locations.—We tracked bats to 35 roost sites (33 roosts for females and two roosts for males only; Figure 11). Roosts were relatively close to small streets (mean distance = 183 m), but were typically much further from TIPs (mean distance = 2.1 km) and primary or secondary roads (mean distance = 1.2 km; Table 7). TIP projects nearest to roost sites were R-2566, R-2710, R-2811, R-5016, B-4315, B-4316, and B-4707 (Table 7). We tracked 42 of the 44 radio-tagged individuals to ≥ 1 roost. We tracked two males to a total of four roosts: the primary maternity roost (see Roost 7 description below), two secondary cave roosts, and one building that was also used by a female. The two secondary caves used by males were relatively large ($\geq 81 \text{ m}^3$) fracture caves; one was 0.3 km from BRCC and the other was 2.2 km from the primary maternity roost. Hereafter, we present data on roost characteristics only for roosts used by female bats.

We tracked adult female Virginia big-eared bats to 33 roosts, including the primary hibernaculum (BRCC); we located 14 roosts in 2013 and 19 additional roosts in 2014. Thirty of the 32 new roosts were north of BRCC in Avery and Watauga counties, North Carolina, and Carter and Johnson counties, Tennessee (Figure 11). Two roosts were south of BRCC in the Pisgah National Forest in Avery County, North Carolina (Figure 11). Roosts were 14.2 ± 1.3 km (range 0.1–24.1 km) from BRCC. In April 2013, we discovered the primary maternity roost (Roost 7) used by this population; this cave is 14.4 km north-northwest of BRCC. All roosts other than BRCC were 7.1 ± 0.9 km (range 0.2–18.9 km) from Roost 7. Twenty-eight roosts, including Roost 7, were located on private property. For all bats that we tracked to more than one roost, we estimated mean maximum roost switching distance (excluding seasonal movements from the hibernaculum) to be 4.1 ± 0.7 km (range 0.4–10.3 km). The mean elevation of roosts (excluding BRCC) was $1,022 \pm 40$ m (range 646–1,422 m).

Roost use.—Visits and emergence counts indicated that 31 roosts were used by 1–9 bats, whereas tens or hundreds of bats used two roosts, BRCC and Roost 7. Spring exit counts revealed that ≥ 292 Virginia big-eared bats (276 ± 3 bats for nine counts) used Roost 7 from May to June 2013 (not counted in April 2013) and ≥ 359 bats (310 ± 12 bats for nine counts) used this roost from April to June 2014. During two springtime trips into BRCC on 15 June 2013 and 13 June 2014, we observed approximately 30 and 125 Virginia big-eared bats (including young of the year), respectively. We did not perform emergence counts on BRCC because multiple entrances were inaccessible and, thus, counts would have been incomplete. We refer to both BRCC and Roost 7 as “primary” maternity roosts based on the number of bats using the roosts in springtime and the fact that we observed young of the year in BRCC in 2013 and in both caves in 2014. We tracked 35 of the 42 radio-tagged bats to Roost 7. Although most bats were radio-tagged at BRCC, only three radio-tagged bats were observed using the cave after 12 April in either year. Thirty-six radio-tagged bats used secondary roosts in addition to one of the primary maternity roosts (BRCC or Roost 7). Four secondary roosts were used in both 2013 and 2014. Most roosts were solo roosts; only BRCC, Roost 7, and Roost 11 were used by multiple radio-tagged bats in the same year. Excluding the primary maternity roosts, tracked bats used roosts 2.2 ± 0.3 days (1–17 days), sometimes switching between a primary or secondary roost and another roost up to 14 times.

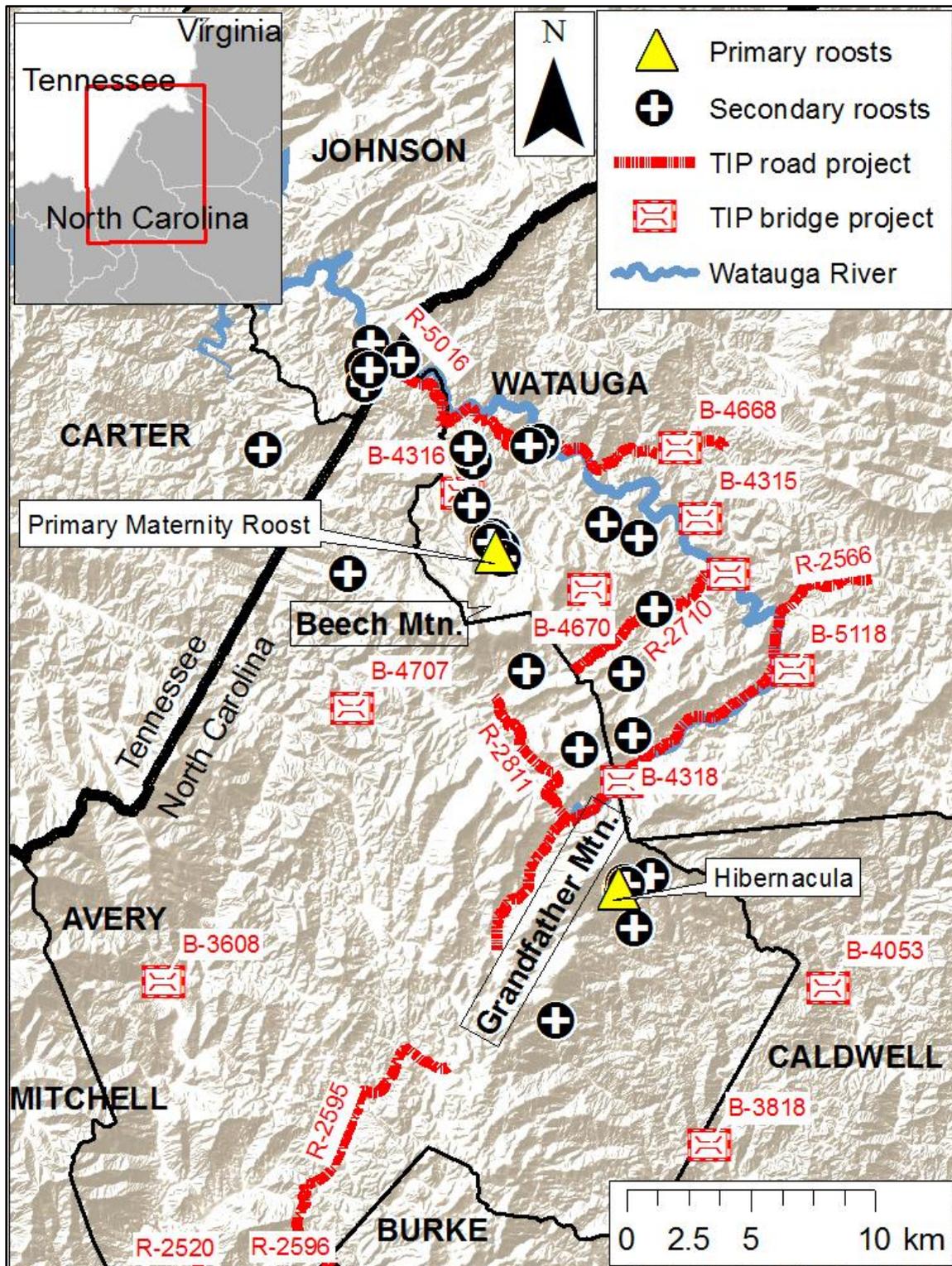


Figure 11. Virginia big-eared bat roost locations found from March to June 2013 and 2014, in northwestern North Carolina and eastern Tennessee. The primary maternity roost near Beech Mountain and the hibernaculum on Grandfather Mountain both served as primary roosts during this period (housing 30–359 bats each). All other roosts were secondary, containing 1–9 bats on any given day.

Table 7. Distances from Virginia big-eared bat roosts to nearest NC DOT TIP, primary or secondary road, and all streets.

Roost	Distance to nearest TIP (m)	Nearest TIP	Nearest primary or secondary road (m)‡	Nearest street (m)*
BRCC 1	3367	R-2566	418	162
2	3384	R-2566	384	110
3	409	R-2710	409	342
4	2251	B-4316	1831	103
5	2110	B-4316	2104	192
6	2101	B-4316	1921	197
Primary maternity roost 7	2748	B-4316	1670	210
8	5424	B-4707	3348	124
9	6088	R-5016	3062	244
10	1400	R-2811	1405	144
11	2176	R-5016	2174	206
12	3581	R-2566	280	92
13	2641	B-4316	1902	293
14	2542	B-4315	1788	365
15	110	R-5016	115	101
16	1109	R-5016	865	865
17	2231	B-4316	1857	126
18	158	R-5016	159	18
19	400	R-5016	401	385
20	36	R-5016	30	30
21	1296	R-2710	1295	261
22	1614	R-2811	415	13
23	1001	R-2566	1000	21
24	1012	R-5016	64	4
25	958	R-5016	101	22
26	3217	R-2566	481	179
27	1266	R-5016	464	8
28	804	R-5016	118	118
29	3051	B-4316	1579	35
30	569	B-4316	2795	390
31	4586	R-2566	767	365
32	3666	R-2566	2812	190
33	1431	B-4316	1469	62
34	1234	R-5016	1231	362
35	3313	R-2566	374	77
Mean distance	2094	-	1174	183
Range	36–6088	-	30–3348	4–865

‡Primary roads generally included divided, limited access highways under federal and state management. Secondary roads were main arteries with one or more lanes of traffic in each direction.

