IMPROVING URBAN FLYWAYS FOR BATS: THE IMPORTANCE OF THE TREE CANOPY STRUCTURE.

By

MANUEL DE OYARZABAL BARBA

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Santa Clara University
Santa Clara, California

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INTRODUCTION

Urbanization is the process of converting natural habitats to areas that are primarily intended to benefit humans (Uchida et al. 2018, Beller et al. 2020, Zhang et al. 2020). Urban areas comprise a high density of structures, including houses, public and commercial buildings, roads, parking lots, bridges, and railways (Chen et al. 2018, Li et al. 2020a, Yang et al. 2020). Consequently, much of the native vegetation is cleared and often replaced with non-natives (Atasoy et al. 2018, Martinez et al. 2021), while top soil is removed or compacted and covered in concrete or asphalt forming an impervious surface to precipitation (Shao et al. 2019, Wang et al. 2020). Thus, we tend to perceive the urban environment as a homogeneous expanse that offers little or no resources for wildlife (Murray et al. 2019, Schneiberg et al. 2020, Wei et al. 2021). For an urban environment to support healthy, stable wildlife populations, it should provide a diversity of foraging resources, shelter, water sources, mating opportunities, and movement corridors (Kilheffer and Underwood 2018, Choquette et al. 2020). The latter may be the most important of these, as corridors enable wildlife to access the other resources (Jones et al. 2018, Scharf et al. 2018, Gregory et al. 2021), migrate (Huang et al. 2018, Liu et al. 2021, Rycken et al. 2021), disperse (Smith et al. 2019a, Penteado 2021, Garcia-Sanchez et al. 2022), and colonize or recolonize habitat patches (Cadavid-Florez et al. 2020).

In natural habitats, the ability to move across the landscape is integral to ecology and life history of nearly all species (Allen and Singh 2016, Doherty et al. 2019, Janmaat et al. 2021). Movement corridors are the vector that allows wildlife to move between habitats, often defined as a linear two-dimensional landscape feature along which wildlife can travel to access habitats and resources (Saunders and Hobbs 1991). One classic example of animal movement is the mass migration of over a million wildebeest (*Connochaetes taurinus*) due to seasonal changes in food availability from the Serengeti plains to the Maasai Mara (Li et al. 2020b, Owen-Smith et al.

2020, Stabach et al. 2022). For many species, it is the presence of features in the landscape that dictates how effectively individuals can move. Mountain ranges, for instance, guide birds migrating to or from overwintering and breeding grounds (Eisaguirre et al. 2018, Yoda et al. 2021). The golden eagle (*Aquila chrysaetos*) in western North America uses the Rocky Mountain range to migrate north from Wyoming to British Columbia in the Fall and *vice versa* in the Spring (Bedrosian et al. 2018). Likewise, riparian habitat can serve as movement corridors. These linear features provide a path along which wildlife can move to access habitats and resources (Cortes and Gillam 2020, Sahlean et al. 2020, Bateman et al. 2021). Jaguar (*Panthera onca*), for instance, uses the riparian habitat along the Yaqui River to access prey and disperse in the Sonoran Desert (Ragan et al. 2023).

It is these linear features, and even smaller features, such as woodland edges (Port et al. 2021, Tellería et al. 2021), hedgerows (Mony et al. 2022), connected tree canopies (Tielens et al. 2019), grasslands (Wimberly et al. 2018, Kimberley et al. 2021, Sabatino et al. 2021), and discrete habitats patches (Gardiner et al. 2019, Rocha et al. 2021), that can create pathways or stepping stones (defined as small, vacant forest patches that allow species to move between larger forest patches) that link habitats and resources. These pathways, not only include migratory routes, but also dispersal (i.e., the movement of individuals across a landscape that affect gene flow; Clobert et al. 2012) and commuting (Alavi et al. 2022) corridors used by wildlife to get from one resource to another (Loggins et al. 2019, Millward et al. 2022). For example, gray leaf-eared mouse (*Graomys griseoflavus)* relies on woodland edges to move through a matrix of agricultural fields in South America (Spirito et al. 2020).

Similar to agriculture, studies have shown that the presence of urban areas in the landscape can act as filters and barriers to movement (Pirnat and Hladnik 2018, Carlier et al. 2019, Choi et al. 2021). Filters are features in the landscape that reduce, but not obstruct, wildlife movement (Lerman et al. 2020, Wat et al. 2020, Rega-Brodsky et al. 2023). Roads, for instance, act as a filter to movement as some individuals are involved in fatal wildlife-vehicle-collisions, while others are able to cross successfully (Assis et al. 2019, Chyn et al. 2021, Schmidt et al. 2021). Moreover, in an urban environment the road network has a greater negative impact on wildlife movement as a higher concentration of roads with higher traffic volumes, increase the risk of wildlife-vehicle-collisions (Kreling et al. 2019b, Moore et al. 2020, Seiler and Bhardwaj 2020).

In contrast, barriers in the landscape are features that obstruct wildlife movement (Kreling et al. 2019a, Smith et al. 2019b, Herbert et al. 2021). Buildings and densely built-up areas with concrete and asphalt surfaces can physically prevent movement and access to other habitat patches (Carvalho et al. 2018). For example, the threatened eastern indigo snake (*Drymarchon couperi*) cannot disperse across paved surfaces (Bauder et al. 2020). In addition, the presence of humans can induce anti-predator avoidance responses, causing many species to avoid areas with high concentrations of human activity, such as urban areas (Kimmig et al. 2020, Schell et al. 2021, van Bommel et al. 2022).

Cumulatively, filter and barrier effects caused by urban development and sprawl have hindered the immigration and emigration of wildlife across the landscape (Fusco et al. 2021), reduced dispersal rates (Perrier et al. 2018), interrupted migration routes (Kideghesho et al. 2020), increased mortality rates (Bowne et al. 2018), and halted gene flow (Thomassen et al. 2018). In turn, a decrease in the abundance and distribution (Gorosito and Cueto 2020, Deeley et al. 2021, Delaney et al. 2021), breeding success (Vander Haegen et al. 2018, Wang and Hung 2019, Wilder et al. 2020), and survival of numerous wildlife populations at the landscape scale has been attributed to the presence of urban areas (Finch et al. 2020, Freitas et al. 2020, Dri et al. 2021).

Despite these negative implications, urban areas may facilitate wildlife movement if they are managed, modified, and designed effectively (Choquette et al. 2020, Freitas et al. 2020, Gregory et al. 2021). For example, green belts (Svensson et al. 2020) and spaces (Rico-Silva et al. 2020, Kaushik et al. 2021, Von Thaden et al. 2021), parks (Greenspan et al. 2018, Han et al. 2019), cemeteries (Löki et al. 2019, Villaseñor and Escobar 2019), residential yards (Lynch 2018), and golf courses (Wurth et al. 2020) can provide a matrix of habitats and resources that wildlife need to thrive (Pétremand et al. 2017, Moraes et al. 2018, Bhakti et al. 2021). For example, green spaces provide essential stopovers sites for migrating cinnamon teal (*Spatula cyanoptera septentrionalium*; Wyckoff 2018, Mackell et al. 2021). While linear features such as fences (Martinez-Fonseca et al. 2020), culverts (Lu et al. 2023), hedgerows (Mony et al. 2022), drainage ditches (Mazerolle 2005), walking trails (Whittington et al. 2022) or public rights-of-way (Lynch 2019), and roads (Ouédraogo et al. 2020) can form movement corridors enabling wildlife to traverse the urban landscape (Fernández et al. 2019). The latter three are typically used as movement corridors when they are tree-lined (Ossola et al. 2019, Freitas et al. 2020, Liu and Slik 2022).

Many species within a variety of taxonomic groups need trees to provide cover and shelter as they move, including birds (Pejchar et al. 2018, Amaya-Espinel and Hostetler 2019, Brush 2020), reptiles (Choquette et al. 2020, Delaney et al. 2021), mammals (Vander Haegen et al. 2018, Moretto et al. 2019), amphibians (McKenzie and Cecala 2020, Wilk et al. 2020, Simpson et al. 2021), and invertebrates (de Oliveira and Schmidt 2019, Zacharyasiewicz et al. 2021, Jensen et al. 2022). Thus, throughout the urban matrix the presence of trees and specific characteristics of trees are important to wildlife movement (Fingland et al. 2021). The tree canopy, for example, is used by red harvester ants (*Pogonomyrmex barbatus*) to access foraging resources (Elliott-Vidaurri et al. 2023), by eastern whip-poor-will *(Antrostomus vociferous*) to return to breeding grounds annually (Tonra et al. 2019), and by fox squirrels (*Sciurus niger*) to evade predators while commuting (Larson and Sander 2022). Collectively, the trees within an urban area make up what is known as the urban forest and is defined as all of the trees found on private properties (Steenberg et al. 2019), in parks and other public spaces (Xing and Brimblecombe 2020), and along roadways (Elsadek et al. 2019, USDA 2022). The ability of many species to move across the landscape is dictated by the configuration and composition of the urban forest (Gelmi-Candusso and Hämäläinen 2019, Lynch 2019, Zungu et al. 2020). More specifically, the connectivity of the urban forest for wildlife will depend on both structural and functional connectivity (Ritchie et al. 2019, Wang and Liu 2019, Han and Keeffe 2021, Von Thaden et al. 2021). The structural connectivity of this forest, defined as the physical proximity of trees, can facilitate the movement of wildlife (Wang and Liu 2019, Cadavid-Florez et al. 2020, Kaushik et al. 2021), while its functional connectivity, depends on the ability of specific species to move from one tree to another depending on proximity (Finch et al. 2020, Choi et al. 2021). For example, a northern flying squirrels (*Glaucomys sabrinus*) can cross gaps that are up to 30 m (Smith et al. 2013), while a black-handed spider monkey (*Ateles geoffroyi*) can only move if the trees canopies of touching (McLean et al. 2016). Thus, identifying the tree characteristics that influence structural and functional connectivity would provide important insights into how we might better improve the urban forest for wildlife.

The objective of this study was, therefore, to determine the combination of tree characteristics that create an effective movement corridor for bats. We selected bats as they depend on trees for many resources, including commuting routes, and their ability to move daily across an urban landscape to access foraging, roosting, and water resources is a good indicator of the functional connectivity of the urban forest (Jung and Threlfall 2018, Pourshoushtari et al. 2018, Gili et al. 2020). For this study, we used thermal cameras and acoustic monitoring to examine tree metrics that affect the ability of bats to commute in Fort Worth and the surrounding area, Texas, USA. Based on previous research, we hypothesized that bats would commute regularly along corridors with tall trees and less undulating interconnected canopies (Blakey et al. 2017, Vasko et al. 2020). By identifying the characteristics of trees that promote commuting activity, planners and wildlife practitioners can manage and plan the urban forest to improve landscape permeability for bats and subsequently aid bat conservation in urban areas.

METHODOLOGY

To identify a set of tree characteristics that influenced bat commuting activity, we first used existing telemetry data from VHS tracked bats in a park system and surrounding neighborhood in Fort Worth, Texas (Fig. 1). Using the locations of tracked bats, we created an activity map to aid in the initial identification of potential study sites that varied in bat activity levels (see *Study Site Selection* below). We then inspected the sites and selected 30 based on bat activity and the *in situ* tree canopy structure. At these 30 sites, we then conducted behavioral observation surveys to confirm levels of commuting activity and number of species present (see *Behavioral Observation Surveys* below). We also recorded basic tree metrics; the first four were derived from a GIS tree canopy layer and the fifth was measure in the field. These included 1) percent canopy cover, 2) canopy rugosity, 3) gap distance, 4) sum of gap distance, and 5) tree height. We then undertook a analysis to identify which tree metrics alone and in combination that increased and decreased bat commuting activity and species diversity.

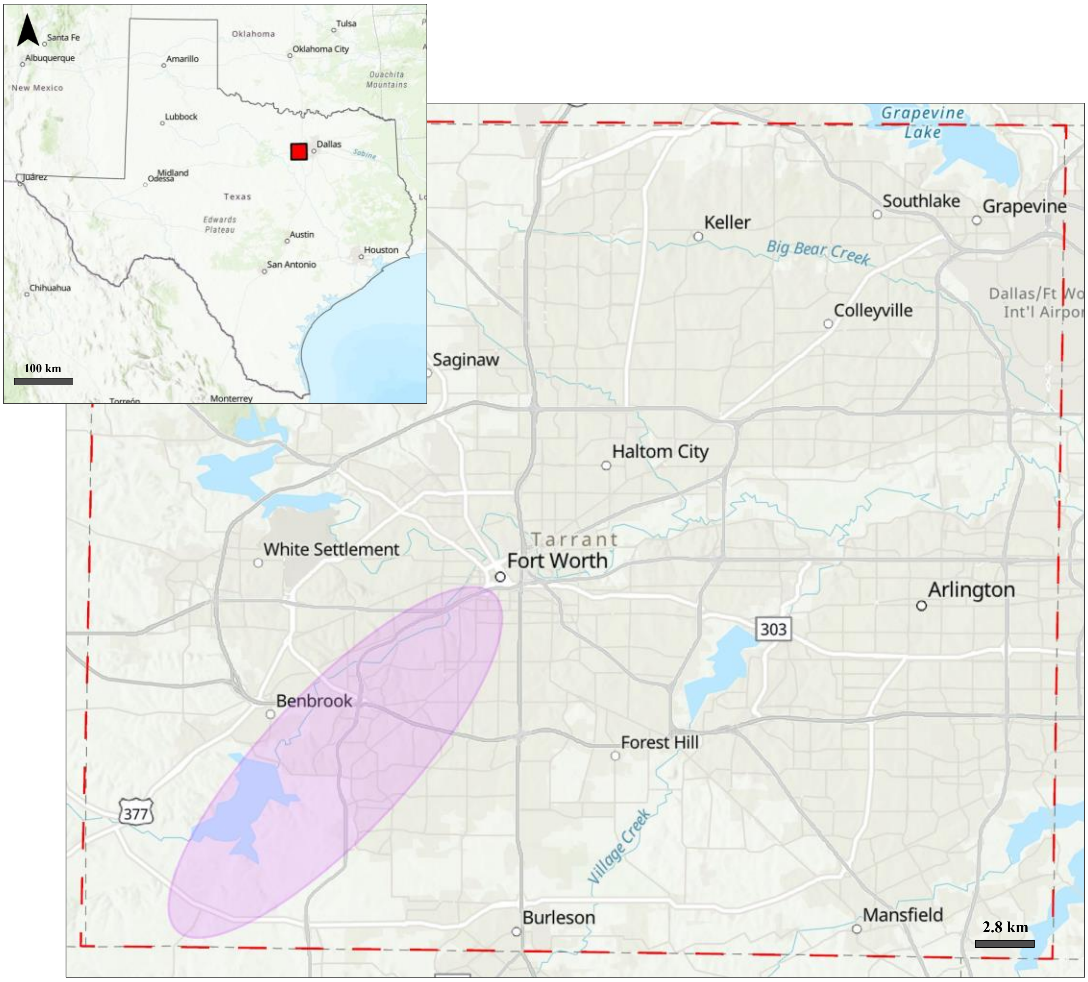


Figure 1: Map of Tarrant County in Texas, USA shown in black and the study area located in the south west corner of Fort Worth shown as a light green filled polygon.

Study Area

The study area was located within Tarrant County, Texas in the United States (32°41’21.17” N, 97°22’46.75” W; Figs.1 and 2). The area comprised parks and greenspaces along the Trinity Trail system, including Rocky Creek Park, owned and operated by the Army Corp of Engineers, Oakmont, Foster, Kellis, Hartwood, and Overton parks, which were owned and maintained by the City of Fort Worth Park and Recreation Department, and Texas Christian University Campus.

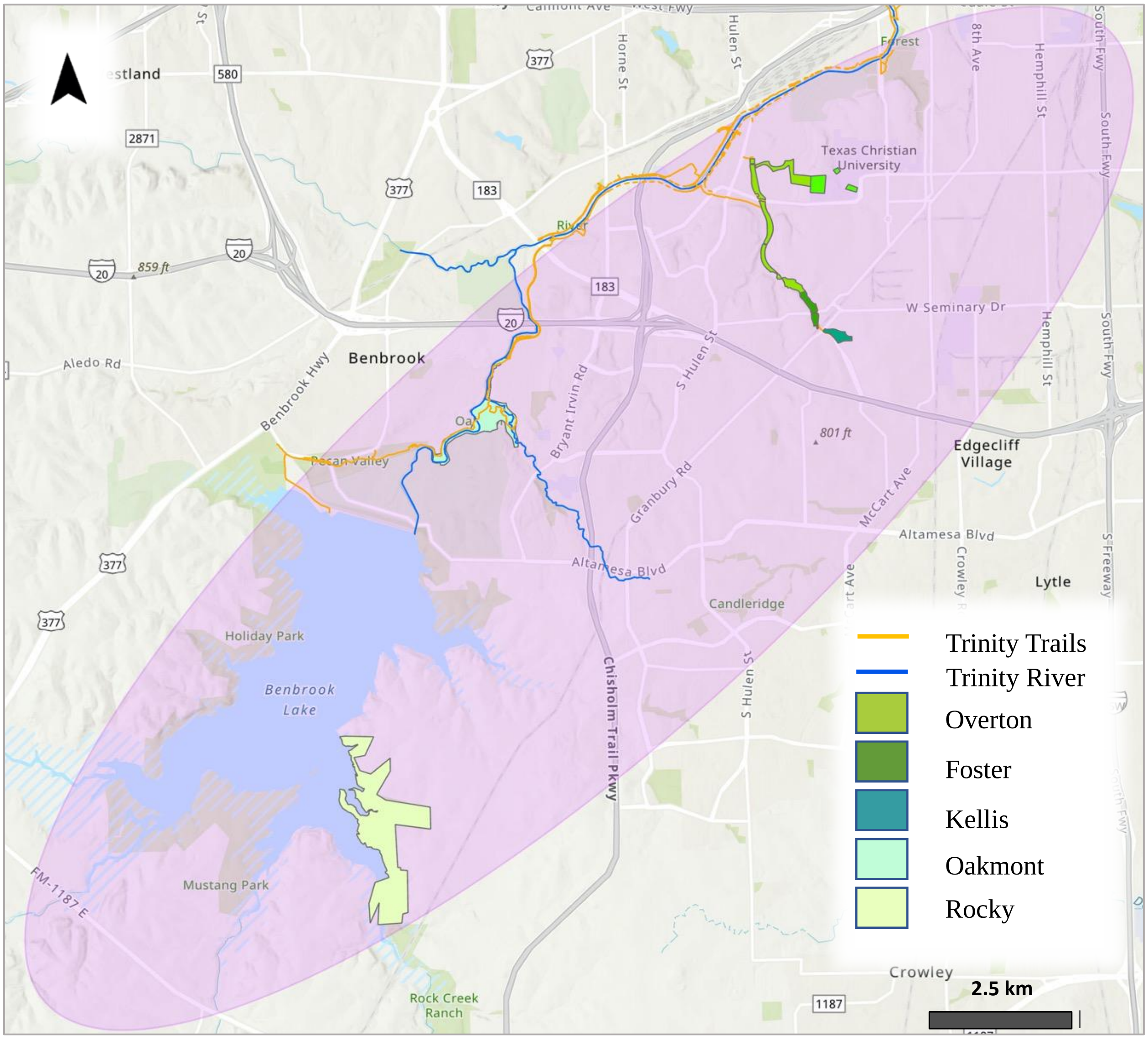


Figure 2: Map of study area with connected park system in Tarrant County Texas, USA. The study area is represented by the transparent purple oval while the parks are represented in solid polygons. Yellow lines show Trinity Trails and blue lines depicts Trinity River.