*Streets were local neighborhood roads, rural roads, city streets, vehicular trails (4-wheel drive), ramps, service drives, walkways, stairways, alleys, and private roads, but also included primary and secondary roads.

Roost characteristics.—We tracked bats to 22 natural rock structures, including 17 caves and five rock shelters or overhangs. Rock structures were formed of granitic gneiss, metasedimentary, and sedimentary rocks. Mean rock outcrop area outside of natural roosts was $637 \pm 205 \text{ m}^2$ (range 8–3600 m^2). All natural rock roosts were within 50 m of ≥ 1 additional cave or potential rock roosting structure (e.g., rock overhang or crevice). In natural rock roosts there were 3.1 ± 0.4 entrances (hole leading to the outside that a bat could fit through; range 1–8) and 1.8 ± 0.3 rooms (range 1–5). In Table 8, we present rock outcrop area and number of entrances and rooms for primary and secondary rock roosts. Bats roosted on ceilings or walls at a height of $2.0 \pm 0.3 \text{ m}$ (range 1.0–4.75 m). Natural rock roosts were $237 \pm 49 \text{ m}$ (range 14–663 m) from water and $230 \pm 37 \text{ m}$ (range 30–865 m) from streets.

Table 8. Roost-scale variables (mean ± 1 SE) for primary and secondary roosts used by Virginia big-eared bats in North Carolina and Tennessee, March–June 2013 and 2014. Sum of entrance area was not measured for buildings due to the high number of entrances in most roosts. We did not measure outcrop dimensions, vegetation, or solar exposure for non-rock roosts.

Variable	Primary roosts	Secondary roosts	
	Rock (n = 2)	Rock (n = 19)*	Buildings (n = 10)
Number of entrances	3.0 ± 1.0	3.2 ± 0.5	8.1 ± 1.7
Sum of entrance area (m^2)	9.5 ± 6.2	18.5 ± 6.9	-
Number of rooms	2.0 ± 1.0	1.7 ± 0.3	5.3 ± 1.2
Sum of room area (m^2)	1172 ± 19	182 ± 82	944 ± 214
Airflow (m/s)	0.06 ± 0.02	0.12 ± 0.03	0.07 ± 0.03 [#]
Lux	0 ± 0	28 ± 12	76 ± 43 [#]
Outcrop dimensions (m^2)	209 ± 115	652 ± 234	-
Percent outcrop vegetation	25 ± 0	30 ± 6	-
Percent outcrop solar exposure	38 ± 13	62 ± 7	-
Temperature mean ($^{\circ}\text{C}$)	7.6 ± 1.8 [†]	11.9 ± 0.6 [†]	16.1 ± 0.2 [†]
Temperature range ($^{\circ}\text{C}$)	4.1 ± 0.1 [†]	9.7 ± 0.9 [†]	21.5 ± 1.1 [†]

* Excludes 1 rock roost that we could not measure due to small entrance size

[#] Excludes 1 building roost where we could not measure airflow and lux

[†] Measured in 2008 for BRCC, for six of 19 rock roosts, and for two of 10 building roosts.

We tracked bats to 10 building roosts, including three uninhabited houses, six barns, and the underside of an apartment building porch deck. Only one building roost was within 50 m of a cave or other natural rock structure that had the potential to serve as a roost; the potential roosting structure was a small overhang/crevice $\leq 1.0 \text{ m}$ from the ground on the underside of a boulder. Buildings were $446.0 \pm 138.7 \text{ m}$ (range 4.0–1295.3 m) from water and $84.4 \pm 37.0 \text{ m}$ (range 4.5–362.3 m) from the nearest street; however most were situated next to or adjacent to a driveway. One barn roost enclosed a driveway and vehicles were driven through it regularly. Owners of all the barns and houses indicated that the buildings received little use and few

visitors. Buildings were $\sim 9 \pm 1$ m in height (range 5–20 m), with an average of 2.3 levels in each building (range 1–4) and interior dimensions > 120 m³. There were 8.7 ± 2.3 (range 1.0–25.0) entrances to buildings (i.e., hole with a length or diameter > 0.2 m leading to the outside). Buildings typically contained five rooms (range 1–13), though one tracked bat roosted in the basement of a large house (in construction) that contained over 20 rooms in the multi-story living space above the basement. Of the 15 bats that we observed in buildings, 10 were hanging from the ceilings of ground level, one was hanging from a basement ceiling, one female and at least two male bats roosted on the walls of a concrete basement foundation, and one bat roosted near the peak (8.5 m from the ground) of a barn. Bats roosted 3.2 ± 0.6 m (range 1.6–8.5 m) above the floor, which was the ground or basement floor in all cases except in the barn mentioned above.

We witnessed a maximum of three Virginia big-eared bats using a building roost at any single time, however one homeowner recounted seeing “several” bats in one of the uninhabited houses several years ago. We witnessed one bat roosting in a live Virginia pine (*Pinus virginiana*) for one day; we think this was an unusual roost, as we found this bat dead under the same tree on the following day.

Bats mainly roosted at sites lower in elevation ($1,034 \pm 40$ m, range 646–1,422 m) than the primary hibernaculum (1,422 m), although one roost ~ 275 m from BRCC was at the same elevation. Mean elevation for all roosts was $1,046 \pm 40$ m (range 646–1,422 m). Most roosts ($n = 17$) were located within forested or riparian land cover (southern and central Appalachian oak, oak montane, and cove forests, Appalachian hemlock-hardwood forests, or south-central interior small stream and riparian), followed by rock-vegetation ($n = 6$; southern Appalachian montane cliff and rocky summit), developed/disturbed ($n = 7$; disturbed/successional-shrub and grass/forb regeneration, developed open space), and pasture/hay ($n = 3$).

Roost selection.—When we assessed the importance of landscape-scale characters through model comparisons, we found that the distance to primary maternity roosts model carried all the weight ($w_{AICc} \approx 1$). In order to explore other factors that might be important in roost selection we eliminated this model from the set of candidate models, recognizing that this was a post-hoc analysis (Burnham et al. 2011). Subsequently, we found the disturbance model to be the best approximating model ($w_i = 0.47$; Table 9). This model was 2.5 times more likely than the next closest model, which was the distance to riparian vegetation/density of water model. The confidence set included five models with accumulative Akaike weights of 0.96, meaning that there was a 96% chance that one of these models was the best approximating model for explaining roost site selection at the landscape level (excepting distance to the primary maternity roost). The disturbance model included distance to major streams, distance to streets, and distance to developed landcover, and the model indicated that bats selected sites closer to potential disturbance. However, these data should be interpreted with caution, as the 85% confidence intervals for all parameters included zero (Table 10). Comparing model parameters for secondary roost sites versus random points, bats roosted closer to major water (1.3 ± 0.2 km for roosts vs. 1.7 ± 0.2 km for random points), closer to streets (182 ± 31 m for roosts vs. 396 ± 69 m for randoms), and closer to developed landcover (79 ± 18 m for roosts vs. 159 ± 32 m for randoms).

Table 9. Number of estimable parameters (K), Akaike’s information criterion for small sample sizes (AICc), difference between AICc value and model with lowest AICc value (Δ AICc), and Akaike’s weight (w_i) for A) a full model set (eight models) and B) a reduced model set (seven models) used to predict springtime (March to June) roost site selection by Virginia big-eared bats in North Carolina and Tennessee. Model descriptions are in the text and Appendix C2.

A. Full model set	K	AICc	Δ AICc	w_i
Distance to primary ¹	3	37.04	0	~1
Disturbance	4	83.92	46.88	~0
RipVeg/water	3	85.67	48.64	~0
Elevation/south	3	86.32	49.28	~0
RockVeg	2	87.32	50.28	~0
Elevation	2	87.78	50.74	~0
Forest	2	89.98	52.95	~0
AnthroStructures	2	90.13	53.1	~0
B. Reduced model set	K	AICc	Δ AICc	w_i
Disturbance ²	4	83.92	0	0.47
RipVeg/water ²	3	85.67	1.75	0.19
Elevation/south ²	3	86.32	2.4	0.14
RockVeg ²	2	87.32	3.4	0.09
Elevation ²	2	87.78	3.86	0.07
Forest	2	89.98	6.06	0.02
AnthroStructures	2	90.13	6.21	0.02

¹ We also considered a post-hoc reduced model set (seven models) that excluded this model (see Results).

² In the post-hoc analysis, the top five models were in the confidence set.

Table 10. Model-averaged parameter estimates and standard errors (SE) for variables used in seven models describing springtime (March to June) roost site selection by Virginia big-eared bats in North Carolina and Tennessee. We present model averaged 85% confidence intervals (CI) for each estimate.

Variable	Estimate	SE	Lower 85% <i>CI</i>	Upper 85% <i>CI</i>
Distance to water	-0.00013	0.00015	-0.00035	0.00009
Distance to streets	-0.00104	0.00118	-0.00276	0.00068
Distance to developed	-0.00110	0.00124	-0.00291	0.00072
Distance to riparian	-0.00041	0.00053	-0.00119	0.00036
Density of streams	0.51492	0.66107	-0.44892	1.47877
Elevation	0.00030	0.00038	-0.00025	0.00085
North and south aspect	-0.09767	0.12877	-0.28541	0.09007
Distance to rock-vegetation	-0.00002	0.00003	-0.00007	0.00002
Percent forest	-0.02194	0.03068	-0.06668	0.02279
Percent developed	-0.01524	0.02133	-0.04635	0.01586

By reducing roost-scale variables (Table 8) to principal components, we were able to identify significant characters that separated primary and secondary roosts. $PCA_{\text{size/cover}}$ reduced nine variables measured at natural rock roosts to two principal components (Figure 12A) that explained 50% of the total sample variance (Appendix C4). Principal component 1, which we termed “size and complexity”, contained number of rooms, number of entrances, sum of room area, and sum of entrance area (Table 11). The two primary roosts grouped relatively high on principal component 1 (Figure 12A), indicating that roosts with more bats were generally more spacious and relatively complex. Although the number of entrances at Roost 7 was below average and the roost contained only one room, its interior dimensions were above average when compared to other roosts, and there were breakdown components (i.e., large fallen rocks from the ceiling) that made the interior of the cave relatively complex. Principal component 2, which we termed “airflow and light”, contained airflow, lux, and outcrop solar exposure (Table 11). The primary maternity roosts and other natural rock roosts used by >1 bat (2–359 bats) scored lower on principal component 2 (Figure 12A), indicating that groups of bats used roosts with relatively little airflow, little light, and less outcrop solar exposure.

PCA_{temp} reduced 11 variables measured at natural rock roosts to two principal components (Figure 12B) that explained 56% of the total sample variance (Appendix C4). Principal component 1, which we termed “airflow and temperature range”, contained airflow, followed by temperature range, number of rooms, outcrop solar exposure, number of entrances, and outcrop vegetation (Table 11). The two primary roosts grouped relatively low on principal component 1 (Figure 12B), indicating that roosts with more bats had less airflow, a smaller temperature range, and were less complex in regards to the number of rooms and entrances. Principal component 2, which we termed “size, temperature, and light”, contained sum of room area, temperature mean, sum of entrance area, and lux (Table 11). The primary maternity roosts scored lower on principal component 2 (Figure 12), which suggests that the two primary maternity roosts had greater room dimensions, a lower mean temperature, less entrance area, and less light.

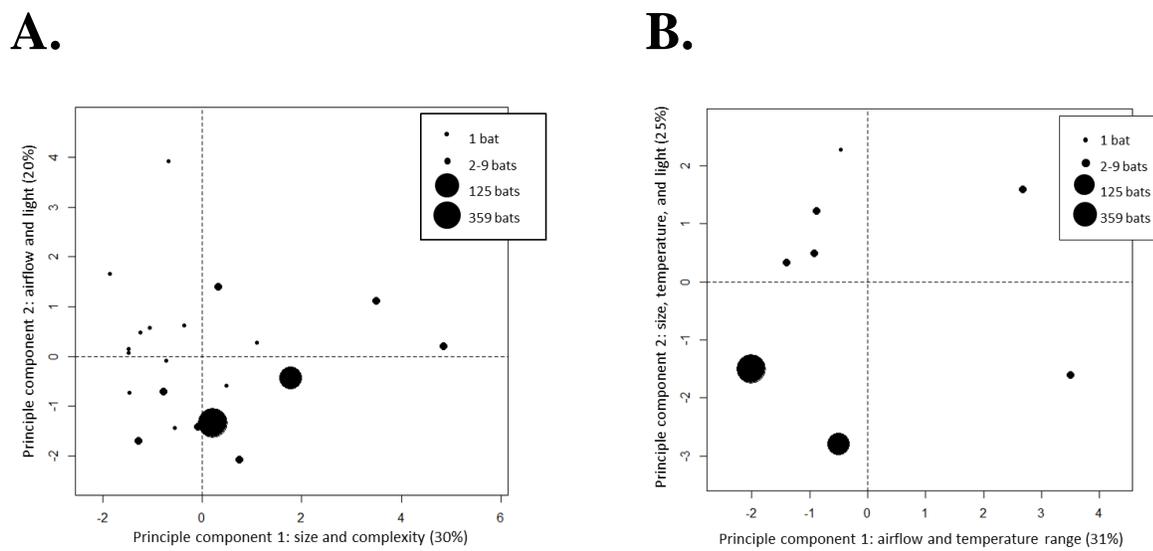


Figure 12. A) Results of PCAsize/cover, which compared 21 natural rock roosts used by Virginia big-eared bats based on structural, light, and vegetation cover variables. B) Results of PCAtemp, which compared eight Virginia big-eared bats natural rock roosts based on structural, light, vegetation cover, and temperature variables. Data were collected at natural rock roosts for Virginia big-eared bats in North Carolina and Tennessee, March–June 2013 and 2014; temperature data were collected in May 2008 (P1) and May 2014 (all other roosts). Values in parentheses along each axis indicate the total sample variance accounted for by each principal component. Sizes of roost symbols represent the maximum number of bats (not of equal scale) observed at each roost during emergence counts or surveys.

Table 11. Principal component loadings for each variable measured at springtime roost sites used by Virginia big-eared bats in North Carolina and Tennessee, March–June 2013 and 2014. Measurements were taken from May to June. Only variables with loadings >0.45 and < -0.45 are listed, and considered fair to excellent, accounting for their respective percentages of variance in the components (Tabachnick and Fidell 2007).

Variable	PCA _{size/cover}		PCA _{temp}	
	Component 1 (Size and complexity)	Component 2 (Airflow and light)	Component 1 (Airflow and temperature range)	Component 2 (Size, temperature, and light)
Airflow	-	0.86	0.97	-
Temperature mean	-	-	-	0.91
Temperature range	-	-	0.79	-
Number of rooms	0.88	-	0.75	-0.47
Number of entrances	0.78	-	0.62	-
Sum of room area	0.77	-	-	-0.92
Sum of entrance area	0.61	-	-	0.54
Percent outcrop vegetation	-	-	0.54	-
Lux	-	0.67	-	0.51
Percent outcrop solar exposure	-	0.60	0.66	-
Outcrop dimensions	-	-	-	-

Roost temperatures.—From 1–26 May, mean temperature and temperature variance inside the primary roosts (Roost 7 and BRCC) were lower than in eight secondary roosts (two barns and six natural rock roosts) where temperatures were recorded during this same period (Figure 13). From 1–26 May, the mean temperature in Roost 7 and BRCC was 7.6 ± 1.8 °C (range 3.8–11.6 °C); this was 5.4 °C cooler than the eight secondary roosts, which averaged 13.0 ± 0.8 °C and ranged from 3.84 to 27.1 °C (ANOVA: $F = 2128_{9,3886}$, $p < 0.0001$). Tukey comparisons showed significant differences amongst many roosts, including significant differences between the eight secondary roosts and the two primary roosts (Figure 13). Furthermore, we determined that temperatures in both Roost 7 and BRCC were significantly less variable (i.e., more stable) than temperatures in the eight secondary roosts ($p < 0.0001$; Figure 13).