Rocky creek park is located on the edge of Benbrook Lake, a 14.7 km^2 reservoir which provides flood risk management and water storage for the Fort Worth metro area. Riparian habitat borders the reservoir with wooded areas extending into restored prairie habitat (Table 1). On the north side of Benbrook Lake, Oakmont park comprises a 0.53 km^2 section of riparian habitat along the Clear Fork tributary of the Trinity River. The park is surrounded by the suburban neighborhoods within the City of Benbrook. Further north in the southwest corner of the City of Fort Worth, Kellis, Foster, Overton, and Hartwood Parks form an interconnected park system centered around a drainage ditch and associated riparian habitat. This system branches through suburban areas until it eventually feeds into the Trinity River. Finally, our study area encompassed the west half of Texas Christian University’s campus 0.5 km east of Overton Park. This half of the campus comprises a retention pond, drainage ditch system that feeds into the Trinity River, athletic fields associated parking lots, and residence halls and other service buildings.

Surveys undertaken in these parks and greenspaces over the past 10 years have shown that the study area has an abundance and diversity of bat species, including evening (*Nycticeius humeralis*), eastern red (*Lasiurus borealis*), hoary (*L. cinereus*), Mexican free-tailed (*Tadarida brasiliensis mexicana*), silver-haired (*Lasionycteris noctivagans*), and tricolored (*Perimyotis subflavus*) bats (Bienz 2016, Agpalo 2019, Nystrom and Bennett 2019, Hall 2020). The presence of this bat community indicated that the area could be used to determine how bats effectively and/or preferentially move across this predominantly urban landscape. We, therefore, selected 30 sites within our study area that varied in levels of bat activity and the structure of potential movement corridors.

Table 1: Parks and greenspaces along the Trinity Trail system in the study area where survey sites were located. Images were taken from Google Earth 12/30/2022.

Rocky Creek Park	**Oakmont Park**	**Overton Park**	**TCU Campus**
			
Kelis Park	Foster Park	Hartwood Park	
			

Study site selection

To select our study sites, we used existing data collected in telemetry surveys that radio tracked 28 resident evening bats across the study area from 2017 to 2019 (Fig. 3; Hall and Bennett 2021). In these surveys, the locations of an individual bat were recorded (referred to as point locations) every minute that it was successfully tracked during its primary activity bout (from dusk for up to three hours; Weier et al. 2018, Frank et al. 2019, O'Mara et al. 2019) for three to ten days. For each of the point locations collected, a bat ID, date, and confidence value was provided from the aforementioned study. The latter value was a measure of the confidence, where the highest value (maximum 12) was allocated to point locations where a bat had been radio tracked effectively to a locale within a <5 m^2 area. To maximize the accuracy of the bat locations used to determine levels of bat activity in the following analysis, we only included bat point locations (n=7580) with confidence values of 12.

Using ArcGIS Pro version 2.9.2 (ESRI Inc., Redlands, CA), we collated this subset of bat point locations to create a map of bat activity (Fig. 4). To build the map, we used the ‘Point Statistics’ tool in the Spatial Analyst Tools toolbox in ArcGIS Pro to delineate the different concentrations of bat activity across the study. This tool summed the number of point locations within a 150 m radius circle at a 10 x 10 m resolution. We reclassified the resulting raster into 21 classes using natural breaks by applying the ‘Reclassify’ tool, also in the Spatial Analyst Tools toolbox (Fig. 5a). We then converted this raster into a polygon with the ‘Raster to Polygon’ tool in the ‘Conversion’ toolbox (Fig. 5b).

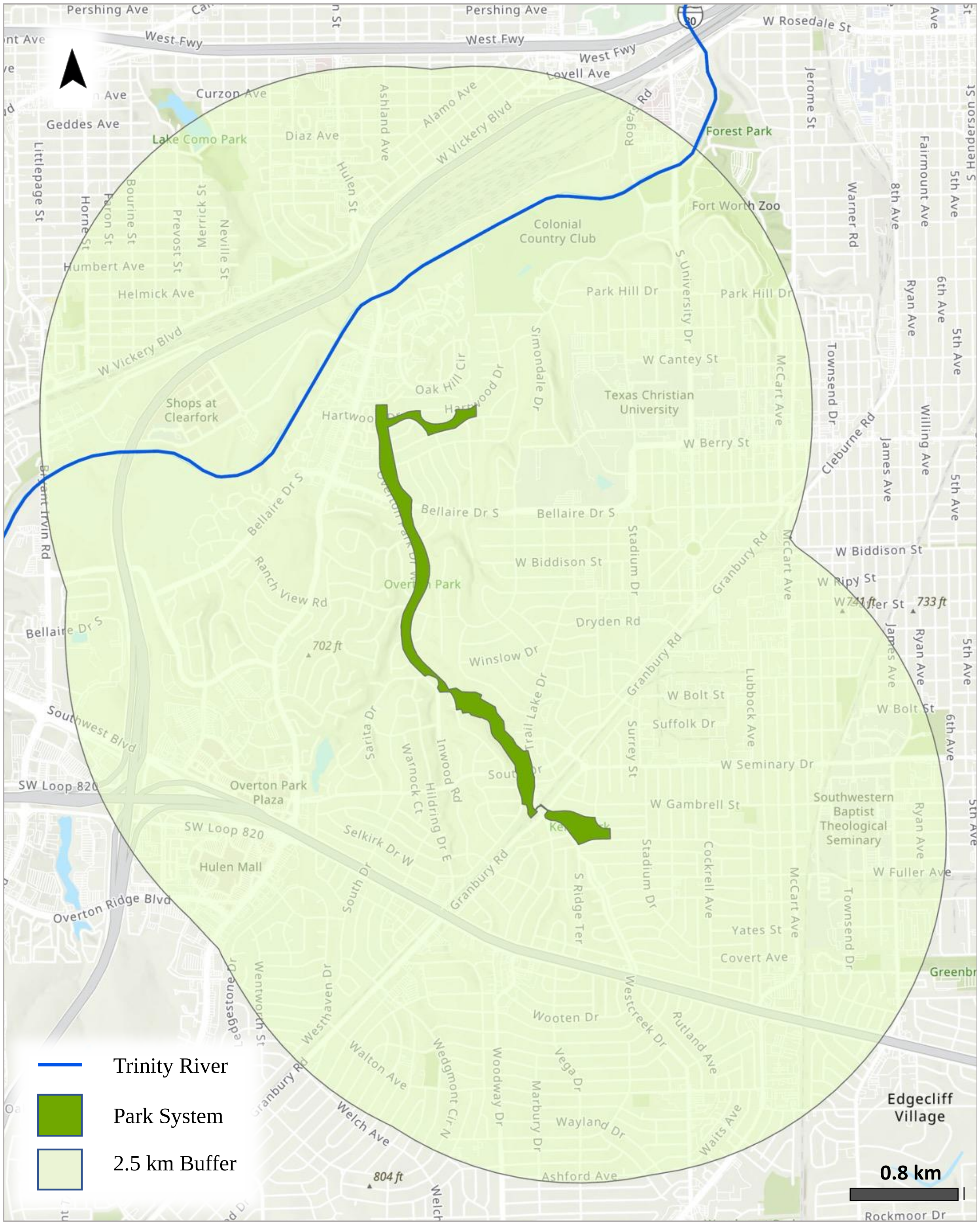


Figure 3: Map of study area in Fort Worth, Tarrant County, Texas, USA. The solid filled polygon represents the park system and the transparent polygon surrounding represents the 2.5 km buffer surrounding the park system.

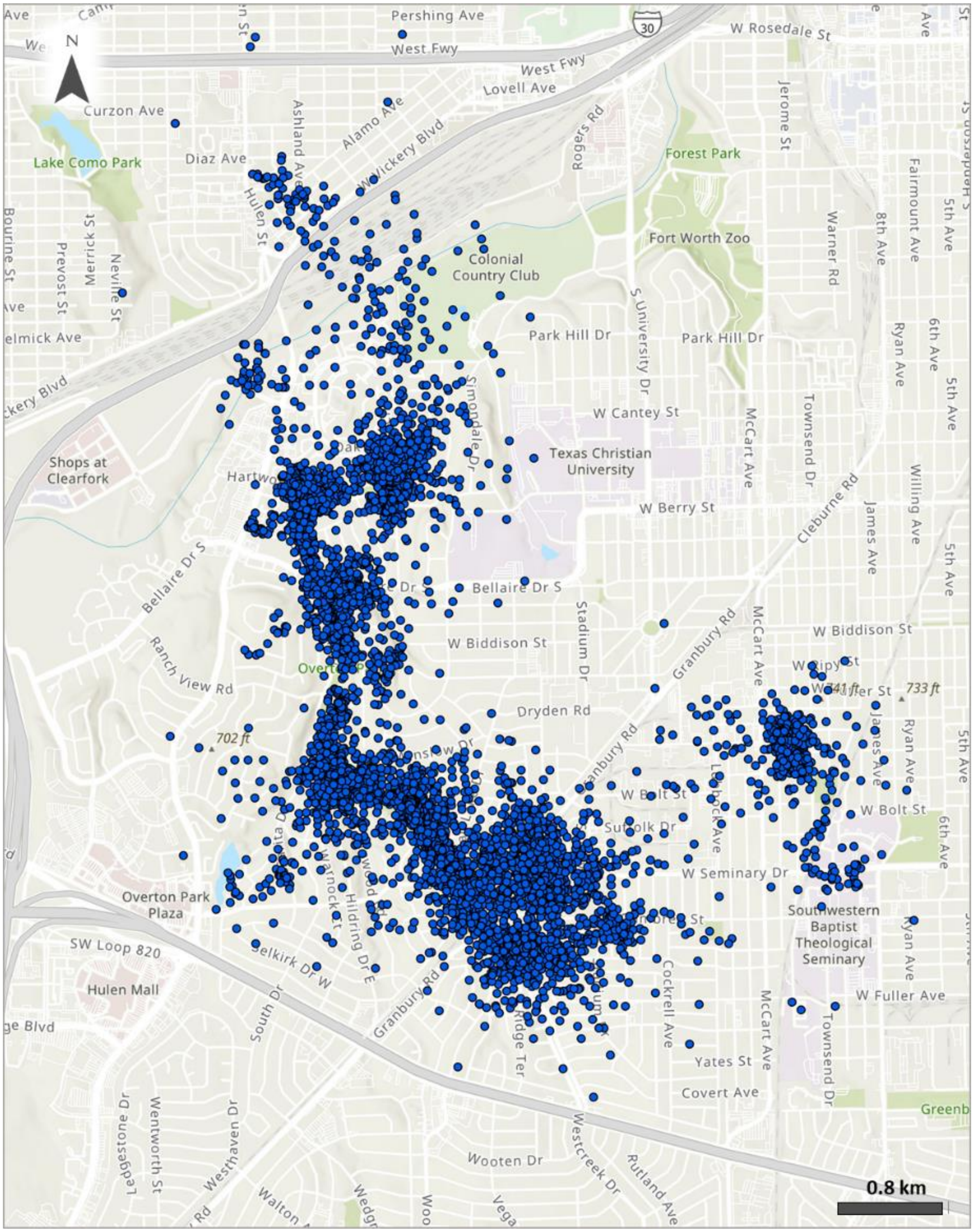


Figure 4: Point locations (blue dots) of bats radio tracked from 2017-2019 in an area surrounding at park system used to create a bat activity map within the study area in Fort Worth, Texas, USA.

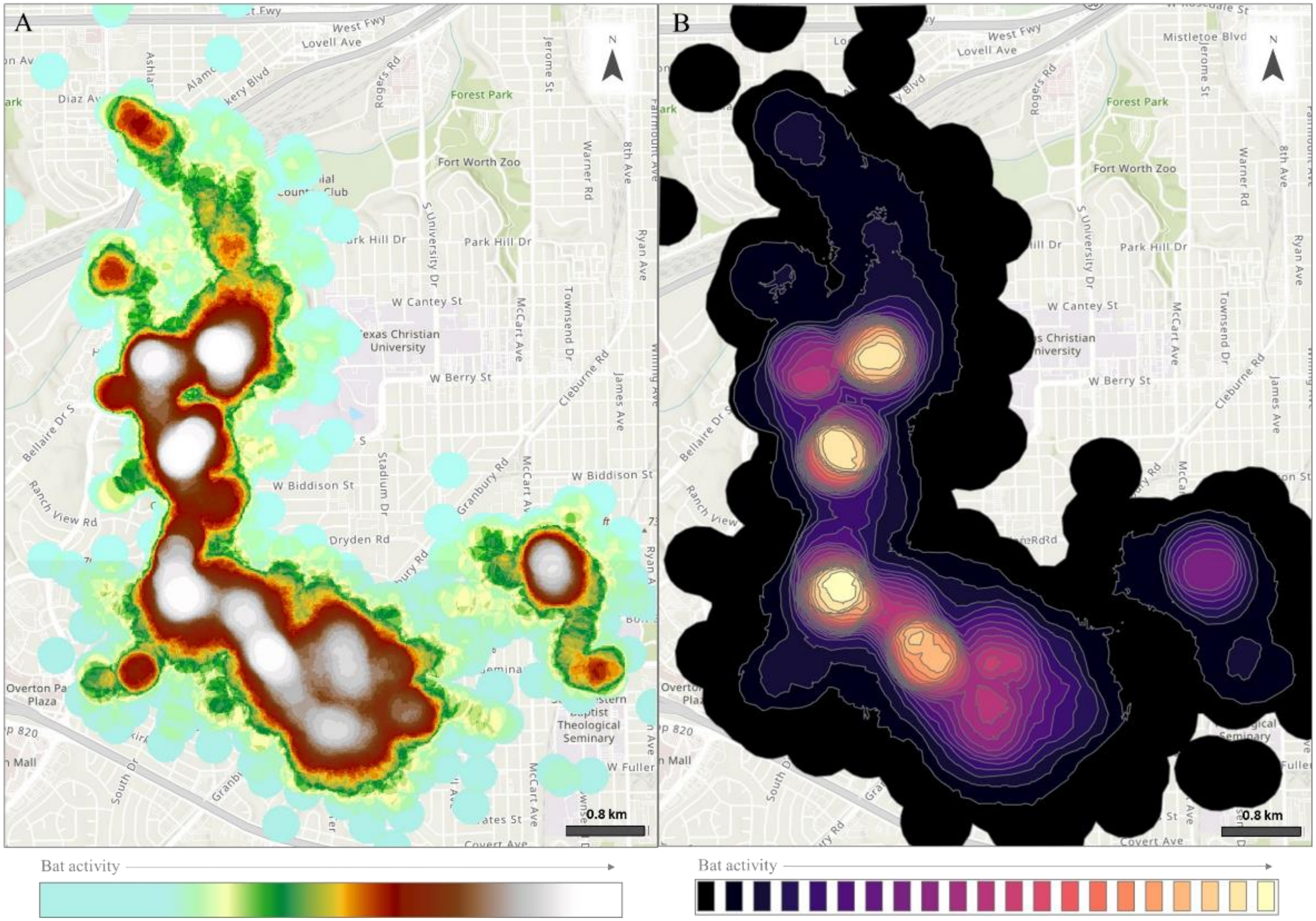


Figure 5: Bat activity map A) derived from the point locations (shown in Fig. 4) of bats radio tracked from 2017-2019 in an area surrounding at park system in Fort Worth, Texas, USA and B) shows this raster map converted into polygons.

Next, we used local convex hulls to exclude areas from the preliminary bat activity map (shown in Fig. 5B) where bats were potentially not active, as they may have not been effectively recorded during the telemetry surveys (i.e., to reduce false negatives). We first used the ‘LoCoH.a’ function in the ‘adehabitatHR’ package in R (R Core Team, Vienna, Austria) to create a 95%, 90%, and 73% (corresponding to first, second, and third standard deviations) local convex hull from the locations (Fig. 6). For this adaptive function, we defined the ‘a’ parameter to be 7 km, representing the distance between the two farthest point locations used in our study. We then selected to use the 90% local convex hull, as the 95% hull appeared to include more areas with no bat activity recorded and the 70% hull excluded more areas with low levels of bat activity that could potentially be used in the study.

Finally, we used the 90% LoCoH bat activity map to select 15 study sites that varied in levels of bat activity. For this selection process, we first excluded all sites from the activity map that could not be readily accessed and surveyed, such as private residence. We combined two shape files taken from the City of Fort Worth website (www.fortworthtexas.gov): 1) line layer delineating the streets in the study area and 2) the polygon layer outlining the park system (refer back to Fig. 3). We created a 10 m buffer around the lines in the former layer to represent the extent of surveyable area associated with the streets. We then merged both polygon files and added areas that we knew we could access (e.g., TCU owned areas and properties; Fig. 7). We then used the ‘Clip’ tool in the Analysis Toolbox to clip the combined layer of accessible areas from the bat activity map (Fig. 8).