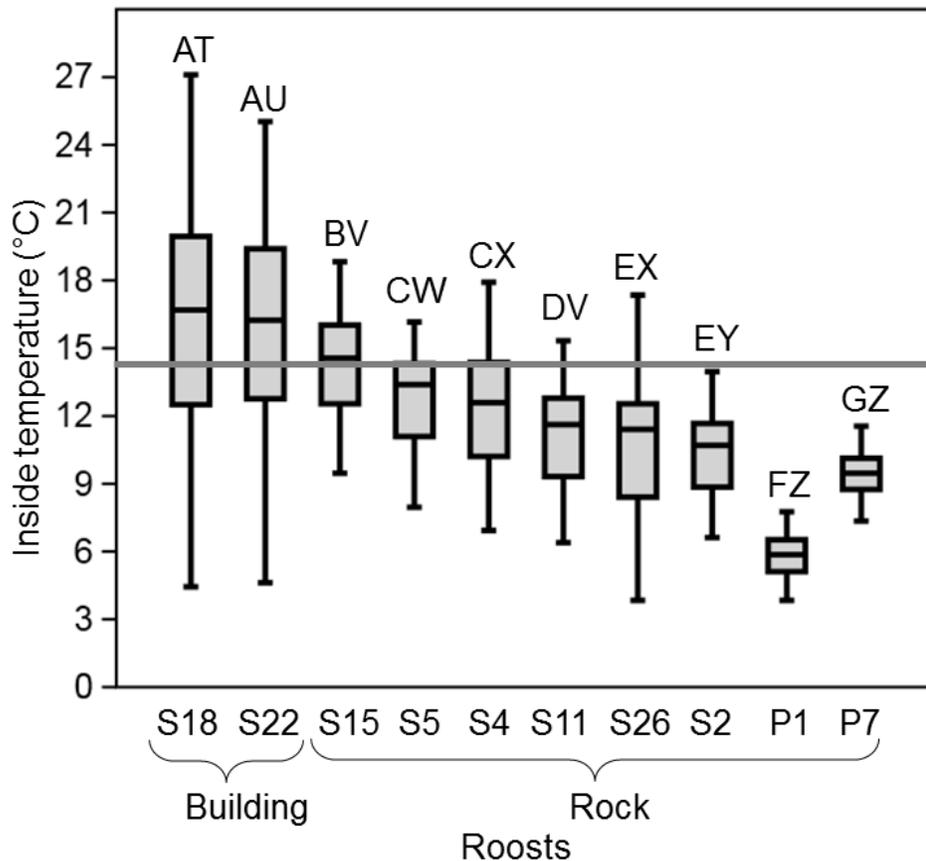


Figure 13. Inside temperatures (bold line = median, lower and upper whiskers = minimum and maximum temperatures, respectively) measured with HOBO Pro Series RH Temperature Data Loggers (Onset Computer Corporation, Bourne, Massachusetts) every 30–120 minutes for eight natural rock (P1, S2, S4, S5, P7, S11, S15, S26) and two barn (S18, S22) roosts of Virginia big-eared bats in North Carolina. Data for nine roosts are from 1–26 May 2014, but BRCC (P1) data are from 1–26 May 2008. At Roost 7 (P7), the mean outside temperature for 1–26 May 2014 (gray line) was 14.4 ± 0.1 °C (range 2.5–25.1 °C). The first letter above the whiskers represents results of Tukey comparisons of means ($p \leq 0.05$) and the second letter represents results of Levene’s test for homogeneity of variance based on medians ($p \leq 0.001$).

Roost Trailcam.—In addition to bats, we detected 12 other animal groups at the primary maternity roost (Roost 7) via the trailcams positioned across from the roost entrances (Table 12). We classified commonly detected animal groups into non-threatening and potential predators prior to graphing activity patterns. White-tailed deer (*Odocoileus virginianus*), small mammals, and bats are non-threatening animals that we detected at low levels throughout the year (Figure 14). Deer, small mammals, and bats were detected at low rates from January to December, with predictably lower levels of activity during the winter months. We detected 0.02 bat images/hour in April and 0.027 images/hour in July, but otherwise there were few bat detections.

Table 12. Organisms detected by camera traps at the entrance of Virginia big-eared bat Roost 7 in western North Carolina.

	Organism	Number of Observations
Predators		
	Black Bear	74
	Bobcat	17
	Canidae	75
	Long-tailed Weasel	6
	Raccoon	779
	Striped Skunk	4
	Virginia Opossum	53
Non-predators		
	Bat	187
	Bird	87
	Groundhog	99
	Insect	18
	Small Mammal	333
	White-tailed Deer	374
Unknown		23
	Grand Total	2129

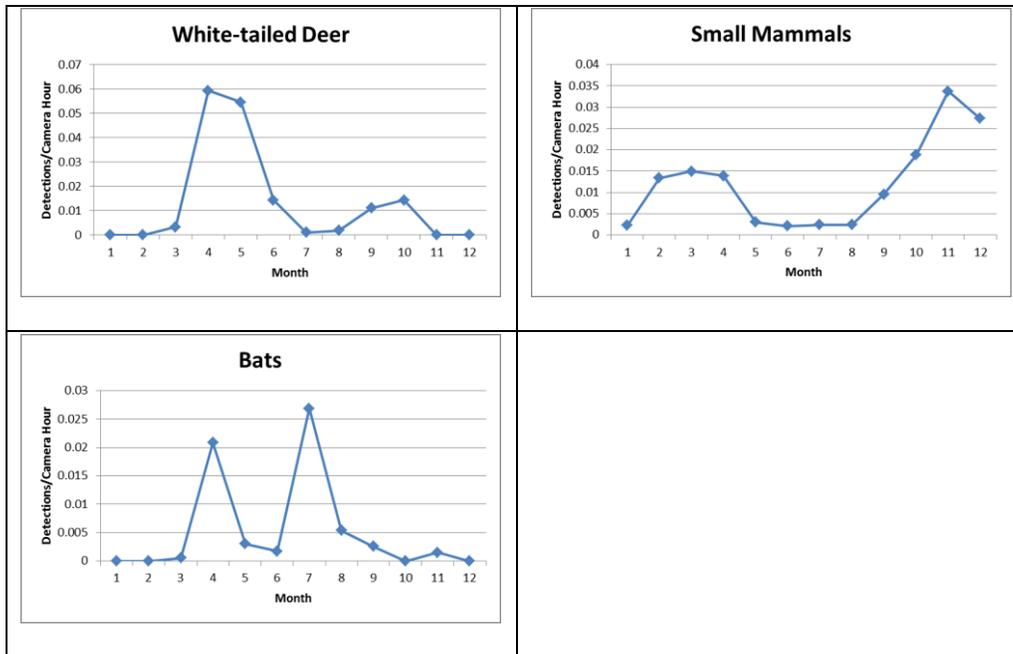


Figure 14. Camera detections per camera hour of common (> 100 total observations) non-threatening animals for each month at the entrance to Virginia big-eared bat Roost 7 in western North Carolina.

With regards to potential predators, we detected raccoons (*Procyon lotor*), opossums, (*Didelphis virginiana*), canids (*Canis latrans* and *C. familiaris*), bears (*Ursus americanus*), bobcats (*Lynx rufus*), long-tailed weasel (*Mustela frenata*), and striped skunks (*Mephitis mephitis*) (Table 12). We detected canids, raccoons, bears, and opossums most often and, thus, plotted monthly activity patterns for these animals (Figure 15). Raccoons were detected at least 10 times more often than other potential predators. On average, we detected 0.02 raccoon images/camera hour, with peak activity in March to May, July, and September. Canids were most active from June to August, opossums were most active June to July and September to October, and bears were most active in May, July, and September.

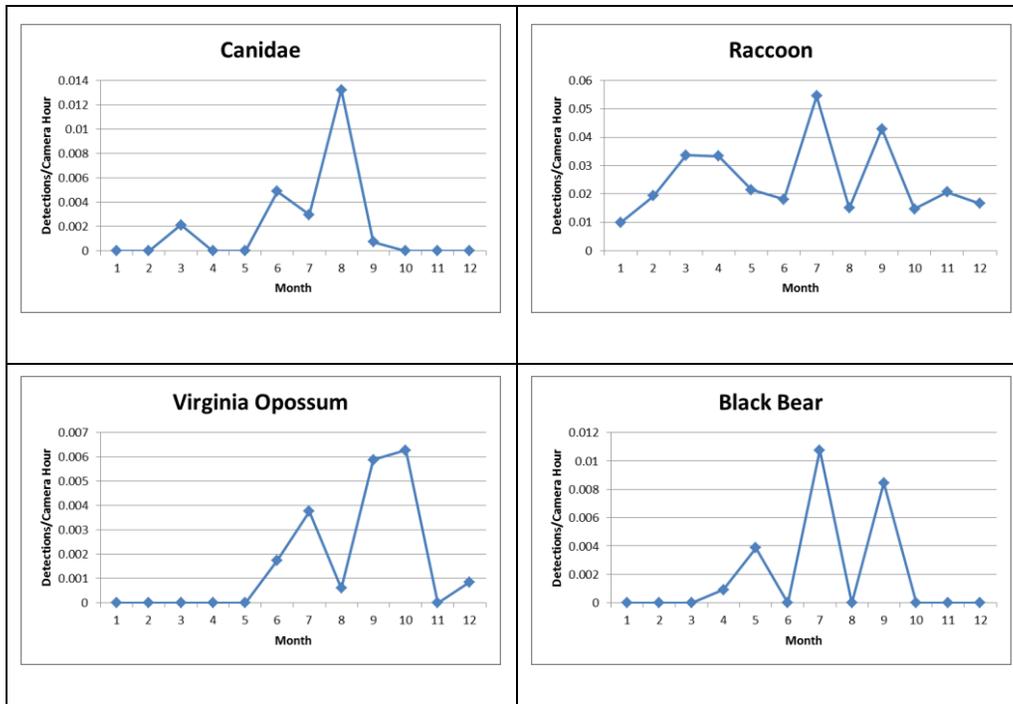


Figure 15. Camera detections per camera hour of common (> 50 total observations) potential bat predators for each month at the entrance to Virginia big-eared bat Roost 7 in western North Carolina. Months are indicated by numbers (1=Jan, 2=Feb, and so forth).

By examining hourly activity rates, we determined that raccoons have the highest activity rates during the months of April to September when compared to other potential predators (Figure 16) and, overall, we captured 10 times more raccoon photos than for other potential predators (Table 12). Raccoons were mainly active at night, with an average of 8.3 detections each hour between 21:00 and 04:00 EDT from April to September, with higher activity rates than other potential predators. Opossums were active between midnight and 7:00, with peak activity of 4 observations/hour at 23:00 EDT in July and 3:00 in September. Canids were generally active during daylight hours; however, we recorded a video from 13 August 2014 showing a coyote chasing bats as they were attempting to reenter the cave at ~07:30 EDT. Bears were active across the early morning to late afternoon hours, with a peak in observations at 9:00 EDT in July.

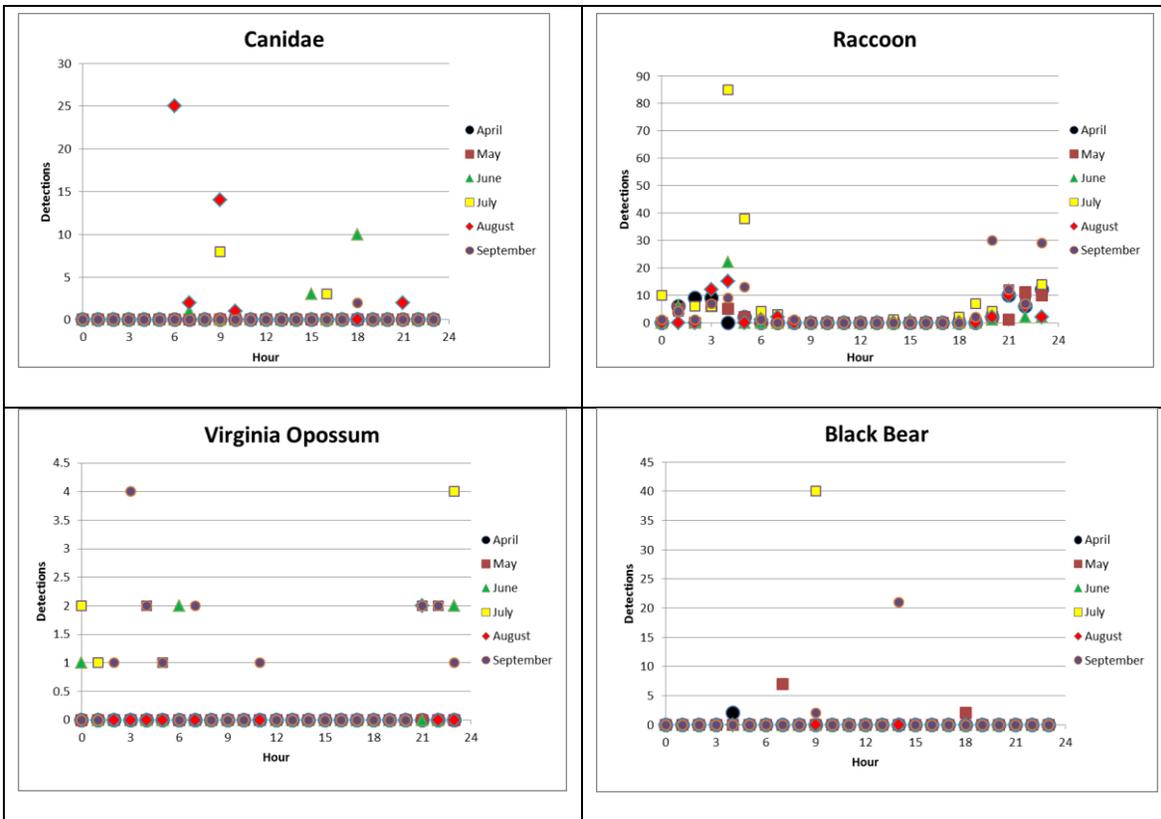
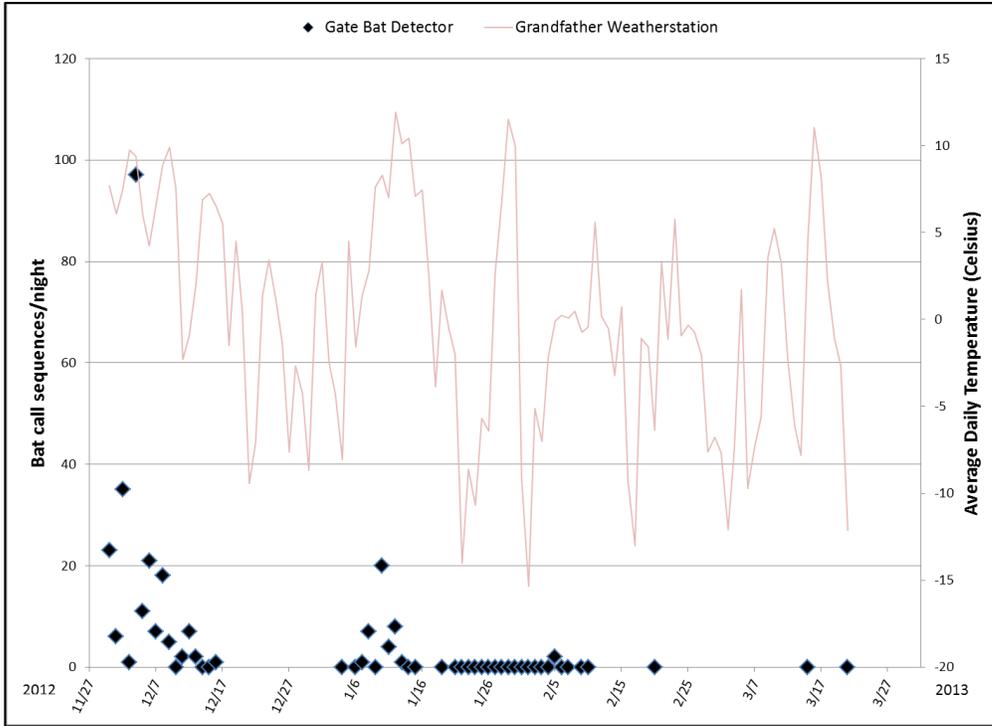


Figure 16. Camera detections of potential bat predators by hour for the months of April–September at Virginia big-eared bat Roost 7 in western North Carolina.

WINTER ACOUSTIC MONITORING

We recorded 61,808 acoustic files at BRCC from 30 November 2012 to 24 March 2013 (Winter 2012) and 9 November 2013 to 30 March 2014 (Winter 2013), of which we identified 377 files as bat calls. During Winter 2012–2013, we recorded 297 bat calls, ranging from 0–97 bat calls/night, and average daily temperatures ranged from $-15.4\text{ }^{\circ}\text{C}$ to $11.9\text{ }^{\circ}\text{C}$ (mean = $0.1\text{ }^{\circ}\text{C}$). Activity peaked on 4 December when the average temperature was $9.4\text{ }^{\circ}\text{C}$ (Figure 17A). There was another spurt of activity (20 bat calls) on 10 January when temperatures averaged $8.3\text{ }^{\circ}\text{C}$; subsequently, the microphone foam cover froze in late January and then we recorded two calls on 5 February. During Winter 2013–2014, we recorded 98 bat calls (66 bat calls at the gate, 32 bat calls outside of the cave), ranging from 0–16 bat calls/night, and average daily temperatures ranged from $-20.7\text{ }^{\circ}\text{C}$ to $12.4\text{ }^{\circ}\text{C}$ (mean = $-0.4\text{ }^{\circ}\text{C}$). Activity peaked at the gate bat detector with 16 bat calls on 7 January, which was the coldest day of the season ($-15\text{ }^{\circ}\text{C}$ on HOBO outside BRCC; Figure 17B).

A.



B.

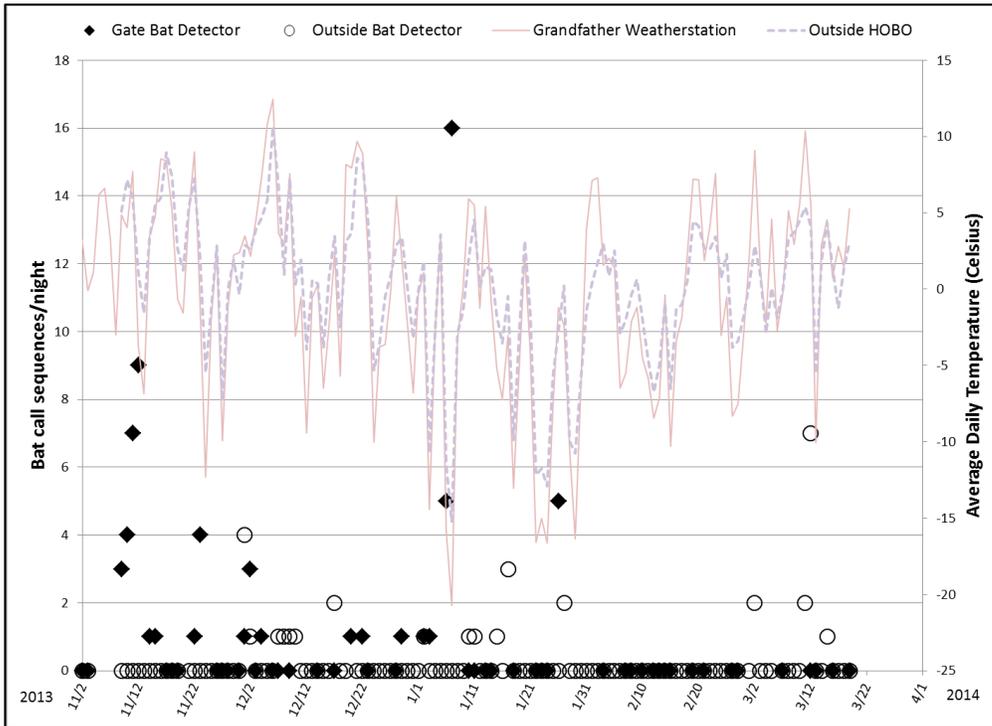


Figure 17. Bat calls (markers) detected and average daily temperatures (lines) recorded from 30 November 2012–24 March 2013 (A) and 9 November 2013–30 March 2014 (B) at the primary hibernaculum (BRCC) of Virginia big-eared bats on Grandfather Mountain, North Carolina.