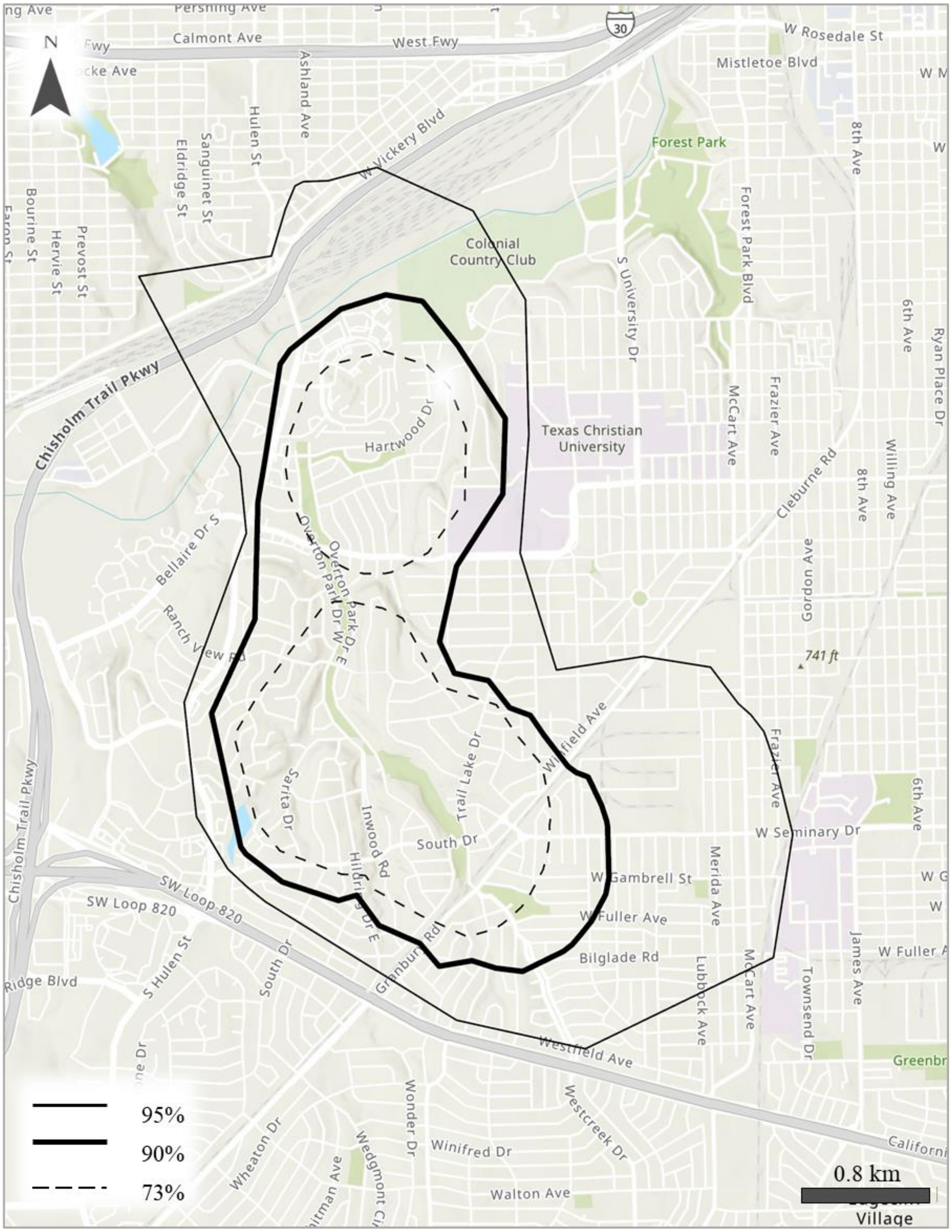


Figure 6: Map of 95% (solid line), 90% (solid thick line), and 73% (dashed line) local convex hulls delineating the area radio tracked bats were recorded from 2017-2019 in an area surrounding at park system in Fort Worth, Texas, USA.

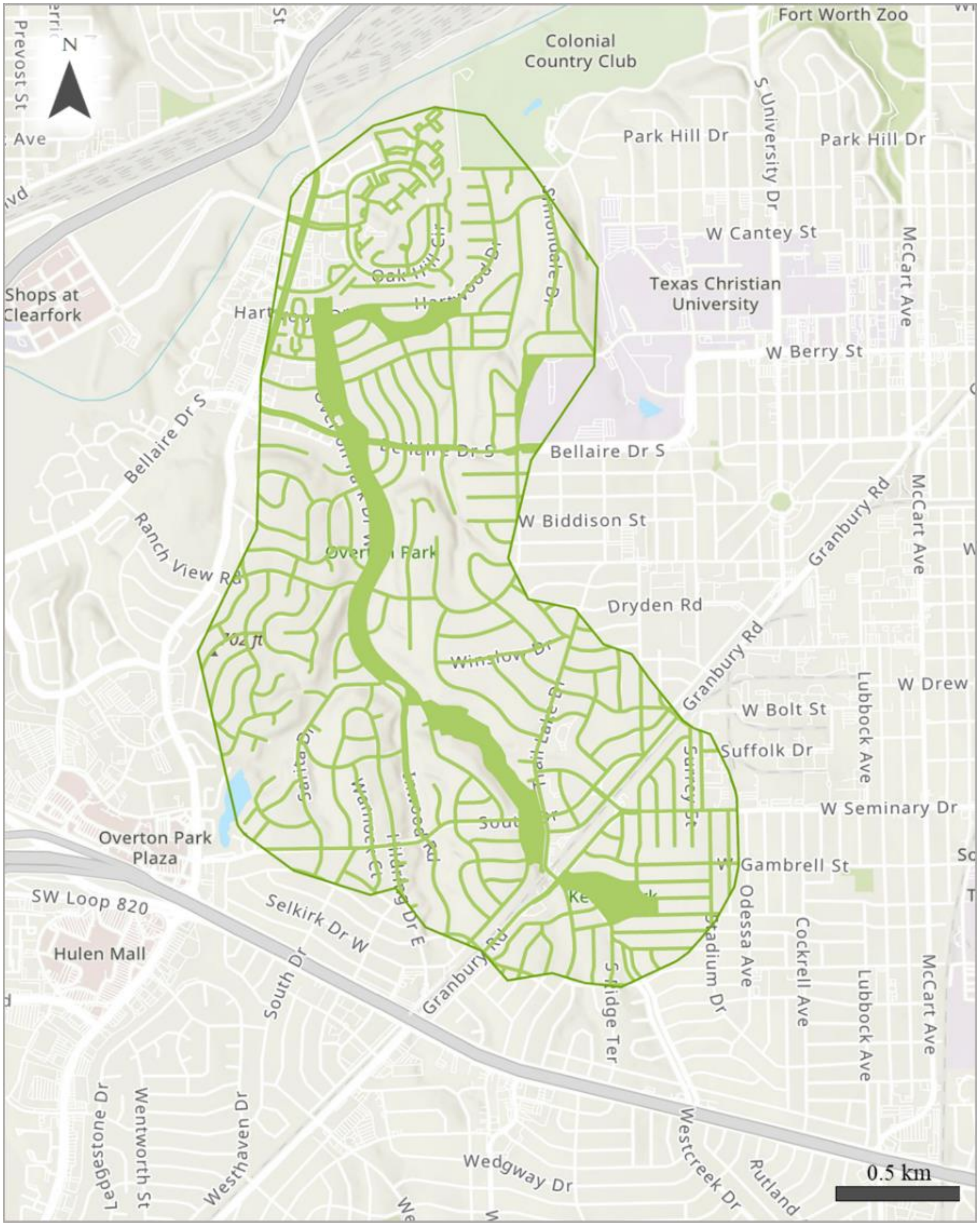


Figure 7: Map of all surveyable areas after inaccessible properties and areas outside the 90% hull were excluded from the area radio tracked bats were recorded between 2017-2019 in Fort Worth, Texas, USA.

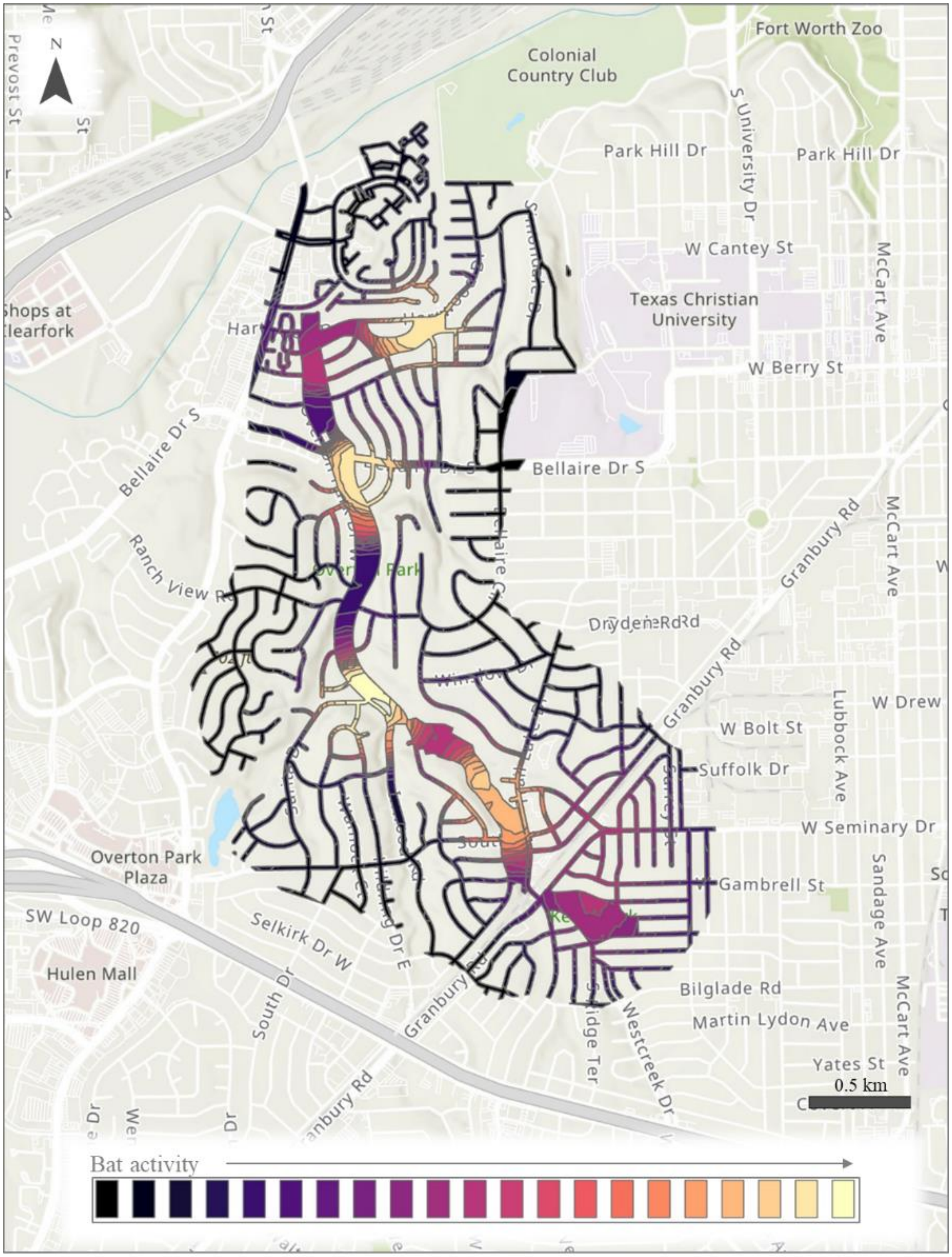


Figure 8: Modified bat activity map after inaccessible areas were removed from the bat activity map derived from the point locations of bats radio tracked from 2017-2019 in an area surrounding at park system in Fort Worth, Texas, USA.

To ensure bat commuting activity could be effectively associated with specific tree metrics (described below), we selected study sites that were located within five discrete levels of bat activity: 0%, 25%, 50%, 75% and 100%. These were based on the 21 bat activity classes with natural breaks used to create the bat activity map (Fig. 8). Thus, 0% represented all areas that fell within classes 1 and 2, 25% represented areas within classes 5-7, 50% encompassed classes 10 to 12, 75% included classes 15 to 17, and 100% activity occurred in classes 20 and 21. We then removed all classes that were not included above from our modified activity map (Fig. 9).

To select sites, we visited areas in each class to identify sites that could be feasibly surveyed. Suitable sites comprised a 10 m by 10 m area bordered by a linear feature which bats could potentially use to commute (e.g., tree or vegetation line, wall, or bank). To be surveyable, sites needed to have a clear field of view for a distance of 20 m from the linear feature, technicians and equipment set ups needed to be safely positioned (i.e., not placed in the middle of a road), and set ups could not cause an obstruction (i.e., equipment could not be placed on pedestrian and bike trails). Based on these criteria, 25 sites were selected within the modified activity map and an additional 5 sites were selected in areas along the Trinity Trail (Fig. 2) that were known to have similar levels of bat activity as one of the five aforementioned classes (Bienz 2016, Smith 2019). Thus, a total of 30 survey sites were selected (Fig. 10).

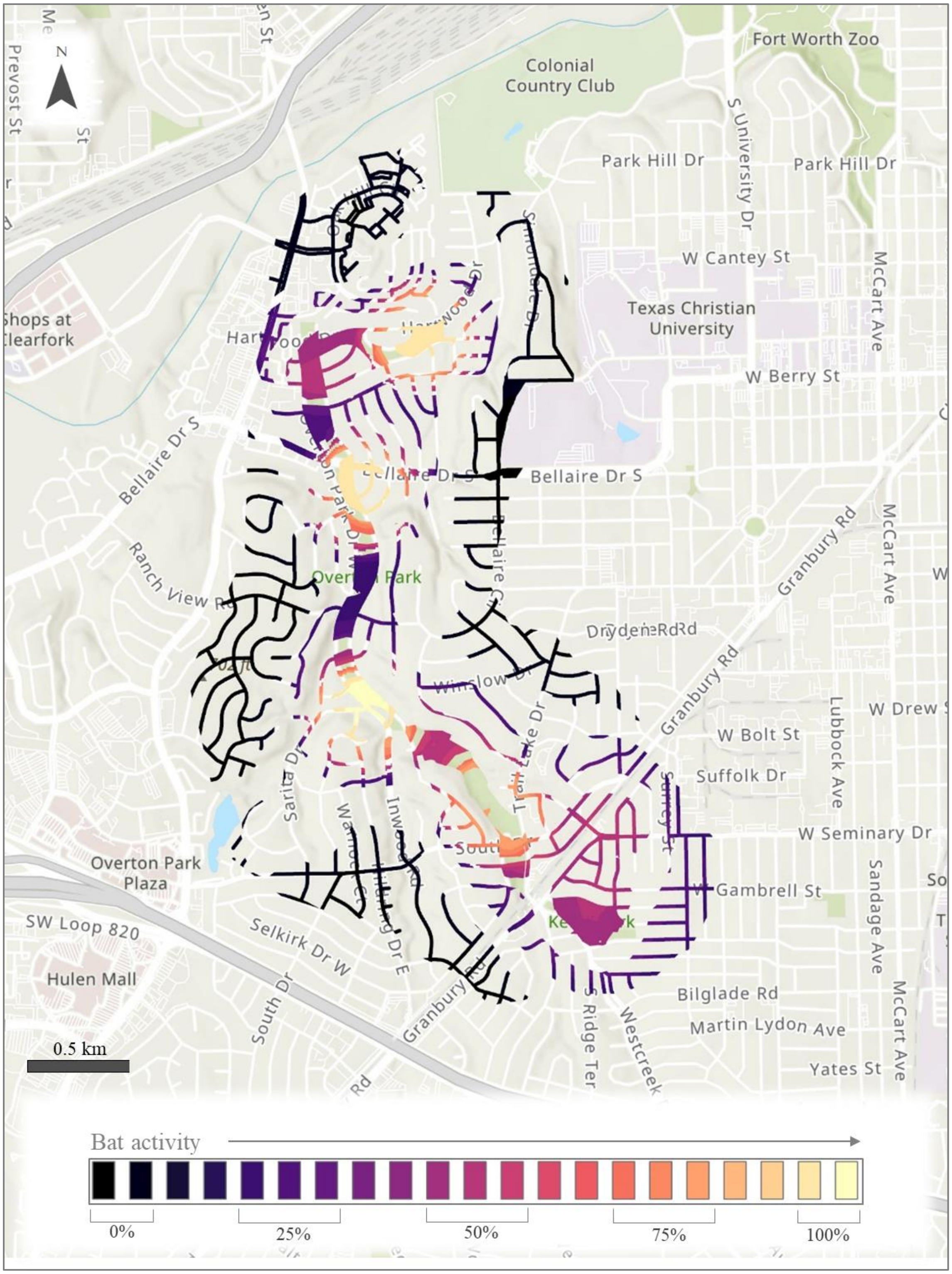


Figure 9: Map delineating surveyable areas within 5 discernable levels of bat activity (0%, 25%, 50%, 75%, and 100%) derived from bats radio tracked between 2017 and 2019 in an area surrounding a park system in Fort Worth, Texas, USA.

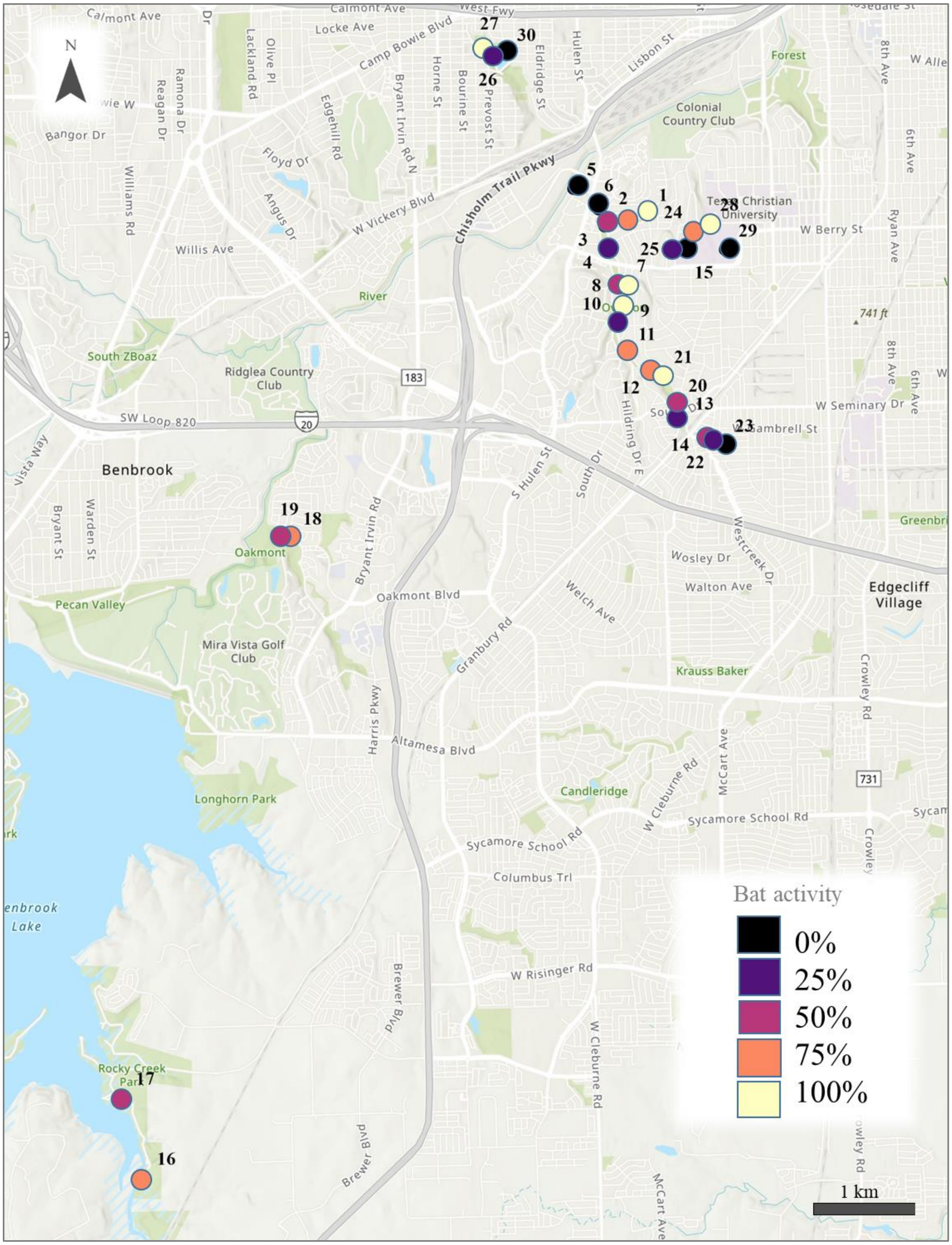


Figure 10: Thirty study sites selected along the Trinity Trail in Tarrant County, Texas, USA.