DISCUSSION

We tracked Virginia big-eared bats to springtime roost sites that were relatively short distances (≤ 24.1 km) from their primary hibernaculum, BRCC. Prior to this study, there were only 13 significant maternity roosts known for Townsend's big-eared bats in the eastern U.S., with colony sizes ranging from 288–1,175 bats (USFWS 2008). We found the first known maternity roost sites for this species in North Carolina, including a primary maternity roost (Roost 7) on private land 14.4 km from BRCC, and we found the first known roosts for Tennessee. Bats moved across NC 105, NC 194, and other roads while commuting the short distance to the primary maternity roost, but generally did not cross major roads during nighttime foraging bouts. We found two primary maternity roosts (used by 30–359 bats); both were spacious caves with stable, cool temperatures and little airflow. We also found 33 secondary roosts, which included caves, rock shelters/overhangs, and buildings used by only 1–9 bats each. Secondary roosts were generally smaller and less complex, with warmer and more varied temperatures than primary roosts. We did not find any evidence for foraging habitat selection at either the landscape or home range levels. Landscape-scale variables also did not appear to be significant factors in selection of secondary roost sites; however, springtime roost sites were at lower elevations than the hibernaculum and closer than expected to development (roads, developed landcover). Our findings build on existing data for Virginia big-eared bats in North Carolina (Clark 1987, Clark and Lee 1987, McGrath and Marsh 1997) and add presence records for two counties in Tennessee.

BAT CAPTURE

Captures.—The success of this project hinged on our ability to capture bats at the BRCC hibernaculum on Grandfather Mountain. We were able to capture bats by removing individual bats from clusters on the ceiling of the cave in late March and early April both years. However, we noted that at least 9 out of 38 bats radio-tagged at BRCC moved >10 km away from BRCC the same night that we handled them, which indicates that we may have prompted their departure. In order to minimize impacts to bats, we suggest that future projects only handle bats at BRCC during the known migration period (late March to late April) on days when the weather is suitable for bats to fly long distances that same night.

To minimize disturbance to bats during hibernation, we suggest exploring other ways to capture Virginia big-eared bats. During spring, we found that bats often used buildings or rock overhangs relatively near (~ 7 km) Roost 7, the primary maternity roost. It might be possible to find bats for a radio telemetry study by searching for occupied secondary roosts. Though we did not attempt this, we believe it may be possible to capture bats near Roost 7. We suggest placing mist nets at least 100 m from Roost 7 to minimize disturbance to the colony, perhaps in the Beech Creek drainage to the northwest or in other foraging areas.

MOVEMENT AND FORAGING ECOLOGY

Seasonal movements.—We gathered a variety of radio telemetry data to assess the nature of Virginia big-eared bats' seasonal movements from the hibernacula on Grandfather Mountain to their springtime roosts. The best data on bat movements came from radio telemetry to find daytime roosts or from the datalogging receivers and telemetry towers that were stationed near

Grandfather Mountain and along NC 105. Driving transects along NC 105 yielded detections for only two bats, despite the extensive time spent driving (> 58 hours) and road coverage (> 2,116 km driven). We had much greater success in gathering movement data via other methods, detecting 14 bats on telemetry towers and relocating 42 of 44 tagged bats in their daytime roosts.

We tracked Virginia big-eared bats moving relatively short distances (0.1–24.1 km) from the hibernaculum to springtime roost sites at lower elevations. Most bats ($n = 31$) moved 14.4 km from BRCC in Avery County to Roost 7 in Watauga County, North Carolina. Contrary to the expectations of McGrath and Marsh (1997), Virginia big-eared bats did not make long-distance movements between winter and summer habitats in western North Carolina. In fact, the distance moved between BRCC and springtime roost sites was relatively short compared to other species of bats. For example, *Myotis grisescens*, another cave-obligate bat that is similar in size, migrates up to 770 km (Tuttle 1976). Virginia big-eared bats in our study moved an average distance (13.6 km) that is slightly greater than the 11.6 km average distance reported by Humphrey and Kunz (1976), but within the range known for the species (≤ 64 km). Our findings confirm that Townsend's big-eared bats are relatively sedentary (Kunz and Martin 1982) and matches expectations based on the low wing aspect ratios and wing loadings of Townsend's big-eared bat (Findley et al. 1972).

In late March to early April (mean date = 31 March), bats departed BRCC for springtime roosts (mean arrival date = 6 April). Many bats moved from the BRCC hibernaculum to Roost 7 or another nearby roost in one night (e.g., 10 of 21 bats in 2014). However, some bats used stopover roosts on the way to Roost 7 or even flew beyond Roost 7 on their initial flight from BRCC. Given the typical distance between roosts and foraging areas (mean = 2.7 km), it must not be trivial to fly between BRCC and Roost 7; however, two bats (one female, one male) commuted back across Grandfather Mountain to roost on its eastern slope after using roosts 9.4–14.4 km north of Grandfather Mountain. Nine bats used one or more roosts at the top of Grandfather Mountain (Attic Window area) before commuting across the western slope of the mountain to lower elevation roosts. It is possible that bats were “staging” in the Attic Window roosts in order to reduce the commute across Grandfather Mountain.

When commuting from BRCC to Roost 7, it is likely that bats would have traveled along a sinuous but overall north-northwest route from the top of Grandfather Mountain. We found many secondary roosts along the north-northwest route between BRCC and Roost 7 and note that, even though not all bats moved directly to Roost 7 from BRCC, bats probably crossed NC 105 at a similar point if they were traveling to secondary roosts along this pathway. In 2014, when we positioned telemetry towers along NC 105, we detected all 10 of the bats carrying coded tags at these towers, with the highest probability of detection of high-power signals near the area covered by the TNC-Profile-Barker towers (see map in Figure 7). Collectively, our data suggest that bats were most likely to have flown across NC 105 near the TNC-Profile-Barker telemetry towers, ~1.2 km (0.7 miles) northeast of the junction of NC 184 and NC 105, though the crossing points could be anywhere from the Linville tower to 5 km northeast along NC 105. The crossing point on NC 105 likely varied for individual bats (see Appendix B2), though slow-flying bats like *Corynorhinus* species are more likely to cross where there are trees or shrubs adjacent to the road (Fensome and Mathews 2016). Indeed, the treeline is within a few meters of NC 105 and the grassy shoulders are narrow along the stretch of road between the TNC-Profile-Barker telemetry towers, which is unique for NC 105 between NC 184 and Foscoe, NC.

Foraging ecology.—Virginia big-eared bat foraging ranges were larger than in other parts of the eastern U.S. (e.g., Clark et al. 1993, Adam et al. 1994, Stihler 2011). In this study, 95% MCP foraging ranges were 331.2 ± 111.6 ha, which is almost three times larger than foraging ranges for adult female Virginia big-eared bats in a heavily forested area in Kentucky, where 95% MCPs are 121.9 ± 109.2 ha (Adam et al. 1994). Similarly, we estimated that 100% MCP foraging ranges were 633.6 ± 202.6 ha, at least four times larger than median foraging area estimates for Ozark big-eared bats (*C. townsendii ingens*) in open habitats in Oklahoma (100% MCPs are 65.5–156.9 ha; Clark et al. 1993). Foraging ranges might be larger in our area because of the distribution of potential night roosts or if we recorded more foraging points for each bat. Easy access to night roosts (e.g., barns and other building) may facilitate bats having larger foraging ranges than in other study areas. Furthermore, we had access to an extensive road network, which may have allowed us to document more widespread foraging locations and at greater distances from known locations. In West Virginia, tracking female Virginia big-eared bats throughout the entire night, Stihler (2011) reported a maximum foraging distance of 11.3 km. In this study, Virginia big-eared bats typically foraged within 4.7 km of roosts, moving a maximum of 1.8–8.1 km from roosts between dusk and ~03:00.

We did not observe selection for any particular landcover types, which suggests that Virginia big-eared bats are habitat generalists in our study area. The Virginia big-eared bat is a lepidopteran specialist, with $\geq 90\%$ of its diet consisting of moths (Dalton et al. 1986, Bauer 1992, Sample and Whitmore 1993) and, thus, we expected Virginia big-eared bats to select for forests, which generally support diverse and abundant populations of favored moth species (Burford et al. 1999, Dodd et al. 2008). Approximately 75% of the landscape was forested in our study area and bats used forests ~75% of the time (Figure 9). Lack of habitat selection is consistent with findings for Oklahoma, where female Ozark big-eared bats use range (i.e., rangeland and pasture), edge, and forest habitats in proportion to their availability during the months of August through October (Wethington et al. 1996). We might have detected evidence for foraging habitat selection if we had access to more specific landcover types or if we used structural configuration components (e.g., edge or interior) to define available areas.

Seasonal movements and foraging near TIPs.—Our data showed that the Virginia big-eared bat colony crossed NC DOT TIPs while commuting between roosts and some bats crossed TIPs while foraging at night. Bats crossed both NC 105 (R-2566) and NC 194 (R-2710) while moving between BRCC/Grandfather Mountain and Roost 7 or nearby secondary roosts. It is likely that most of the bats in the maternity colony using Roost 7 (at least 359 bats) cross these two roads at least twice per year when commuting between winter and summer habitats. Three bats that were using Roost 7 crossed US 321 (R-5016) while foraging at night, but most bats foraged inside and away from the boundaries of NC 105, NC 194, and US 321. Five roosts were on the north side of US 321 (roosts were 0.1–0.9 km from US 321), which bats had to cross to access those roosts. Foraging points were typically >1.5 km from a primary/secondary road or a TIP (Table 6) and most bats foraged inside the area bounded by NC 194, NC 184, US 321, and the NC/TN border (see Figure 9).

ROOSTING ECOLOGY

Roosting ecology.—Virginia big-eared bats shifted from a higher elevation hibernaculum (1,422 m) to lower elevation springtime roost sites ($1,022 \pm 40$ m) as they moved relatively short distances from the hibernaculum. Our results are consistent with other studies showing Townsend's big-eared bats moving from higher elevation hibernacula to lower elevation maternity sites (Cryan et al. 2000, Szewczak et al. 1998). Although altitudinal shifts are thought to reflect the thermoregulatory and foraging needs of reproductive females, it is important to note that both of the maternity roosts used in this study were cool (e.g., May–June 2014 mean temperature for Roost 7 was 11.09 ± 0.03 °C, range 7.35–14.16 °C) and that some bats with young of the year used the very cool hibernaculum in June (21–30 June 2014 mean temperature for BRCC was 12.80 ± 0.01 °C, range 11.77–13.56 °C). Perhaps the shift to a lower elevation allowed adult female Virginia big-eared bats to access a larger prey base than at higher elevations (Cryan et al. 2000). Smaller numbers of bats at the hibernaculum during summer suggest that it offers less optimal roosting or foraging conditions for a maternity colony.

Data from the two primary maternity roosts suggests the regional population may be larger than has been documented in earlier surveys and that additional hibernacula may be used by this population. At least 359 bats used Roost 7 and ≥ 125 bats used BRCC. The majority of adult female bats used Roost 7 as a primary maternity roost (including 35 of 42 tracked bats), while a smaller percentage of bats used BRCC in the springtime (3 of 42 tracked bats returned to the cave after mid-April). Winter hibernacula counts at BRCC and Mystery Hole, the two known hibernacula, indicate that the population size is approximately 376 bats (USFWS 2008), which is lower than the total number of bats (438) we counted at the two primary maternity roosts on 13 June 2014 (exit count at Roost 7 and interior count at BRCC). This suggests the total population may be larger than what has been estimated based on winter counts. The presence of males in maternity roosts (we tracked one male to Roost 7 in May 2014) may partly explain the higher than expected numbers, but we believe there may be additional undiscovered hibernacula for this population. We tracked nine bats to undetermined roosts near Attic Window at the top of Grandfather Mountain and, thus, suggest searching here for additional hibernacula when winter conditions are appropriate for hiking in this area.

Primary roosts.—The two primary maternity roosts were larger, relatively more complex, had less airflow, and were cooler than secondary natural rock roosts, which matches findings for Townsend's big-eared bats in other parts of its range (e.g., maternity sites are larger and more complex in Utah, Sherwin et al. 2000). Maternity roosts in this study were relatively cooler (3.8–11.9 °C) than maternity roosts in Kentucky (14.8–23.8 °C, Lacki et al. 1994) and California (19.0–30.0 °C, Pierson et al. 1991), but similar to roosts in British Columbia (mean = 15.7 °C, range = 7–24.9 °C, 15 June–31 August; Reid et al. 2010). Stable temperatures are an indication that the caves are moderating outside temperatures (Lacki et al. 1994), which may be more important for the primary roost vs. secondary roosts.

Secondary roosts.—Although secondary roosts held only 1–9 bats each, these were important to the colony. Most bats used at least one secondary roost as a stopover during their commute from BRCC or after using Roost 7 for a period of time. Secondary roosts were rock shelters, caves, or buildings; most were north of NC 105 and Grandfather Mountain, relatively close to Roost 7 (mean = 7.1 km, range = 0.2–18.9 km). In an earlier study, McGrath and Marsh (1997) found a

Virginia big-eared bat in a secondary roost on Horse Bottom Ridge, 5.8 km south from Roost 7. Secondary roosts varied in size, number of entrances, and temperature, but tended to have a low percent vegetative cover (for rock roosts). One fairly consistent character is that in these roosts bats were able to hang within 2–3 m of the ground. Though Virginia big-eared bats are thought to select the warmest positions within a roost (Pearson et al. 1952), the bats we tracked to buildings tended to select roosts closer to the ground where temperatures would be cooler than at the peak of a building. This positioning may have afforded bats more stable temperatures than if they hung higher in the roost and, early in spring, may have facilitated the use of torpor for energy conservation or slowing fetal development (Racey 1973).

Other than proximity to primary maternity roosts, the main landscape-scale factor separating secondary roosts from random points was their close proximity to disturbance. Twenty-seven secondary roosts were on private property and we observed 15 individual bats in 10 different buildings. On average, secondary roosts were relatively close to roads, generally smaller streets (mean = 182 m), and developed landcover (mean = 79 m); building roosts typically sat alongside a driveway. Fifteen roosts were < 500 m from a primary or secondary road, but roosts were typically farther from larger roads and TIPs (mean = 1.2–2.1 km; Table 7). We suggest that caves, rock structures, and barns within 10–15 km distance of known primary roosts in this region should be considered potential roosting habitat for Virginia big-eared bats. It may be possible to discover additional roosts via searches of caves, rock shelters, and buildings within this buffer area. It would be prudent to alert local homeowners and developers to the possibility of encountering these federally endangered bats, and what appropriate steps to take when encounters occur.

Predators at maternity roost.—Potential predators are familiar with the most significant primary maternity roost used by this colony. We documented frequent visits to Roost 7 by raccoons, opossums, canids, and bears. Raccoons are of particular concern, as they are known predators of many species of bats (Sparks et al. 2000), and were most often observed during the hours bats were active at Roost 7. We recorded images of a coyote attempting to take bats from the air as they returned to the roost and made visual observations of owls sitting near the roost entrance as bats emerged at dusk. Some animals, including those not identified as potential predators, may scavenge pups or debilitated bats that fall to the floor of the cave.

Roost fidelity.—In our two-year study, bats displayed interannual fidelity to both primary roosts and to four secondary roosts. Benefits of fidelity include familiarity with high quality roosts and the maintenance of valuable social relationships (Lewis 1995). Bats tend to display higher rates of fidelity to more permanent roosts (Brigham 1991). In California, Townsend’s big-eared bats exhibit strong interannual fidelity; bats from 10 maternity colonies returned to the same 10–11 sites each year over a multi-year study (Pearson et al. 1952). Because the majority of the North Carolina and Tennessee population of Virginia big-eared bats used only one of two permanent caves as primary maternity roosts, it is crucial to have long-term protection for these sites in order to ensure the survival of this population; we suspect it is also important to protect known secondary roosts.

WINTER ACOUSTIC MONITORING

Virginia big-eared bats were active at the BRCC hibernaculum during both winters that we surveyed the cave, generally on warmer days. Acoustic activity was highest on days when temperatures exceeded 5 °C, but bats were also active on particularly cold days (e.g., on 7 January 2014, when the outside temperature was -15 °C). During Winter 2012–2013, we recorded bat activity only from late November to early January (plus two call files on 5 February). We recorded activity across the entire season in Winter 2013–2014, despite cooler overall temperatures and more days under 0 °C. High levels of bat activity at hibernacula could indicate that the population is affected by white-nose syndrome, which interrupts hibernation and prompts winter emergences in little brown bats (*Myotis lucifugus*, Reeder et al. 2012). We did not detect mortality from white-nose syndrome, but did observe wing damage on 20 of the 44 bats we handled. We suggest additional acoustic monitoring at BRCC, if feasible, though we note that this is challenging due to ice forming on the microphones and the potential for theft of equipment installed outside the cave gate.