Behavioral observation surveys and acoustic monitoring

We conducted behavioral observation surveys and acoustic monitoring at 15 study sites from June to September in 2022 and at another 15 sites from March through May 2023 to encompass the entire period when bats are active in the study area (Agpalo 2019, Nystrom and Bennett 2019, Hall and Bennett 2021). We surveyed two sites simultaneously, as a paired study, to help identify and account for any anomalies in activity associated with variations in abiotic conditions, such as moon illumination (Vásquez et al. 2020, Appel et al. 2021). Similarly, as there are known conditions in which bats were not active, we did not conduct surveys when temperatures were <5°C, it was raining, or wind speeds were >24 km/hr (Bienz 2016, Hall and Bennett 2021). Thus, we aimed to survey all study sites once a month on rotation with approximately four sites surveyed in a week.

To record bat activity, we used two thermal camera set-ups consisting of an Axis Q1942-E 19mm ThermNetCam 30 FPS (Axis Communications, Lund, Sweden) surveillance cameras mounted on a Manfrotto MT055xPRO3 tripod. The thermal cameras were set to the “Ice-and-Fire” false-color scheme setting, a resolution of 640 by 480 pixels, and a sampling rate of 30 frames per second. At each study site, cameras were placed to record bat activity along (side-facing field-of-view) and in front (front-facing field-of-view) of the selected linear feature. For the side-facing field-of-view, the first camera was set-up 2 m from the linear feature pointing parallel to that feature, while the second camera was positioned perpendicular to the feature (Fig. 11). To ensure bat activity was recorded within the 10 x 10 m area in front of the feature, both cameras were placed 10 m from the corresponding edges of the area (Figs. 11 and 12; also see Huzzen et al. 2020) for further details regarding camera field-of-view). In addition, we angled the cameras 24° upwards to capture a height at which the bats were likely to be flying (de Torrez et al. 2018, Erasmy et al. 2021). Note that site specific adjustments to this angle were made to accommodate any slopes that were encountered. Finally, to operate the thermal cameras, we used a HP Compaq 8510w laptop computer via Ethernet cables and a Netgear ProSAFE 8-Port Fast Ethernet PoE Switch, and a lithium-ion battery to power the laptop and thermal camera through the Netgear Ethernet switch. Appendix A provides details of the thermal camera set up at each site, while Table 2 shows the side- and front-facing field-of-views from the thermal cameras at each site.

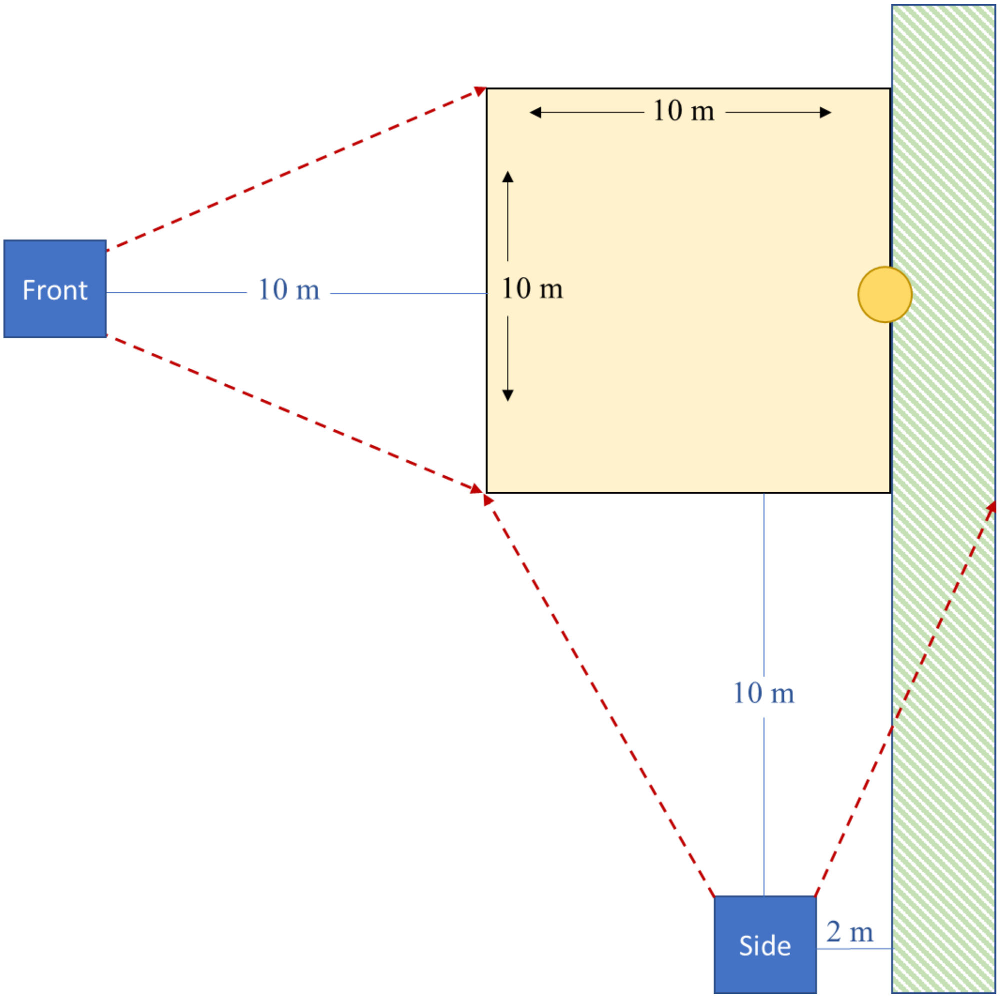
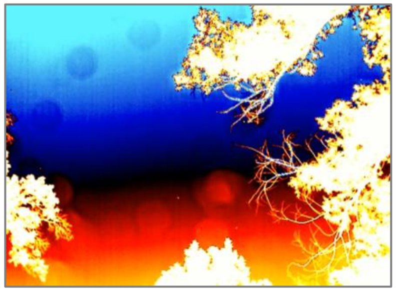
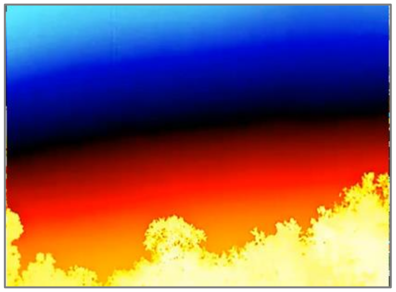
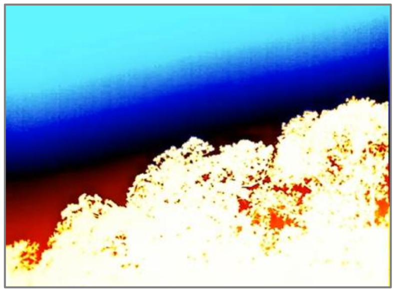
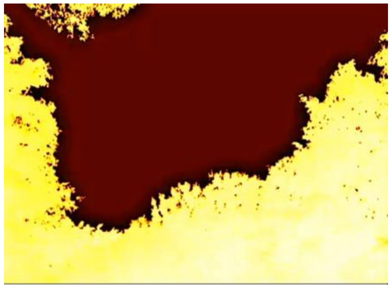
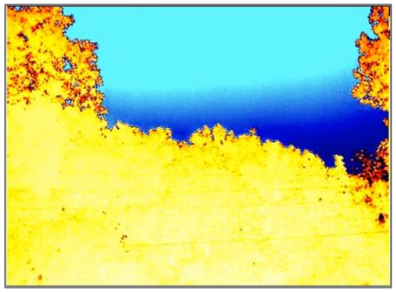
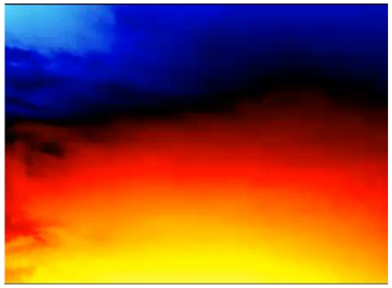
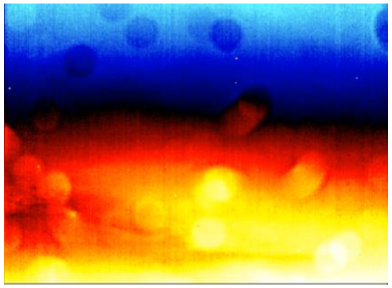
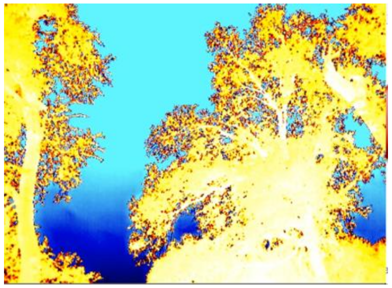
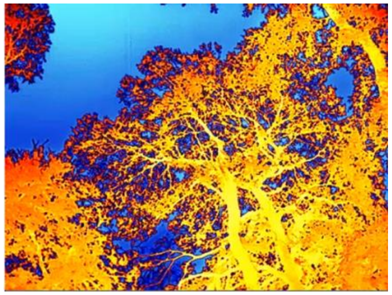
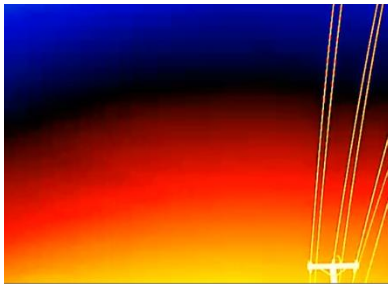


Figure 11: Schematic of thermal camera placement at study sites to capture the 10 by 10 m area (solid square) in front of a selected linear feature (striped rectangle). Positions of the side- and front-facing thermal cameras are show as blue squares and acoustic detector as a yellow circle. The extent of the thermal camera field-of-views are shown by red arrows.

Figure 12: Equipment set up for A) side-facing view and B) front-facing view of the linear feature at study sites. Red polygons represent 10 by 10 m field-of-view surveyed for bat activity.

Table 2: Thermal camera side and front-facing field-of-views for each of the 15 study sites surveyed in behavioral observation surveys.

Site	Side-facing field-of-view	Front-facing field-of-view	Site	Side-facing field-of-view	Front-facing field-of-view
1			4		
2			5		
3			6		

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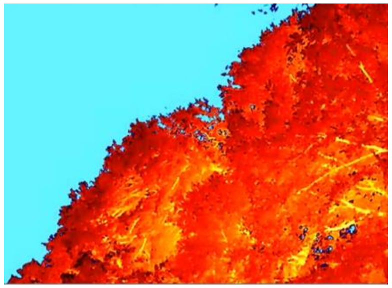
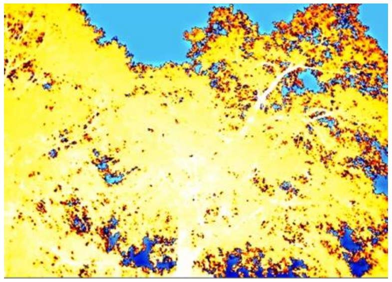
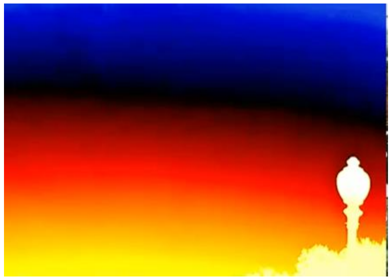
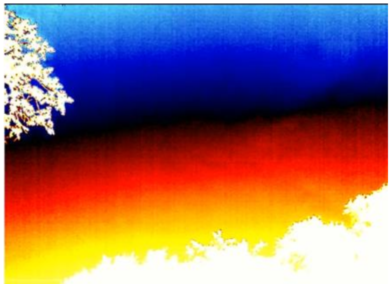
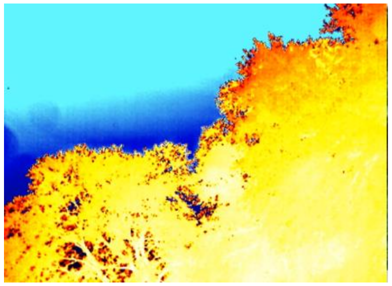
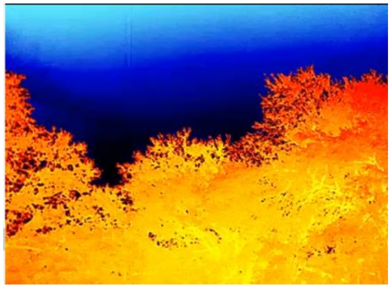
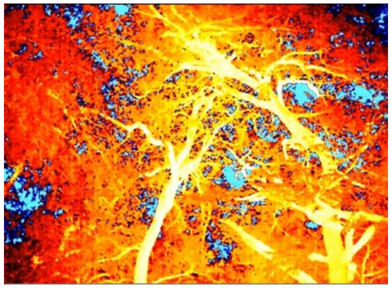
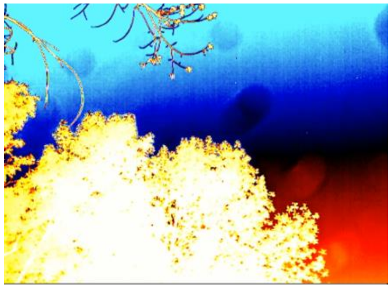
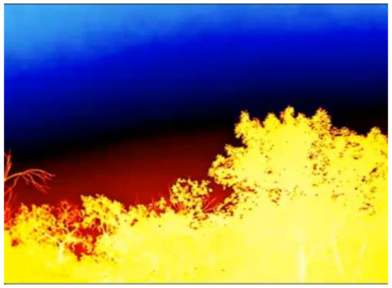
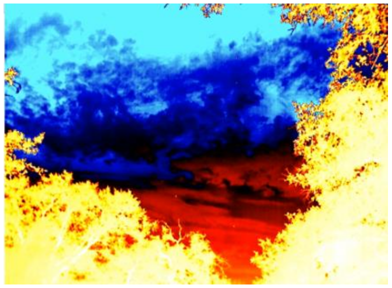
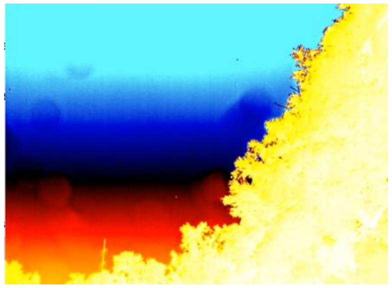
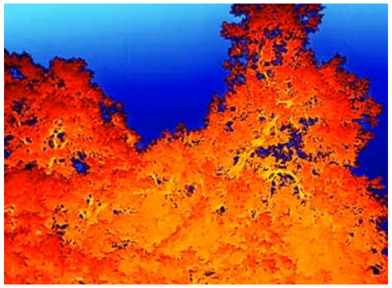
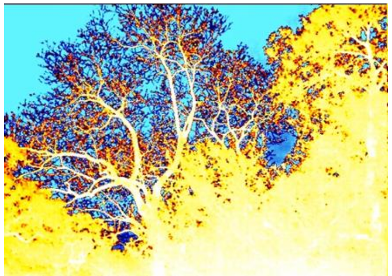
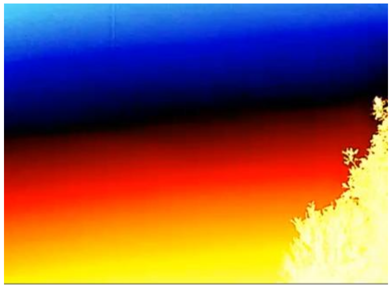
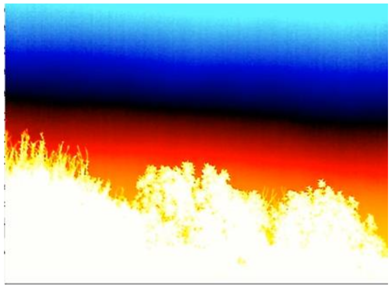
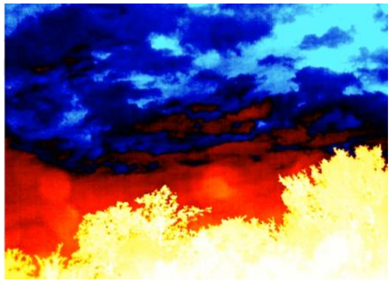
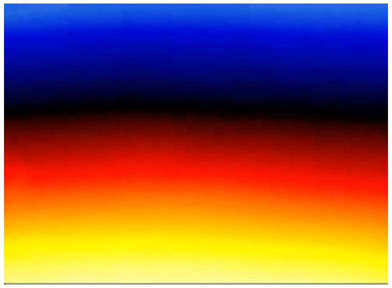
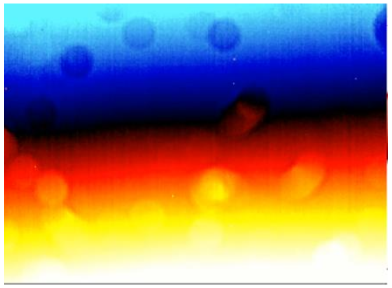
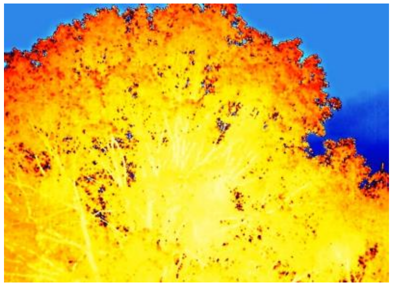
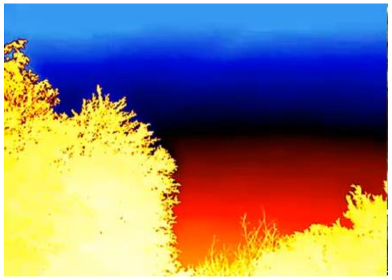
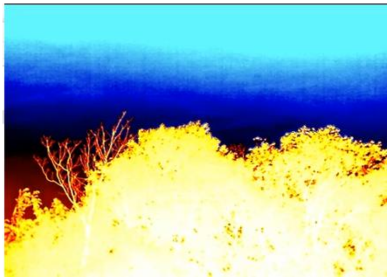
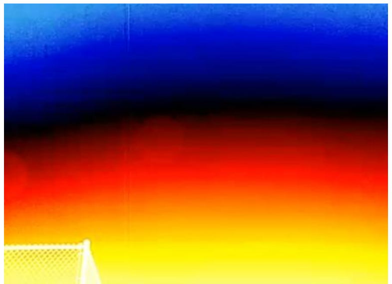
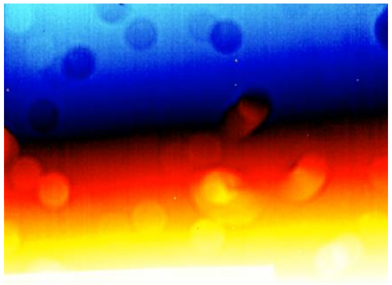
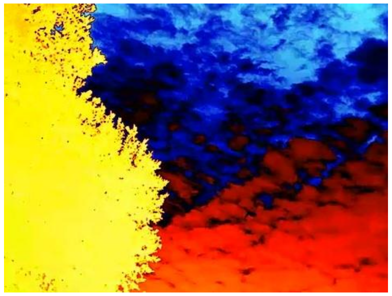
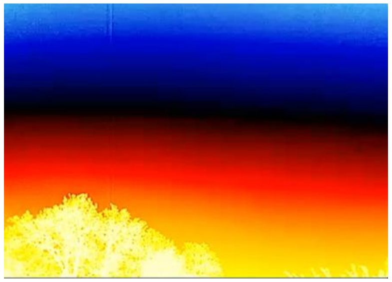
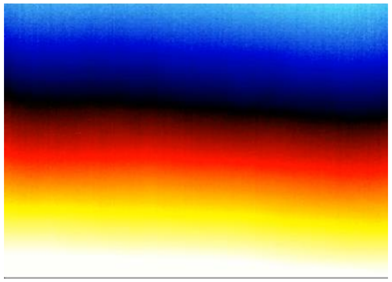
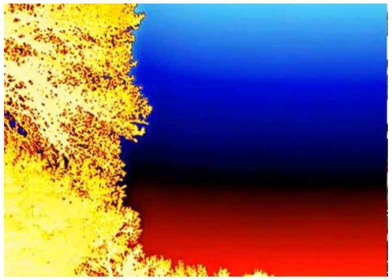
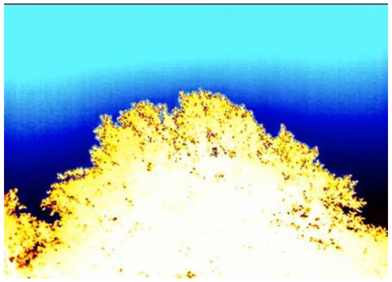
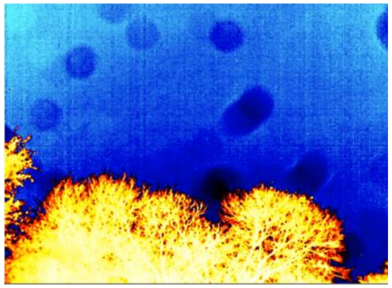
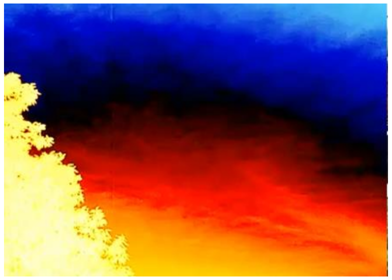
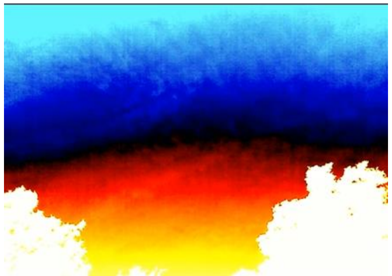
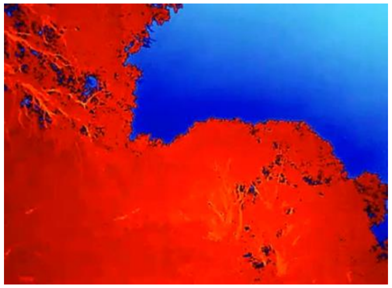
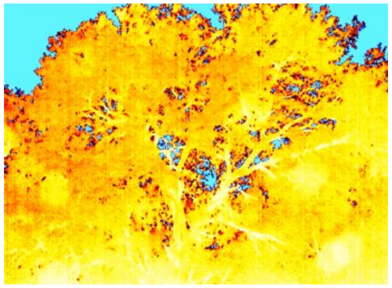
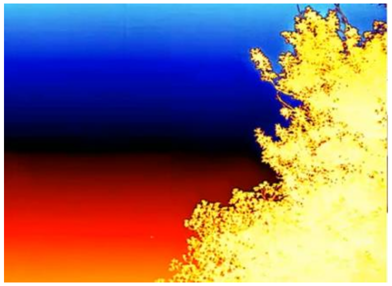
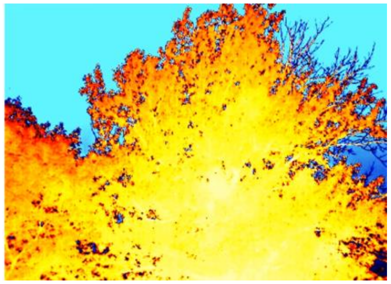
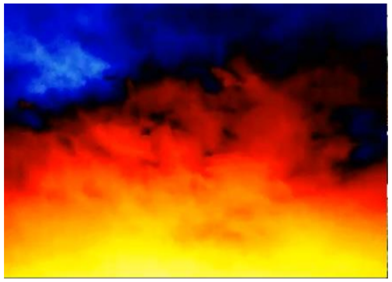
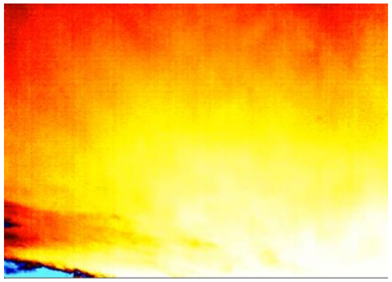
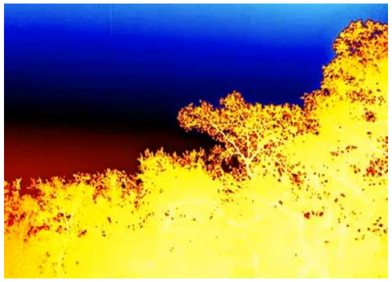
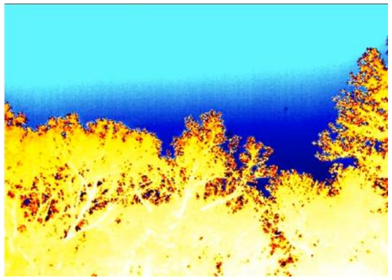
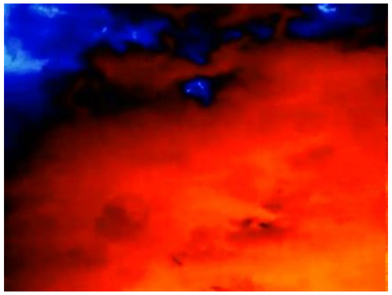
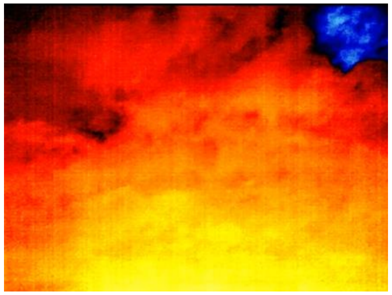
7			10		
8			11		
9			12		

Site	Side-facing field-of-view	Front-facing field-of-view	Site	Side-facing field-of-view	Front-facing field-of-view
13			16		
14			17		
15			18		

Site	Side-facing field-of-view	Front-facing field-of-view	Site	Side-facing field-of-view	Front-facing field-of-view
19			22		
20			23		
21			24		

Site	Side-facing field-of-view	Front-facing field-of-view	Site	Side-facing field-of-view	Front-facing field-of-view
25			28		
26			29		
27			30		

To record bat echolocation calls at the sites during the behavioral observation surveys, we used a BAT iFR-IV integrated field recorder with microphone from Binary Acoustic Technology (Bat Conservation and Management, Inc., Carlisle, Pennsylvania, USA). The detector was set to record bat calls with frequencies between 16 kHz and 192 kHz to encompass the echolocation frequencies of known bat species within our study area (Bienz 2016, Agpalo 2019, Smith 2019, Hall and Bennett 2021). The gain threshold and trigger volume were both set at 12.0 dB with a 3-sec delay set between recordings, along with a sample rate at 256 kHz. Sound files were recorded as 4-sec standard wav files (.wav) and saved on an 8 GB USB drive. The detector was placed parallel to the center of the linear feature being surveyed with its microphone angled directly upwards. As the microphone was omnidirectional, we acknowledge that this set up would record echolocation calls beyond the thermal camera field-of-view (see *Processing* for further details). Finally, prior to the start of the behavioral observation survey the internal clocks of the acoustic detectors were synced with the cameras. In addition, we also used an iPad with an Echometer Touch ultrasonic microphone module from Wildlife Acoustics as a second method to confirm the presence of bats during the surveys in real-time.

We set-up and tested the equipment at least 30 minutes before the survey start time. Surveys then started at dusk (20 mins after sunset) and lasted 1 hr to capture peak bat activity (Fern et al. 2018, Schimpp et al. 2018, Hall and Bennett 2021). To ensure footage from the front and side cameras were synced effectively (see *Processing* below), we uncovered the camera lens simultaneously when we started the 1-hr survey. During these surveys, we also recorded real-time observations of bats in the thermal field-of-view and acoustic activity from the Echometer touch, again to aid thermal footage processing (see *Processing* below). We also recorded the following data using WeatherBug and Lunar Phase applications: temperature (^{o}C), average wind speed (km/h), gust speed (km/h), wind direction (cardinal), humidity (%), dew point (^{o}C), barometric pressure (mb), cloud cover (full, partial, or clear), moon phase, moon illumination (%), and whether the moon was visible. Note these variables potentially influence bat activity on a given survey night (Appel et al. 2019, Vásquez et al. 2020, Whiting et al. 2021) and were only considered if outliers or anomalies in the data occurred.

Processing

Following each survey, we downloaded and converted all footage to m4v files using Handbrake Software (version 1.5.1, HandBrake Team, Paris, France). We uploaded these files to StudioCode video analysis software (Version 5, Studiocode Business Group, Sydney, AU). In the latter, we first stacked the footage from the side and front cameras (i.e., created a side-by-side view), so they could be viewed in unison along a single timeline (Fig. 13). To stack the footage effectively, we synced the two videos at the moment the camera lenses were uncovered. We then viewed the stacked footage and recorded the instances when bats were presence in the field-of-view. Using a code window created in Studiocode, we were able to log these instances along the timeline with the duration of each instance. In addition, we identified a distinct inflight behavior not associated with commuting: foraging, defined as a zig-zagging flight pattern with >3 tight turns in <5 secs (Huzzen et al. 2020). To confirm the presence of bats (i.e., avoid recording non-bat objects, such as birds, moths, and dragonflies), we used real-time bat observations and acoustic detections recorded during the behavioral observation surveys.

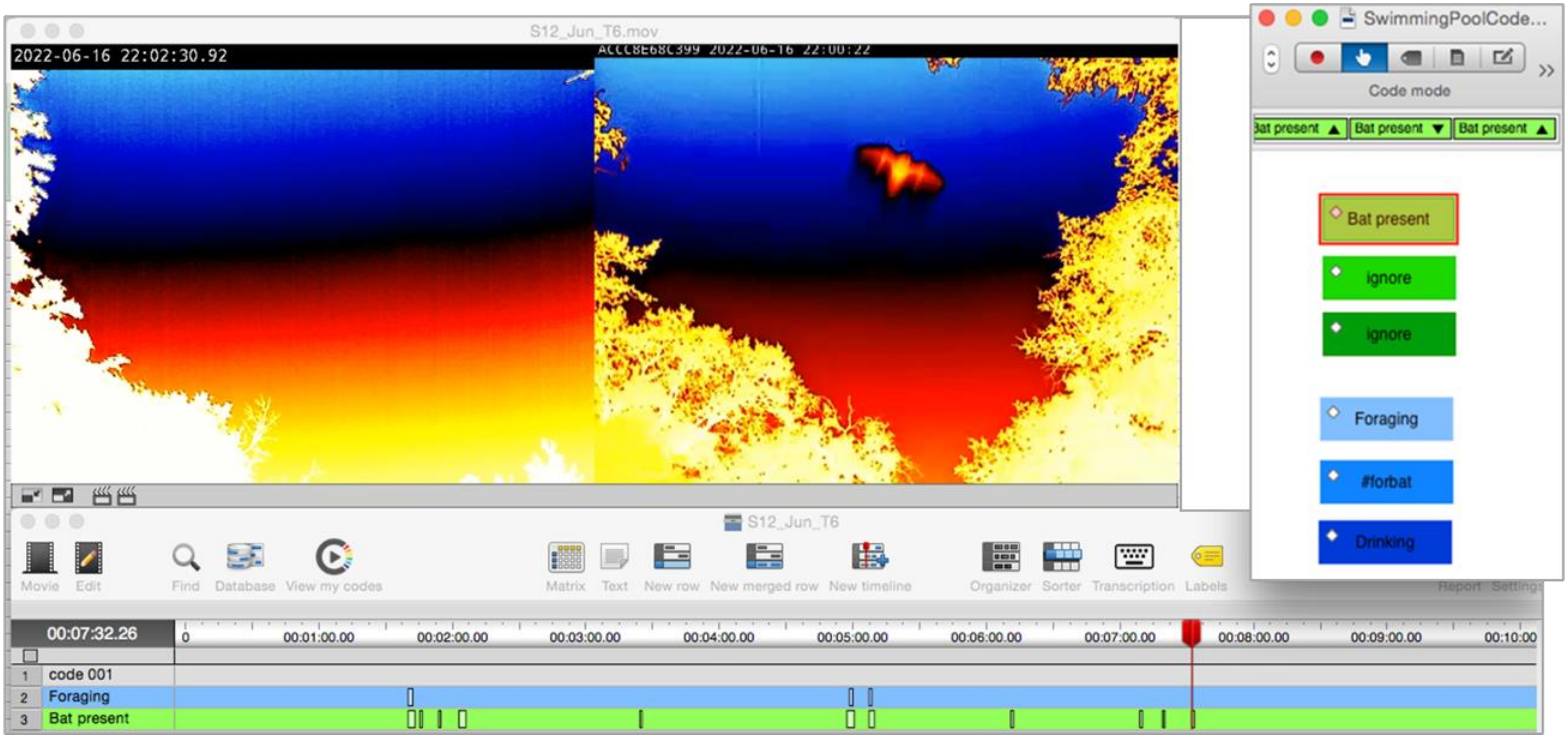


Figure 13: Example of stacked footage for a behavioral observation survey in Studiocode. Image shows code window to the right of the screen and the presence of bats along with foraging activity exhibited by bats logged along a timeline at the bottom of the screen.

To determine how effectively the presence of bats in the field-of-view were observed and logged, we used a second technician to review 25% of the footage. This reviewer viewed the stacked footage blind (i.e., could not see the initial reviewers log and without the aid of the observed and acoustic data recorded in real-time). We then compared the initial reviewer's logged timeline against the second reviewer's timeline to ascertain any differences and determine the percentage of bats missed by the initial reviewer. If over 5% more bat observations were made by the second reviewer, they would then view all footage to ensure bat activity was effectively identified. The results of this preliminary data analysis revealed that only 4% of bats were not observed by both reviewers, indicating that the number of bats potentially unrecorded during the analysis of the footage are unlikely to alter the findings of our study.

Once processing was completed, we exported the marked timelines into excel. We then summed the amount of time bats were present in the field-of-view and the amount of time (secs) bats were observed foraging in the field-of-view for each 1-hr survey. To calculate the amount of time (secs) bats were observed commuting/hr (assuming that all other behaviors observed were related to commuting activities), we subtracted the amount of time bats were observed foraging from the time bats were present in the field-of-view.

For the sound files recorded on the field recorder, we first downloaded the files into SonoBat Scrubber software (SonaBat 2010) to filter and remove any files containing noise only (such as wind and stridulating invertebrates). We then used SonoBat bat call analysis software (SonoBat 2010) to manually identify bat echolocation calls among the remaining files to species, where possible.

Tree metrics

We measured 1) percent canopy cover, 2) canopy rugosity, 3) gap distance, 4) total distance of gaps present, and 5) tree height along the 10 m field-of-view, as well two extended sections, at each survey site to assess whether these metrics influenced bat commuting activity (i.e., connectivity). For the extended sections, we selected lengths of 30 m and 50 m along the potential commuting route because 50 m corresponded with the maximum distance bat species known to be in the area will cross with no available cover (Ammerman et al. 2012) and 30 m represented an effective intermediate. Moreover, the five tree metrics were selected, as they represented characteristics of trees that were known to influence bat commuting activity (Fern et al. 2018, Heim et al. 2018, Moretto et al. 2019). For instance, studies have shown that canopy cover percentage increases the activity and diversity of canopy-dependent species by offering cover from predation and providing structural complexity that increases bat activity (Bailey et al. 2019, Moretto et al. 2019, Tena et al. 2020). In contrast, canopy rugosity (i.e., how linear the canopy edge is) has been shown to negatively affect commuting activity by reducing straight-line flight and, therefore, increases the time and energy it take to get to resources (Suarez-Rubio et al. 2018, Heim et al. 2018). Average gap distance (i.e., distance between tree canopies) and total distance of all gaps present affect bat commuting because there is a threshold distance where bats will not cross to another tree canopy if it is too far away due to the fear of predation (Zurcher et al. 2010). This perceived risk creates barriers or filters to movement and therefore decreases the bat activity and diversity (Arndt et al. 2018, Erasmy et al. 2021, Hooton et al. 2022). Lastly, tree height influences bat diversity, because different species have different flight abilities and perceptions of risk (O'Mara et al. 2019). Subsequently, some species such as the eastern red bat is dependent on the tree canopy for cover when commuting, while the Mexican free-tailed bat has less perceived risk and flies at height (Ammerman et al. 2012). Moreover, studies have shown that typically taller trees have a positive influence on bat activity (Fern et al. 2018).