RECOMMENDATIONS

Bats and Roads.—In order to make recommendations to NC DOT on how TIPs may affect Virginia big-eared bats, it is important to consider what is known about the effects of roads on bats. Berthinussen and Altringham (2011) suggested that roads may affect bats by 1) causing direct mortality via collision with cars, 2) degrading roosting or foraging habitats, or 3) severing commuting/migration routes, but effects will vary by functional species groups (e.g., open-space vs. clutter-adapted bats; Kerth and Melber 2009, Fensome and Mathews 2016). There are few studies that have attempted to measure the effects of roads on bats; a recent review paper assessed data from only 12 studies about bat collisions with cars and eight studies related to roads as barriers (Fensome and Mathews 2016). Most work on this topic has been done in Europe, where bats regularly attempt to cross roads (e.g., Abbott et al. 2012), sometimes with fatal consequences. Summarizing data from 1,207 bat road casualties, Fensome and Mathews (2016) showed that slow-flying species are most at risk, with males and juvenile bats being more susceptible to collisions than females. Casualty rates differ by road type and by season; a daily survey of 51 km of 2-lane highways of varying widths in Portugal found a total of 154 dead bats from March to October 2009, with 1–4 bats casualties/km over the entire season and 27% of carcasses found during two weeks in August when young were newly volant (Medinas et al. 2012). Large, open-space bats (e.g., *Barbastella barbastellus*) may routinely cross highways, but these bats may risk colliding with large trucks if they fly too low (Kerth and Melber 2009). In Indiana, various species of bats most often cross roads at a height of 11–13 m (Bennett and Zurcher 2013). Virginia big-eared bats have been killed by vehicles in other parts of their range (USFWS 2008). Loud vehicles (> 88 dB) and the absence of tree cover often causes bats to turn 180° away from roads when traveling down commuting corridors (Bennett and Zurcher 2013), but bat casualties are actually higher at points where roads are bisected by linear features that could serve as commuting corridors for bats (e.g., hedgerows and rivers; Fensome and Mathews 2016). Bat activity is lower and commuting behavior is delayed in the presence of high pressure sodium lights typically used near roads when compared to unlit areas (Stone et al. 2009); these data suggest road lighting may deter bats from commuting across or foraging near roadways. Risk of collision and the barrier effect of roads may better explain low bat activity near roads (Berthinussen and Altringham 2011), as bat activity is higher farther from both lit highways

(double activity at 300 m vs. 0 m from road; Kitzes and Merenlender 2014) and unlit highways (3–5 times the activity at 1600 m vs. 0 m from road; Berthinussen and Altringham 2011) and highway noise diminishes significantly just 50 m away from major roads (Berthinussen and Altringham 2011). Small, gleaner bats (i.e., clutter-adapted) are likely to use underpasses or avoid large highways altogether. For example, the gleaner *Myotis bechsteinii* rarely crosses a major highway bisecting a forested landscape in Germany for either roosting or foraging, and bats that forage near the highway have smaller foraging home ranges (Kerth and Melber 2009).

The data summarized above suggest that widening NC 105 could have a negative effect on the Virginia big-eared bat population in northwestern North Carolina if these bats are vulnerable to collisions or the barrier effect of a larger road, or if road development and associated projects degrades the foraging and roosting habitats or impedes access to critical habitats used by this population. It is essential that this population is able to cross this road as they commute between their winter and summer habitats, but we cannot adequately predict how Virginia big-eared bats will respond to widening or increased traffic. A high traffic, 6-lane highway with 30–40 meters of severed treeline is a significant barrier to a bat with a similar life history, *M. bechsteinii*, in a heavily wooded area in Germany (Kerth and Melber 2009), whereas *Plecotus auritus* and *Myotis* species (all small, clutter-adapted bats) cross 50–70 m treeline gaps over a less-trafficked road in a heavily fragmented landscape in Ireland (Abbott et al. 2012). If mortality from collisions or reduced reproductive success ensues after road development, Virginia big-eared bats may be slow to recover from population losses because of their slow life history strategy. Like most bats, this species is long-lived, has low reproductive rates, and requires larger than expected home range areas for its body size. Furthermore, the relatively small Virginia big-eared bat population (~400 individuals) is likely vulnerable to local extinction.

Bats and road construction/maintenance.—Activities associated with the construction of transportation corridors or bridges could affect bats directly if conducted near hibernacula or maternity sites or indirectly if such activities change the suitability of available habitat. Possible direct effects from activities within 0.5 miles of summer or winter roosts (USFWS 2016) could include crushing or drowning bats, inundation of the roost with smoke, or disturbance from noise, vibration, or human presence (FHA and FRA 2015). Bats may be crushed during blasting or demolition of old structures (e.g., bridges). Although we did not find bats roosting under bridges during this study, Virginia big-eared bats use a bridge in West Virginia (USFWS 2008) and many other bat species are known to use bridges as day or night roosts. Drowning is possible if alterations to the surrounding landscape change water flow such that roosts are flooded when bats are unable to respond (e.g. during hibernation; Brack et al. 2005) or for non-volant pups. Bats may be at risk from smoke if burning is conducted near summer or winter roosts (e.g., Perry 2011). In general, bats seem to be somewhat resilient to noise and vibrations, as some bats roost in urban areas (e.g., the federally endangered Indiana bat, *Myotis sodalis*, has maternity roosts under the flight path of a major airport in Indiana; Kaiser and O’Keefe 2015) and bats in underground mines can withstand vibrations of 0.06-0.2 inches per second (WV DEP 2006). However, the duration of noise is important (FHA and FRA 2015). If road construction or maintenance disturbs hibernating bats, this could negatively affect survival; however, simulations suggest that disturbances during winter are only of significant concern when they are frequent and clumped in occurrence (Boyles and Brack 2009). To avoid direct or indirect effects to hibernating or non-volant bats, we suggest there be no major disturbances within 0.5 miles of Roost 7 during the active season (probably March to November) and within 0.5 miles of BRCC,

which served as both a hibernaculum and a maternity roost, at all times of the year. Furthermore, bridges within the project area (Figure 1) should be checked for bats prior to maintenance if such activities will cause vibrations or noise, and prior to demolition, during the active season.

Recommendations regarding widening NC 105.—There are a number of possible approaches to the need to increase capacity along NC 105, though the alternative of no action (i.e., not widening the road in the area where bats cross) may be the best option for this bat population. With the current road condition, it appears that Virginia big-eared bats are successful in making the twice-annual commute from BRCC to Roost 7 across NC 105. There were no casualties from road crossing in spring for the 37 radio-tagged bats that crossed either NC 105 or NC 194, though a carcass search could have yielded different results for untagged bats. During this study, radio-tagged Virginia big-eared bats likely crossed NC 105 between the Linville Tower and the Ennis Tower (see Appendix B2), which is ~5 km of road; based on detections of high-power signals, we think that the most likely crossing point is the area between the TNC-Profile-Barker towers where the treeline is close to the road on both sides. Regardless of NC DOT's approach, we suggest that state and federal partners work together to protect the forested areas adjacent to this section of NC 105 in order to maintain the overall integrity of the commuting corridor for Virginia big-eared bats.

If NC 105 is widened in the area where bats cross, then it will be important to implement measures that promote continued crossing of this roadway but that minimize the risk of mortality of Virginia big-eared bats moving between Grandfather Mountain and spring/summer roost sites near Beech Mountain. One way to promote crossing would be to maintain a closely-connected tree canopy across the roadway (Bennett and Zurcher 2013), with tree canopies above the height of large trucks that will use this road. Currently, the tree canopy does not connect across the roadway where bats are likely crossing, but we do not know how large of a gap can be traversed by commuting Virginia big-eared bats. We also suggest maintaining continuous tree cover alongside the road, as bats will turn away from roads when trees and shrubs are absent (Bennett and Zurcher 2013). Minimizing lighting along the roadway may also decrease the likelihood that bats will abort crossings. Speed restrictions may reduce the likelihood of bat mortality, though we are not aware of any empirical evidence to support this idea.

Data from Europe suggest that building an underpass or, possibly, an overpass could provide Virginia big-eared bats with a safe route to cross NC 105. In Germany, radio-tagged *M. bechsteinii* crossed a major highway only via an underpass (Kerth and Melber 2009) and in Ireland various bat species use underpasses and river bridges more than overpasses when crossing a major highway (Abbott et al. 2012). Tree-lined river corridors under bridges were deemed highly important habitat for eight resident bat species, particularly two clutter-adapted species, in Ireland (Abbott et al. 2012). Fensome and Mathews (2016) suggest that over-road gantries and underpasses may be effective mitigation tools for bats, but note that more research is needed to confirm their effectiveness. Any crossing structure built along NC 105 would need to coincide with the commuting corridor of Virginia big-eared bats, which may be difficult if bats vary in their crossing points along the ~5 km stretch of NC 105 where we detected commuting bats in 2014. Kerth and Melber (2009) observed that one radio-tagged *M. bechsteinii* flew 3.5 km out of her way to commute through an underpass.

Suggestions for future work.—There is an opportunity to assess the long-term effects of transportation improvement projects that coincide with this Virginia big-eared bat colony's roosting and foraging area. Fensome and Mathews (2016) stressed the need for additional research on the impacts of roads on bats, particularly for pre- and post-construction surveys. With acoustic and night vision surveys, and targeted radio-telemetry studies, we may gain a better understanding of how Virginia big-eared bats approach and fly across roads such as NC 105, which may enhance our ability to mitigate for impacts with future development projects. Carcass searches during the migration periods (both spring and fall) may generate data that allows us to quantify the effects of roads on bats. It may be prudent to radio track males and juveniles if these individuals are more susceptible to colliding with vehicles on roadways. We believe it is crucial to protect this small, disjunct population of Virginia big-eared bats and note that studies leading to safer crossing points over roads should have a positive impact for this species throughout its range.

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