To determine these five tree metrics at each of our 30 sites, we first used ArcGIS Pro version 3.1 (ESRI Inc., Redlands, CA) to estimate canopy cover percentage, canopy rugosity, average gap distance, and total distance of gaps present. More specifically, we used a landcover raster derived from NAIP imagery at 60 cm resolution with the following land cover classes: barren, impervious roads, impervious surfaces, low vegetation, tree canopy and shrubs, and water (Halff Associates 2022). We first projected this raster file to 'NAD 1983 (2011) StatePlane Texas N Central FIPS 4202 (meters)' before we converted this imagery into a polygon file using the 'Raster to Polygon' tool and then removed all but the tree canopy and shrubs land cover class (hereafter referred to as a *tree canopy layer*). Next, we created a *survey sites layer* containing the 30 10 m by 10 m cells representing the area within the field-of-view for each survey site with an additional four 10 m by 10 m cells extending along the potential commuting route to establish the 30 m and 50 m sections (Fig. 14). We then used the survey sites layer and the original landcover raster to measure the percent canopy cover for each 10 m, 30 m, and 50 m section. For this, we used the 'Tabulate Area' tool to calculate amount of canopy cover (m^2) in each cell and then divided that area by the total area (i.e., 100 m^2, 300 m^2, and 500 m^2) to determine a percent canopy cover value.

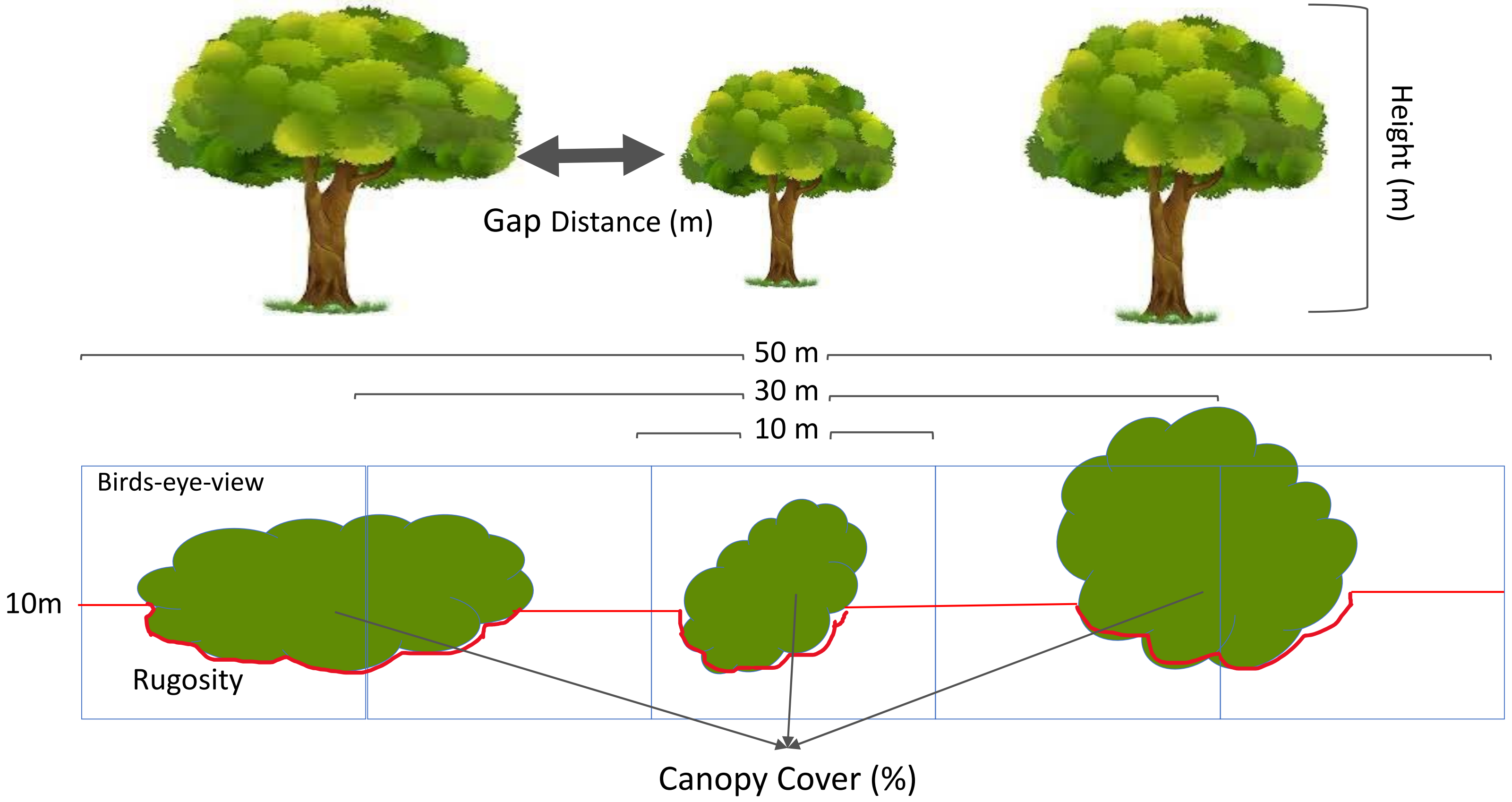


Figure 14: Image shows the five-tree metrics that were collected at distances of 10 m (i.e., the survey site), 30 m, and 50 m.

Next to calculate rugosity, and maximum and total gap distance, we used the ‘pairwise intersect’ tool to create a layer that had both the cells and the tree canopy within them (hereafter referred to as *site canopy layer*). To calculate rugosity, we adapted a method used to measure the structure of coral reefs (Bozec et al. 2015). For this, we used the site canopy layer to create a line that traced the tree canopy edge for each section. We then divided the length of each line created by the length of the corresponding section to determine a rugosity value for each section at each site. Essentially, this value represents the level of clutter the canopy creates, where 1 denotes a straight line and >1 indicates increasing clutter. For gap distance (m), we drew a series of straight lines between the tree canopies along the potential commuting route. These lines provided the shortest distance between two trees. We then selected the maximum gap distance in each section, as gap size influences whether bats can commute along tree-lines (LOEB and O'KEEFE 2006, Bennett and Zurcher 2013) and summed all the gap distances along each section to calculate total gap distance.

Lastly, we measured the height (m) of trees *in situ* along the potential commuting route using a Nikon Forestry Pro II rangefinder. For this, we used the three-point measurement method while standing 30 m away from the tree; this method calculated the tree height by marking the point on the tree directly in the line of sight of the rangefinder, then marking the top of the canopy, and finally marking the bottom of the tree. Again, we selected to use the maximum tree height recorded for each section, as bat activity has been reported to be higher at taller more mature trees (O’Mara et al. 2019).

Analysis

As a preliminary analysis to determine whether we need to conduct parametric or non-parametric statistics, we conducted a test for normalcy. This test revealed that both our dependent variables and one independent variable were not normally distributed (Tables 3-6), we therefore opted to perform non-parametric statistics in the following analysis.

Table 3: Descriptive statistics for our dependent variable: bat commuting time (secs). Grey shading indicates non-normal distribution.

Mean	11.2
Standard Error	2.3
Median	2
Mode	0
Standard Deviation	23.6
Sample Variance	558.1
Kurtosis	16.9
Skewness	3.7
Range	160.4
Minimum	0
Maximum	160.4
Sum	1198.7
Count	107
Confidence Level(95.0%)	4.5

To determine which tree characteristics, alone and in combination, influenced bat commuting activity, we first ranked sites according to their average tree metric values and compared this ranking to the average time bats spent commuting per hour for the 10 m, 30 m, and 50 m sections at each site.

Table 4: Descriptive statistics for tree metrics in 10 m sections. Abbreviations are as follows: percent canopy cover (PPC), rugosity value (RUG), maximum gap distance (MAD), total gap distance (TGD), and maximum tree height (MTH).

	MAD	**SOG**	**PCC**	**RUG**	**MTH**
Mean	3.7	3.7	26.2	0.9	8.1
Standard Error	0.4	0.4	2.6	0.1	0.6
Median	0.0	0.0	12.6	1.1	6.7
Mode	0.0	0.0	0.0	0.0	0.0
Standard Deviation	4.4	4.4	27.1	0.6	6.4
Sample Variance	19.3	19.5	731.9	0.4	41.3
Kurtosis	-1.5	-1.6	-0.8	-0.9	-0.5
Skewness	0.6	0.5	0.6	-0.3	0.5
Range	10.0	10.0	88.6	2.0	23.6
Minimum	0.0	0.0	0.0	0.0	0.0
Maximum	10.0	10.0	88.6	2.0	23.6
Sum	385.4	392.8	2747.5	98.2	845.9
Count	105.0	105.0	105.0	105.0	105.0
Confidence Level(95.0%)	0.9	0.9	5.2	0.1	1.2

Table 5: Descriptive statistics for tree metrics in 30 m sections. Abbreviations are as follows: percent canopy cover (PPC), rugosity value (RUG), maximum gap distance (MAD), total gap distance (TGD), and maximum tree height (MTH). Grey shading indicates non-normal distribution.

	MAD	**SOG**	**PCC**	**RUG**	**MTH**
Mean	9.2	9.5	31.4	1.1	9.8
Standard Error	1.2	1.2	2.4	0.1	0.7
Median	1.7	1.7	34.2	1.2	10.3
Mode	0.0	0.0	0.0	0.0	0.0
Standard Deviation	12.2	12.3	24.3	1.0	7.2
Sample Variance	149.2	152.0	589.4	0.9	52.5
Kurtosis	-0.8	-1.0	-1.4	5.0	-1.0
Skewness	1.0	0.9	0.0	1.5	0.1
Range	30.0	30.0	69.2	4.9	23.6
Minimum	0.0	0.0	0.0	0.0	0.0
Maximum	30.0	30.0	69.2	4.9	23.6
Sum	969.8	1000.1	3301.6	120.5	1027.5
Count	105.0	105.0	105.0	105.0	105.0
Confidence Level(95.0%)	2.4	2.4	4.7	0.2	1.4

Table 6: Descriptive statistics for tree metrics in 50 m sections. Abbreviations are as follows: percent canopy cover (PPC), rugosity value (RUG), maximum gap distance (MAD), total gap distance (TGD), and maximum tree height (MTH).

	MAD	**SOG**	**PCC**	**RUG**	**MTH**
Mean	16.1	15.8	35.4	1.1	11.6
Standard Error	2.0	2.0	2.5	0.1	0.7
Median	6.0	4.7	36.6	1.2	13.8
Mode	0.0	0.0	0.0	0.0	0.0
Standard Deviation	20.5	20.3	25.3	0.7	7.5
Sample Variance	419.9	412.4	642.2	0.5	56.3
Kurtosis	-1.0	-1.0	-1.4	1.1	-1.1
Skewness	0.9	0.9	-0.2	0.2	-0.3
Range	50.0	50.0	69.4	3.4	23.6
Minimum	0.0	0.0	0.0	0.0	0.0
Maximum	50.0	50.0	69.4	3.4	23.6
Sum	1690.8	1654.0	3720.9	116.5	1213.3
Count	105.0	105.0	105.0	105.0	105.0
Confidence Level(95.0%)	4.0	3.9	4.9	0.1	1.5

To establish whether any thresholds that influenced bat commuting activity within each tree metric occurred, we performed a Dunn's test to tentatively identify groups of sites in which levels of commuting activity were similar. Depending on the number of groups, we then used Kruskal-Wallis test or Mann-Whitney-Wilcoxon test in R (Version 2023.06.2+561, Posit Software, Vienna, Austria) to verify if these groups were significantly different from each other.

Finally, we conducted a series of Classification and Regression Tree (CART) analyses using Salford Predictive Modeler's CART ® (version 19, State College, PA) in Minitab. The CART analysis was useful in discerning important thresholds (Bennett and Agpalo 2022) within each tree metric by stratifying the frequency of bat commuting activity (continuous dependent variable) under different combinations of tree metrics. This method identifies what metrics in combination influenced commuting.

For this, our dependent variable (total time spent commuting per hour [TTC]) and all independent predictors (percent canopy cover [PCC], canopy rugosity [RUG], maximum gap distance [MAD], total gap distance [TGD], and maximum tree height [MTH]), were treated as continuous. Mean Squared Error (MSE) and r^2 values were used to optimally prune the tree as part of a 10-fold cross validation. For this CART analysis, we generated three stratified model regression trees for bat commuting activity; one for each section.

RESULTS

We conducted surveys from 1 June 2022 to 28 September 2022 and 6 March 2023 to 24 May 2023 for a total of 56 survey nights. During these surveys, we observed bats at 27 of the 30 sites, totaling 1,262 recorded occurrences of bat activity. Bats were present in the field of view on average 20.5 ± 88.6 SD sec per site per night (ranging from 1 to 857 sec). We identified bats to be foraging on 154 occasions at 14 of the 30 sites on 19 survey nights, which averaged 4.4 sec

± 26.1 SD per site per night (ranging from 1 to 244 sec). By subtracting the foraging activity from total time bats were present, we determined bats to be commuting on 1,108 occasions, which averaged 16.1 sec ± 62.7 SD per site per night (ranging from 0 to 613 sec). In the acoustic surveys, we recorded a total of 3,023 bat calls at 29 of the 30 sites, averaging 33.6 ± 38.8 SD per site per night (ranging from 0 to 171).

From the acoustic surveys, we identified 279 commuting calls, 2157 searching calls, 319 foraging calls, and 250 feeding buzzes. Furthermore, the number of commuting calls ranged from 0 to 21 per hour, with an average of 2.7 ± 4.3 per hour across all survey sites. The number of searching calls ranged from 0 to 128 per hour, with an average of 20.5 ± 27.4 per hour across all survey sites. The number of foraging calls ranged from 0 to 62 per hour, with an average of 3.1 ± 6.3 per hour across all survey sites. The number of feeding buzzes ranged from 0 to 33 per hour, with an average of 2.4 ± 5.6 per hour across all survey sites. We grouped commuting and searching calls into commuting activity since it is distinct from foraging activity which included foraging calls and feeding buzzes. Six bat species were identified at the survey sites, including evening (n=2155 of 3023), eastern red (n=386), Mexican Freetail (n=15), silver-haired (n=339), hoary (n=88), and tricolor (n=40; Fig. 15). All six species were identified at four sites.

For the average and range of values for the five tree metrics collected for each 10, 30, and 50 m sections refer to Table 7.

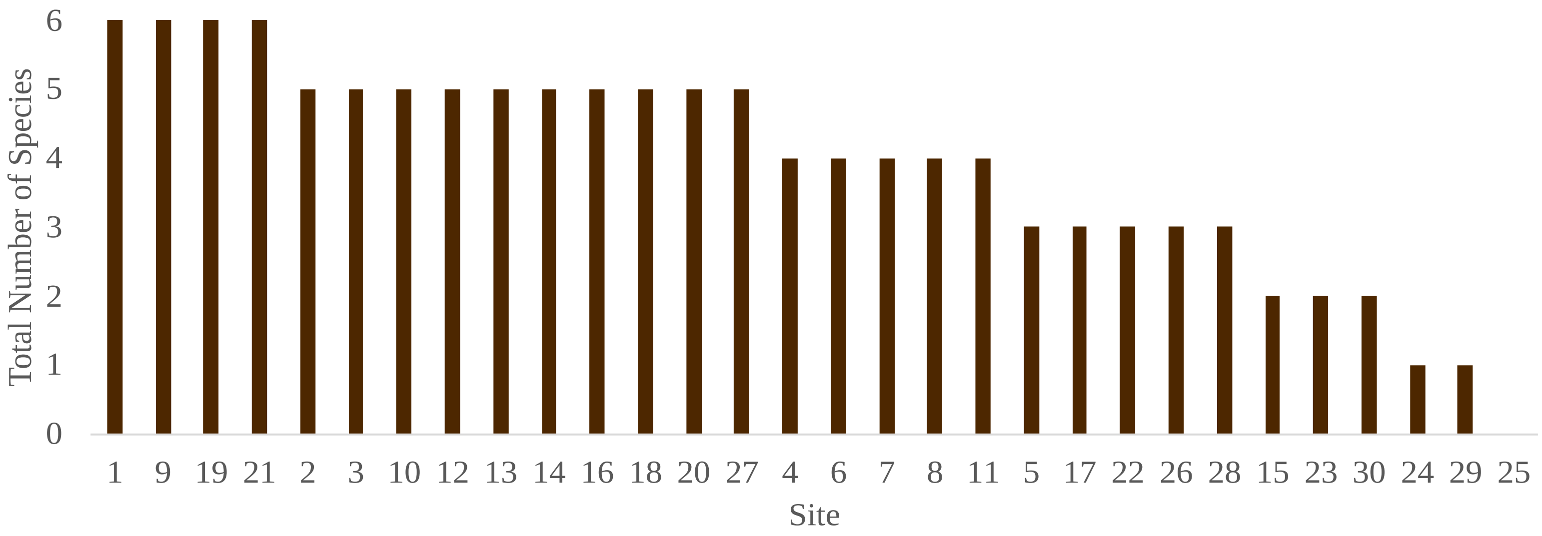


Figure 15. Total number of bat species observed at each site in behavioral observation surveys at potential movement corridors in Tarrant County, Texas from June to September 2022 and March to May 2023. Note that our thirty survey sites are ranked by the total number of bat species observed from highest to lowest.

Table 7: Summary of five tree metrics recorded along 10 m, 30 m, and 50 m sections of potential movement corridors surveyed for bat commuting activity in Tarrant County, Texas recorded from June to September 2022 and March to May 2023.

		Section		
		10	*30*	*50*
Percent canopy cover (%)	*Average*	26.81	31.85	35.8
	Std Dev	27.64	24.61	25.76
	Range	0-90	0-69	0-70
Rugosity	*Average*	0.93	1.17	1.12
	Std Dev	0.64	1.02	0.77
	Range	0-2	0-5	0-3
Maximum gap distance (m)	*Average*	3.61	9.95	16.1
	Std Dev	4.45	12.79	20.82
	Range	0-10	0-30	0-50
Total gap distance (m)	*Average*	3.68	10.31	17.21
	Std Dev	4.48	12.9	21.24
	Range	0-8	0-30	0-50
Maximum tree height (m)	*Average*	8.13	9.84	9.84
	Std Dev	6.64	7.36	7.36
	Range	0-24	0-24	0-24

All five tree metrics were found to influence bat commuting activity, but this depended on the length of the section along the potential commuting route being considered. We found that percent canopy cover influenced bat commuting activity at the 10, 30, and 50 m sections (Appendix B Table B1). For canopy cover in the 10 m section, we identified three separate groups; Group 1 included all sites with 0% canopy cover, Group 2 included sites with canopy cover >0% up to 16%, and Group 3 had sites with >16% cover. Sites within Group 2 had significantly more bats recorded than the other two groups (Fig. 16; Groups 1 and 2: W=256, P<0.01; Groups 1 and 3: W=625, P=0.711, Groups 2 and 3: W=883, P=0.057).

For the 30 m section, we also identified three groups; group 1 included all sites with <9.4% canopy cover, group 2 contained sites with 9.4 to 42.6% canopy cover, and group 3 had sites with >42.6% canopy cover (Fig. 17). Group 2 had significantly higher bat commuting activity compared to the other two groups (Groups 1 and 2: W=329.5, P<0.01; Groups 1 and 3: W=551.5, P=0.64, Groups 2 and 3: W=1249.5, P=0.022).

In the 50 m section, we identified 4 distinct groups; sites with 0% cover comprised group 1, group 2 with >0% to 50.7% canopy cover, group 3 with >50.7% to 62.4% canopy cover, and group 4 with canopy cover >62.4% (Fig. 18). Sites within Group 3 had significantly higher bat activity than the other three groups (Groups 1 and 2: W=536, P=0.92; Groups 1 and 3: W=305, P<0.01, Groups 1 and 4: W=479, P=0.81; Groups 2 and 3 W=165, P=<0.01; Groups 2 and 4: W=479, P=0.81, Groups 3 and 4: W=262.5, P<0.01).

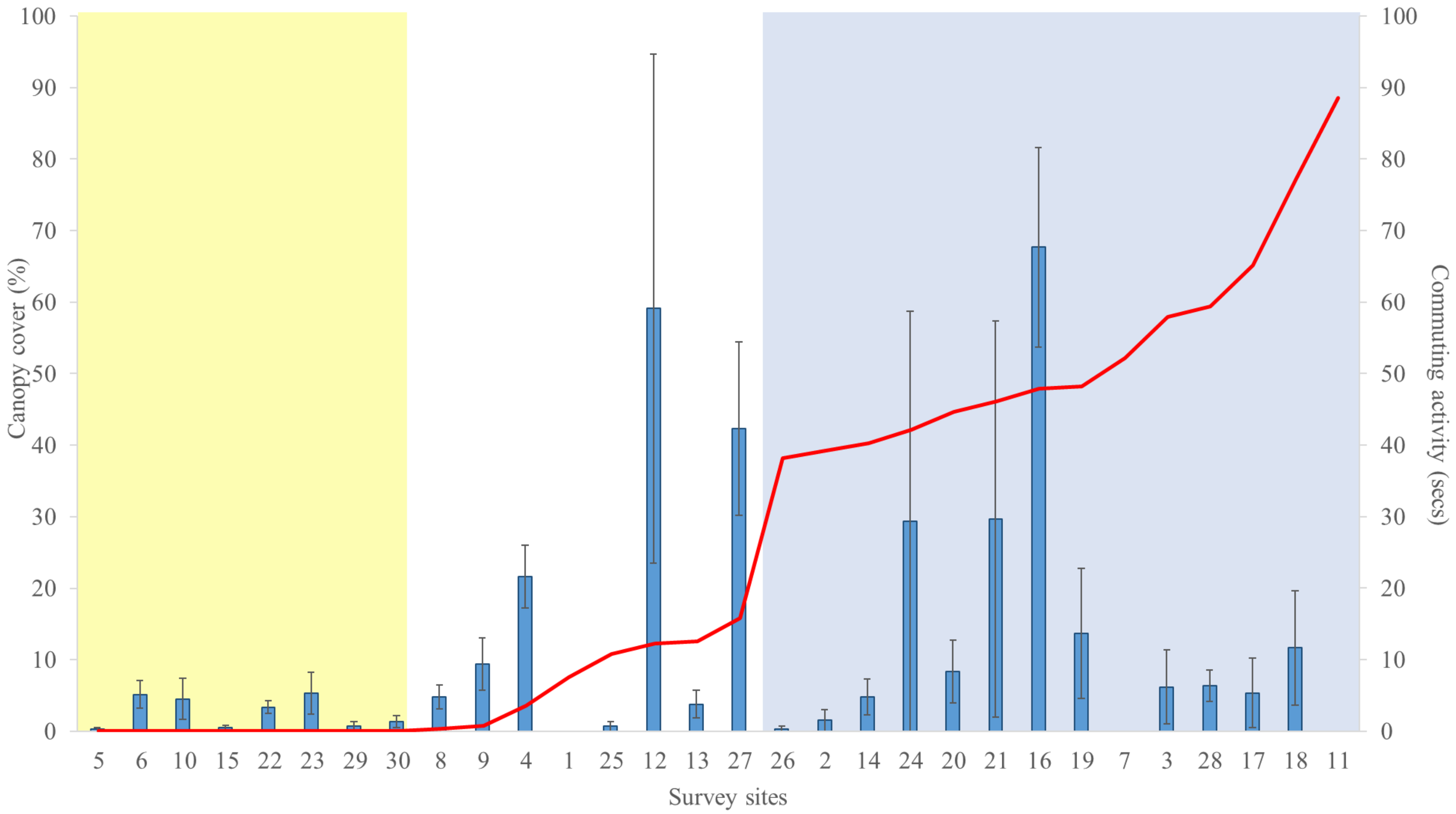


Figure 16: Average bat commuting activity per site (bars with ±SE) recorded in behavioral observation surveys at potential movement corridors with percent canopy cover (lines) measured along the 10 m section of the commuting route. Sites highlighted in yellow represent Group 1 (0% canopy cover), sites in white show Group 2 (0%-16%), and sites shaded in blue represent Group 3 (>16%).

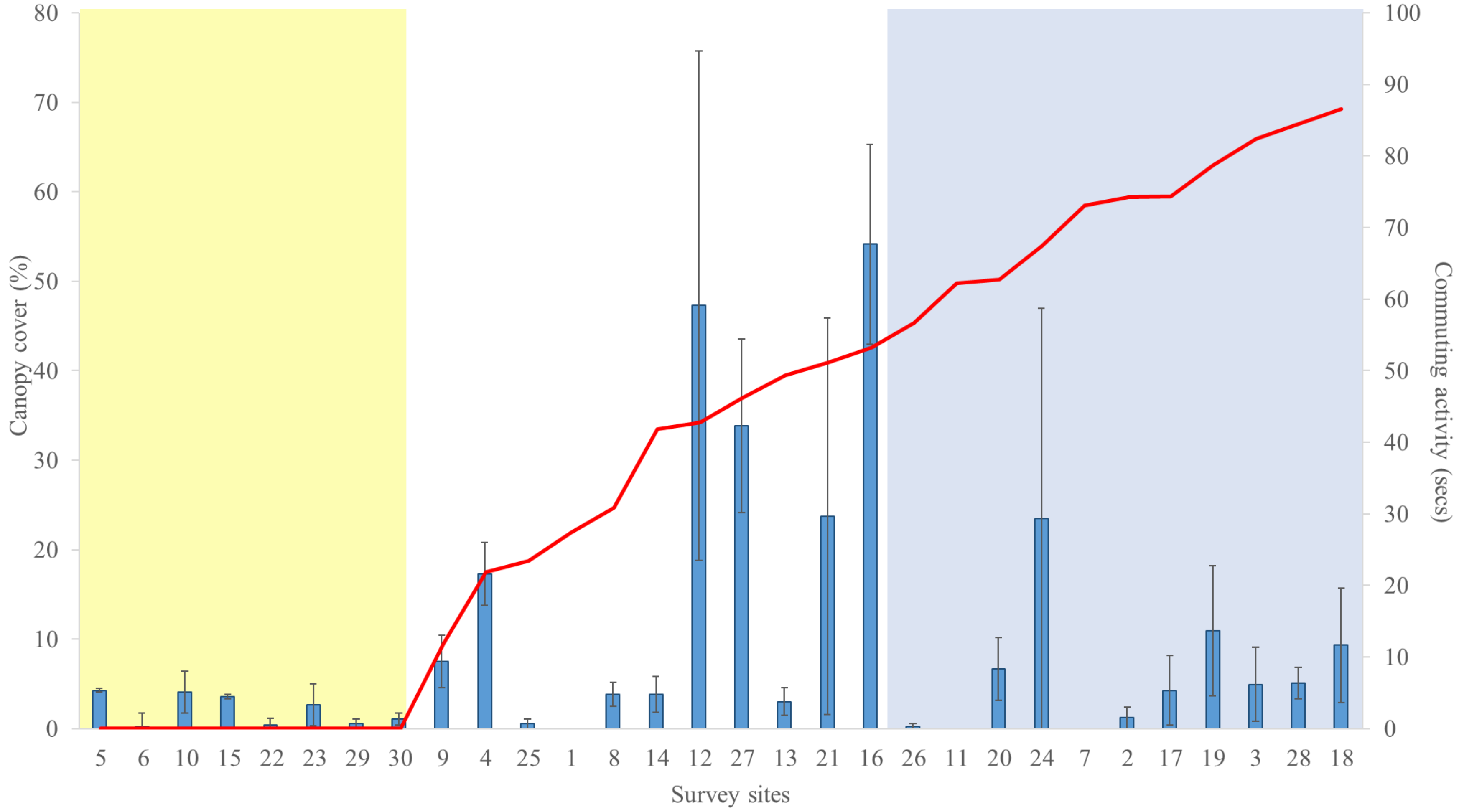


Figure 17: Average bat commuting activity per site (bars with ±SE) recorded in behavioral observation surveys at potential movement corridors with percent canopy cover (lines) measured along the 30 m section of the commuting route. Sites highlighted in yellow represent Group 1 (<9.4% canopy cover), sites in white show Group 2 (9.4%-42.6%), and sites shaded in blue represent Group 3 (>42.6%).

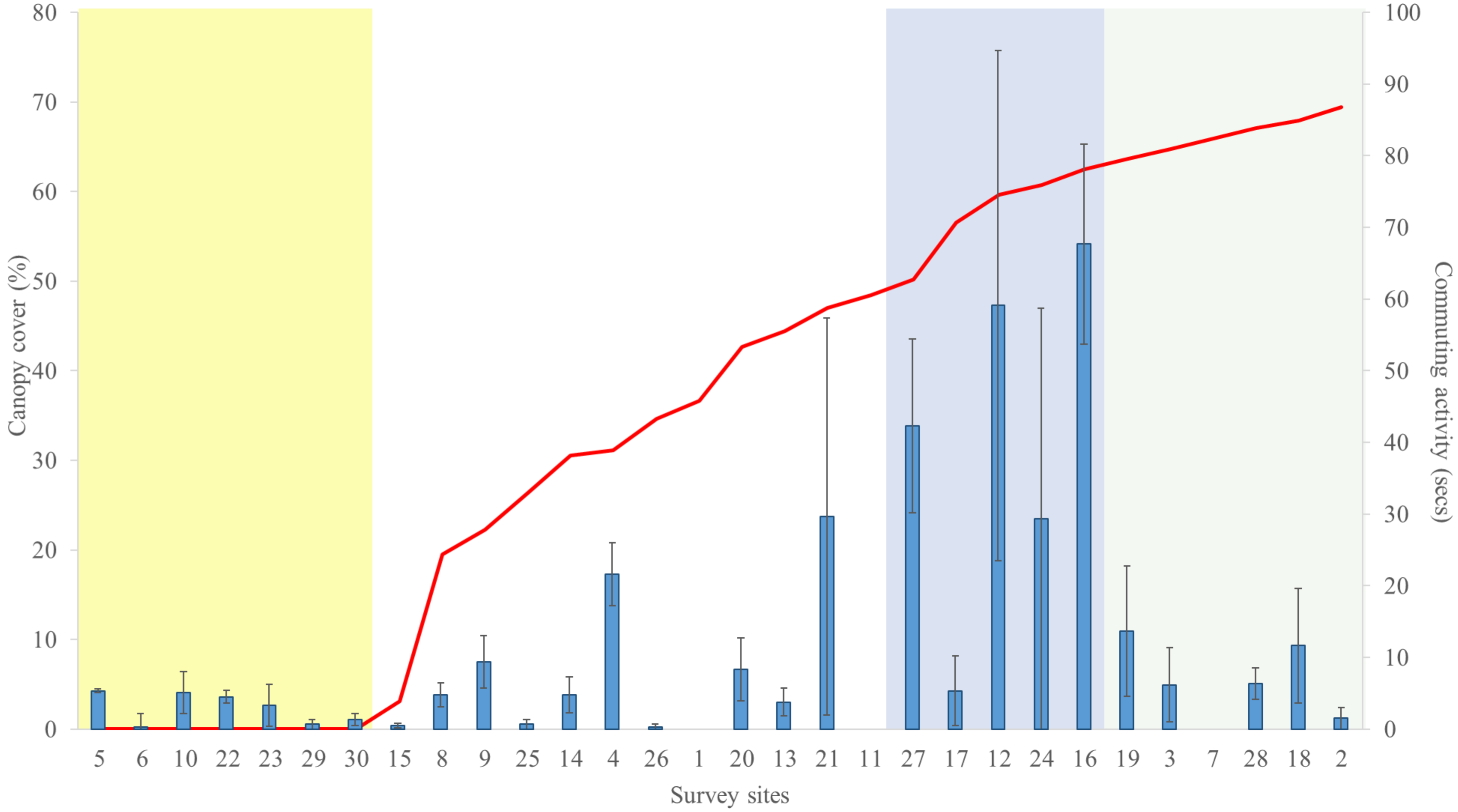


Figure 18: Average bat commuting activity per site (bars with ±SE) recorded in behavioral observation surveys at potential movement corridors with percent canopy cover (lines) measured along the 50 m section of the commuting route. Sites highlighted in yellow represent Group 1 (0% canopy cover), sites in white show Group 2 (0%-50.7%), sites shaded in blue represent Group 3 (>50.7%-62.4%), and sites shaded in green represent Group 4 (>62.4%).

We found that rugosity influenced bat commuting activity in all three sections of the commuting route examined (Appendix B Table B1). The groups identified in the 10 m section were as follows: Group 1 included all sites with a rugosity value less than one, Group 2 had sites with values between 1 and 1.1, and Group 3 included sites with a rugosity greater than 1.1 (Fig. 19). We found that the most bat commuting activity occurred at sites with a rugosity value between 1 and 1.1 (Groups 1 and 2: W=337.5, *P*=0.010; Groups 1 and 3: *W*=543.5, *P*=0.98, Groups 2 and 3: *W*=955.5, *P*=0.025).

In the 30 m section, we divided sites into the following three groups based on rugosity: Group 1 which included sites with a rugosity value less than 1, Group 2 with sites between 1 and 1.3, and Group 3 which was sites with a rugosity value >1.3 (Fig. 20). Unlike the 10 m section, we found that there was significantly more bat commuting activity at sites with a rugosity greater than 1.3 (Groups 1 and 2: W=485.5, *P*=0.95; Groups 1 and 3: *W*=395.5, *P*=0.019, Groups 2 and 3: *W*=545.5, *P*=0.047).

Again, we found 3 distinct groups of sites at the 50 m section; Group 1 with sites with rugosity values less than 1, Group 2 with values between 1 and 1.4, and Group 3 with sites that had rugosity values greater than 1.4 (Fig. 21). Just as in the 30 m section, we found significantly more bats at sites in Group 3, which were sites with rugosity values greater than 1.4 (Groups 1 and 2: *W*=630, *P*=0.72; Groups 1 and 3: W=224, *P*=0.011, Groups 2 and 3: W=488, *P*=<0.01).

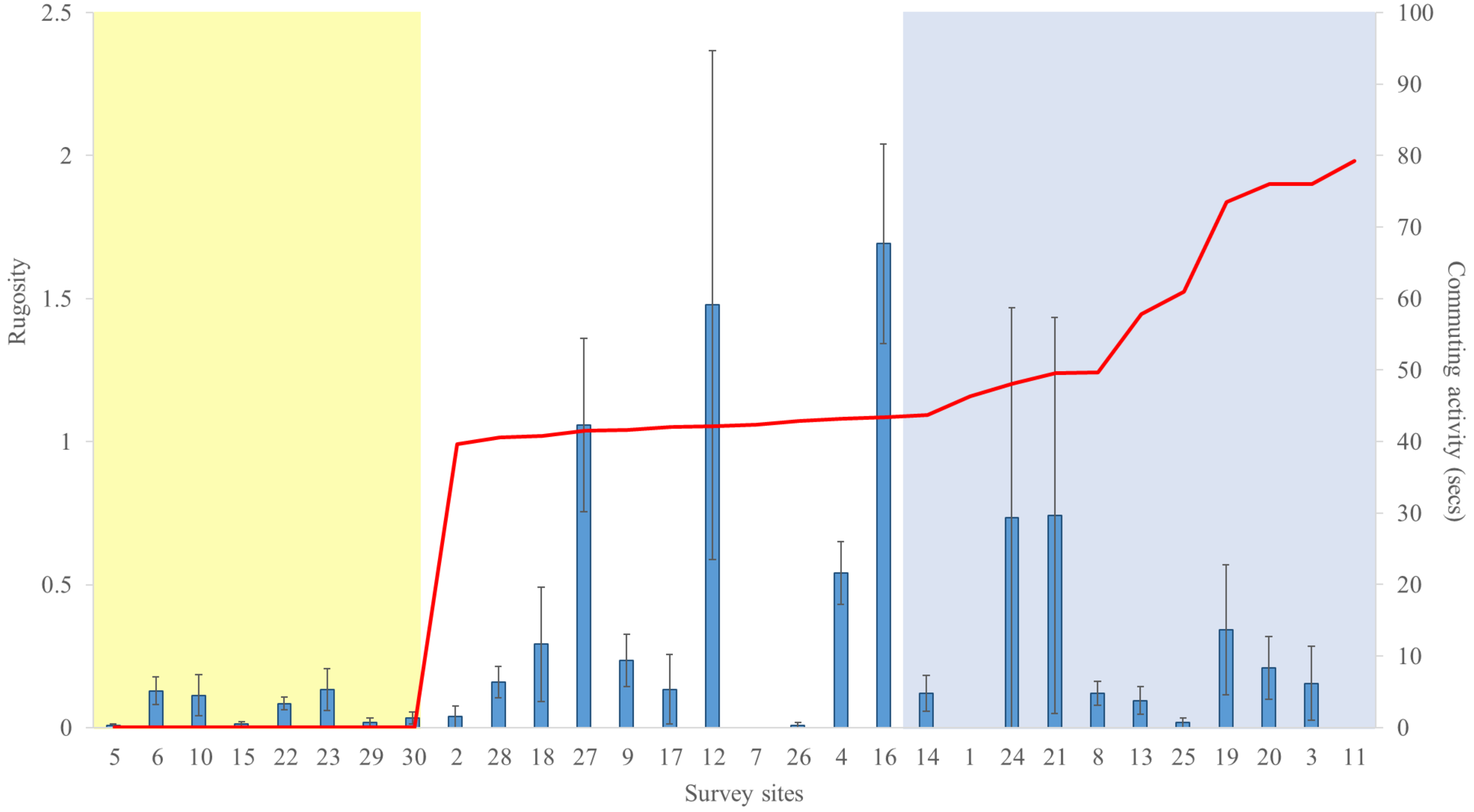


Figure 19: Average bat commuting activity per site (bars with ±SE) recorded in behavioral observation surveys at potential movement corridors with rugosity (lines) measured along the 10 m section of the commuting route. Sites highlighted in yellow represent Group 1 (rugosity value <1), sites in white show Group 2 (1-1.1), and sites shaded in blue represent Group 3 (>1.1).

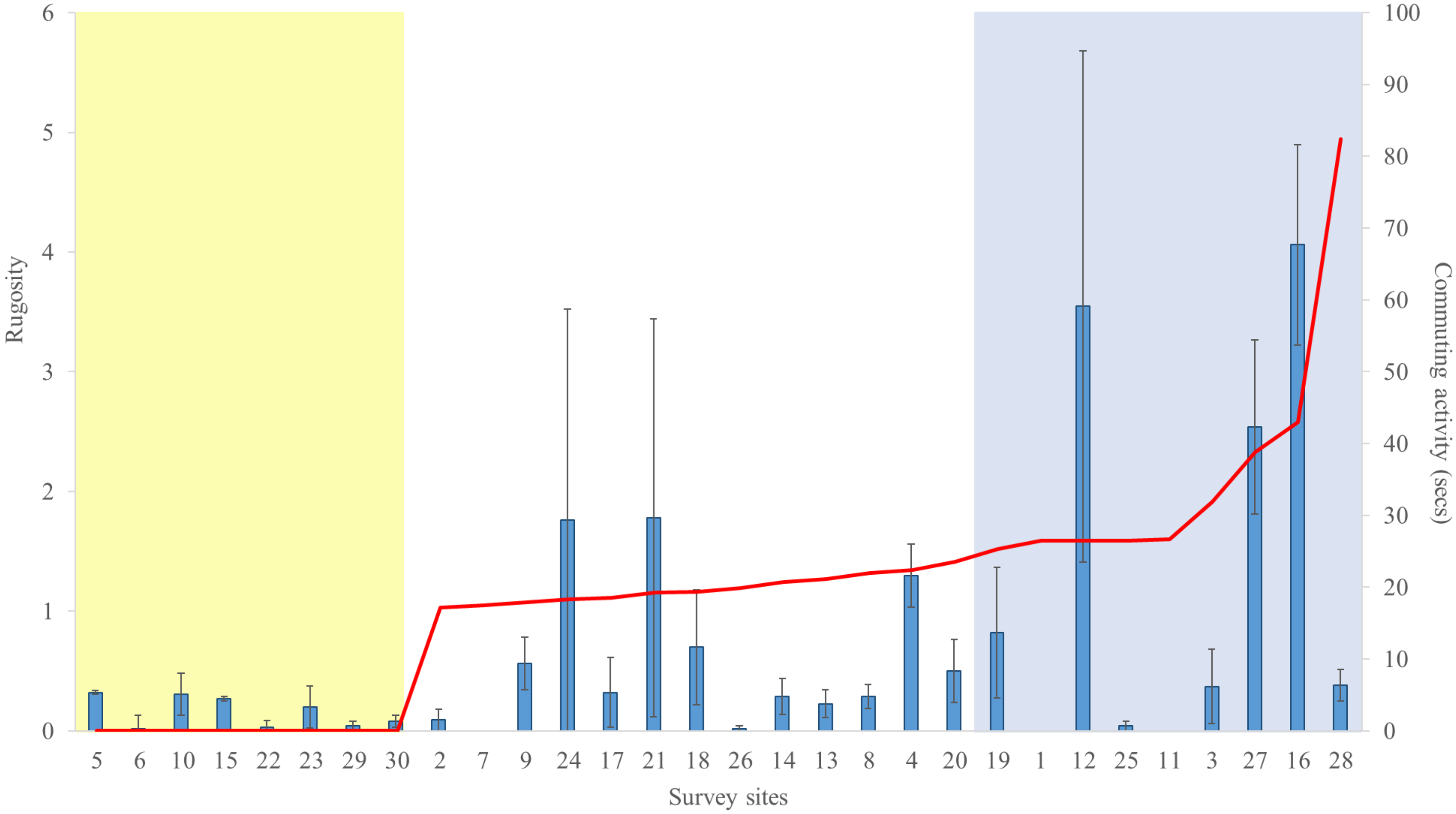


Figure 20: Average bat commuting activity per site (bars with ±SE) recorded in behavioral observation surveys at potential movement corridors with rugosity (lines) measured along the 30 m section of the commuting route. Sites highlighted in yellow represent Group 1 (rugosity value <1), sites in white show Group 2 (1-1.3), and sites shaded in blue represent Group 3 (>1.3).

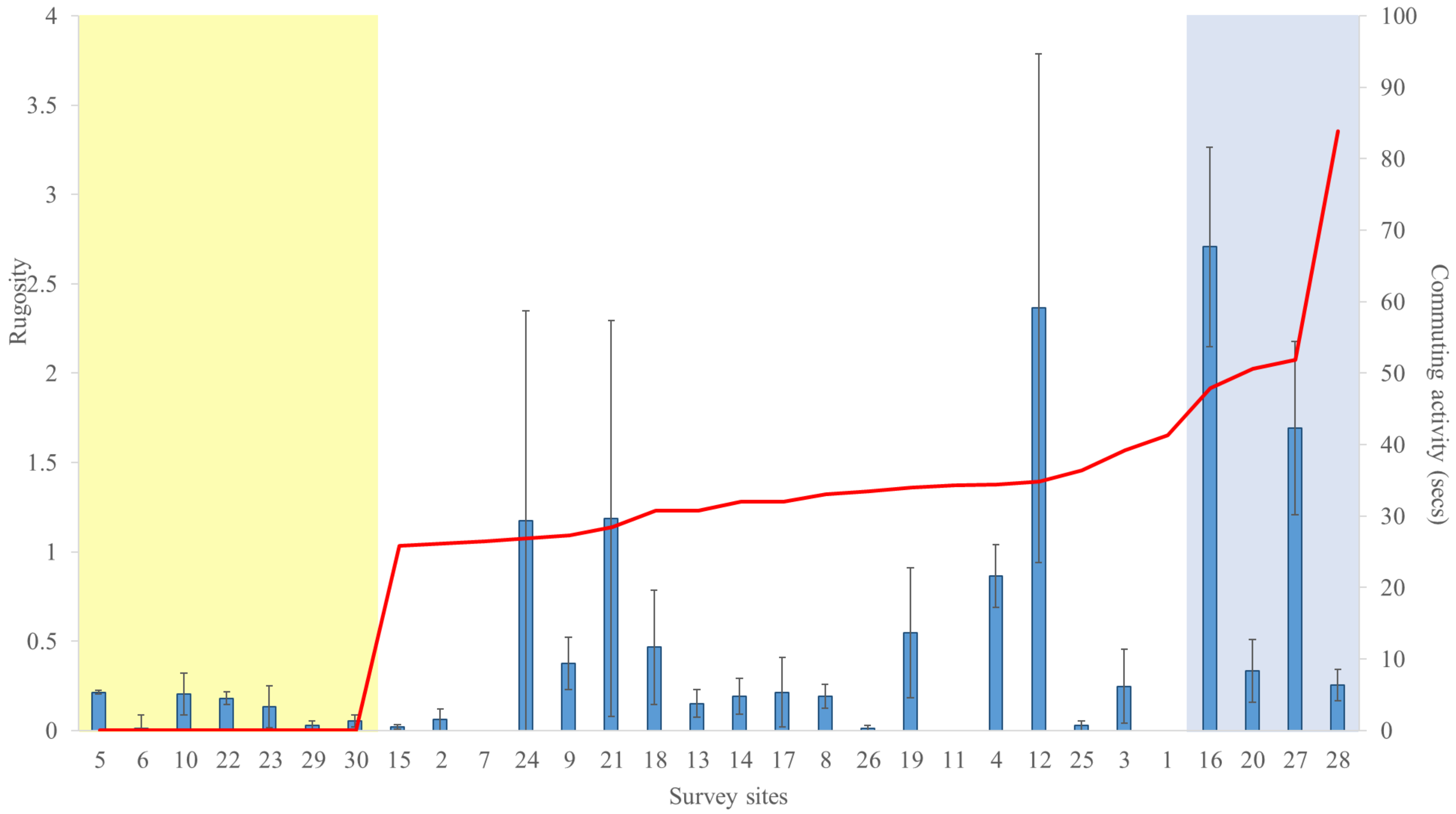


Figure 21: Average bat commuting activity per site (bars with ±SE) recorded in behavioral observation surveys at potential movement corridors with rugosity (lines) measured along the 50 m section of the commuting route. Sites highlighted in yellow represent Group 1 (rugosity value <1), sites in white show Group 2 (1-1.4), and sites shaded in blue represent Group 3 (>1.4).

For maximum gap distance, we found that this metric did not have a significant effect on bat commuting activity at the 10 m section (Fig. 22), but it did have a significant effect on bat commuting activity at the 30 and 50 m sections (Appendix B Table B1). For the 30 m section, we found a significant difference between the two groups; Group 1 containing sites with no gaps had a significantly higher number of bats than Group 2 containing all the sites with gaps in the canopy (Fig. 23; *W*=785, *P*=<0.01). Similarly for the 50 m section, we divided sites into two groups; Group 2 containing sites with gaps and Group 1 containing sites with no gaps. We found significantly more bats in Group 2 compared to Group 1 (Fig. 24; *W*=1084, *P*=0.01).

Similar to maximum gap distance, total gap distance did not have a significant effect on bat commuting activity in the 10 m section (Fig. 25), but this metric was significant at the 30 and 50 m sections (Appendix B Table B1). For the 30 m section, we found that there was a significant difference between two groups; Group 1 with no gaps in the canopy had more commuting activity recorded than Group 2 with gaps in the canopy (Fig. 26; *W*=785, *P*=<0.01). Similarly for the 50 m section, we divided sites into two groups; Group 2 containing sites with gaps and Group 1 containing sites with no gaps. We found significantly more bats in Group 2 compared to Group 1 (Fig. 27; *W*=1084, *P*=0.01).

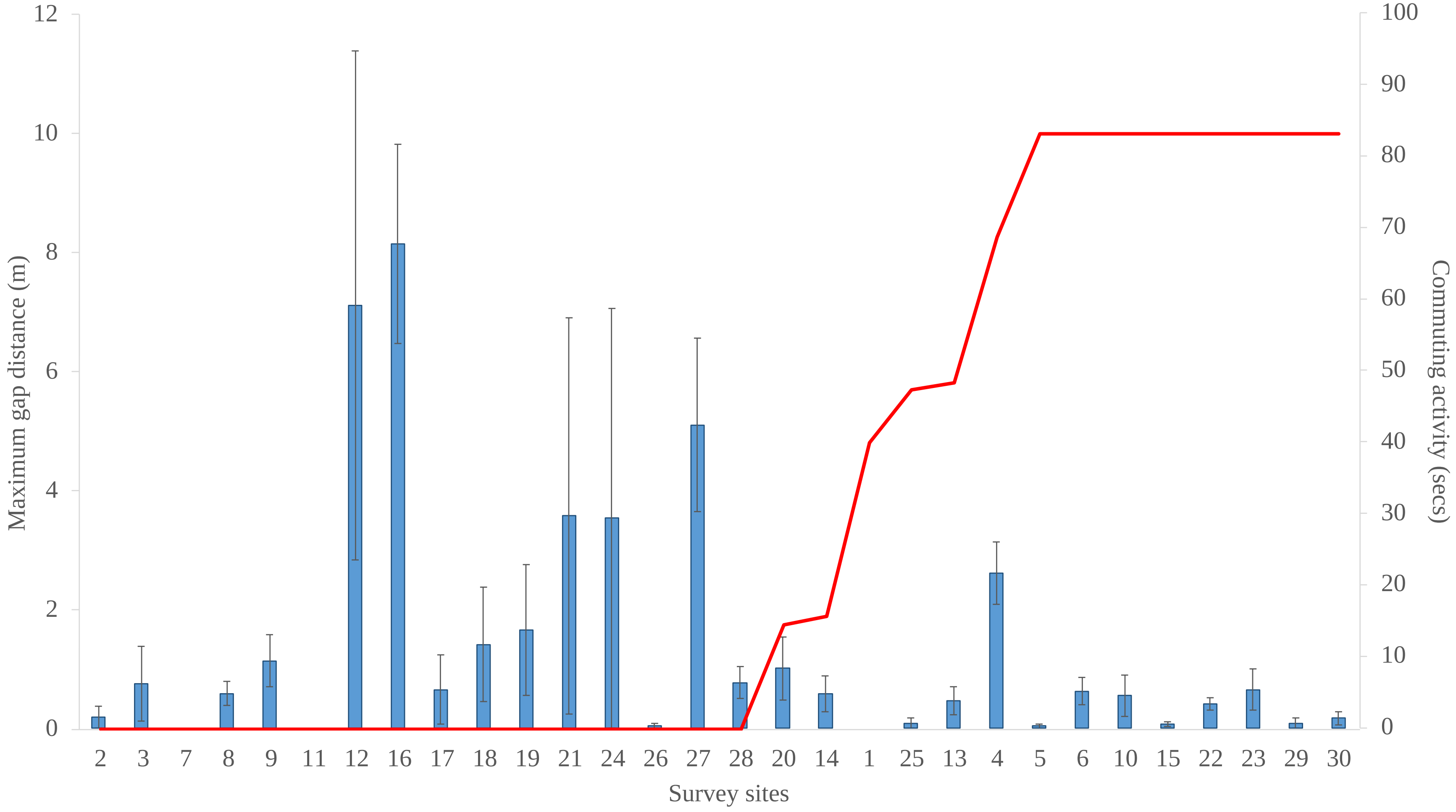


Figure 22: Average bat commuting activity per site (bars with ±SE) recorded in behavioral observation surveys at potential movement corridors with maximum gap distance (lines) measured along the 10 m section of the potential commuting route.

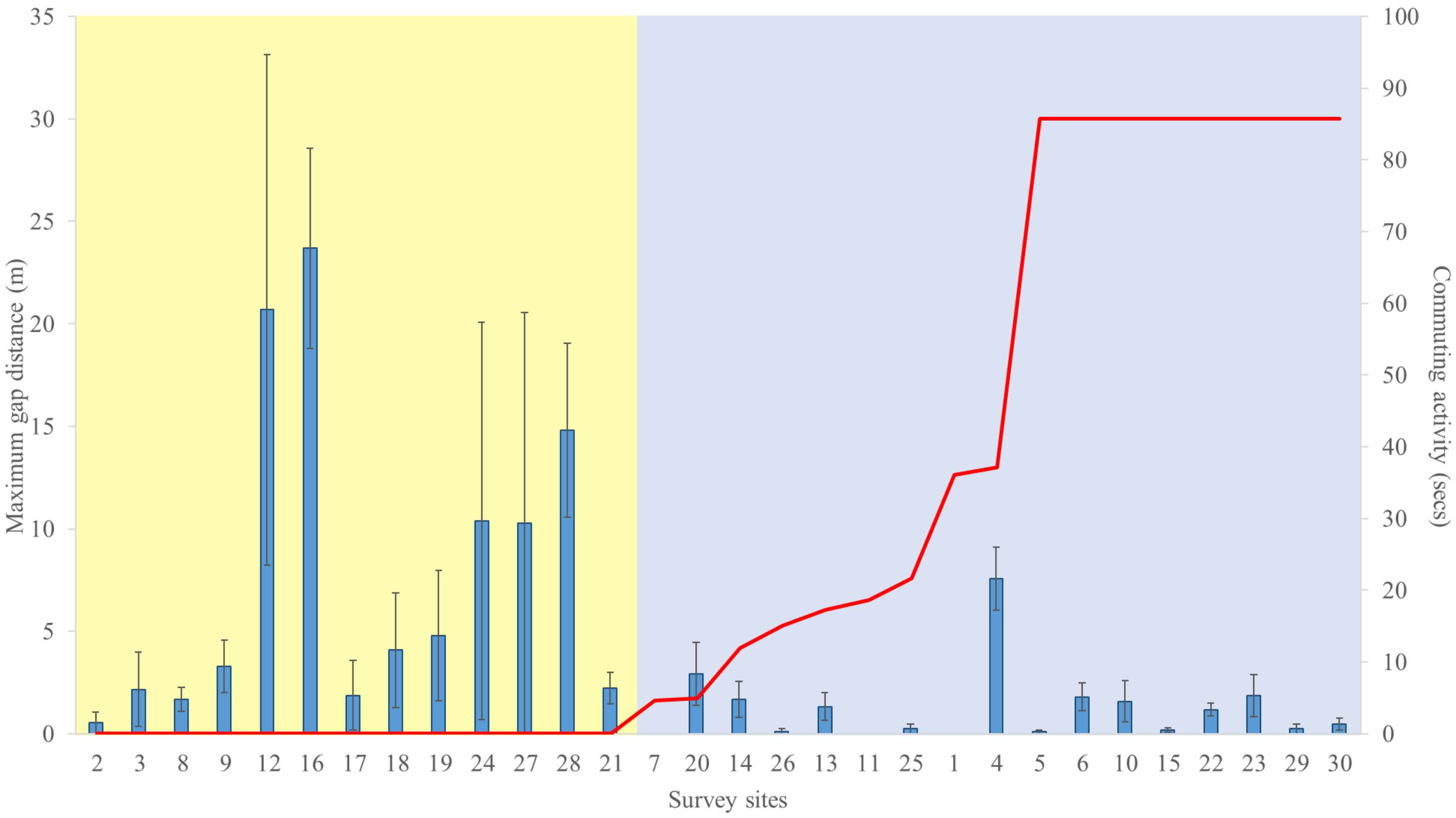


Figure 23: Average bat commuting activity per site (bars with ±SE) recorded in behavioral observation surveys at potential movement corridors with maximum gap distance (lines) measured along the 30 m section of the potential commuting route. Sites highlighted in yellow represent Group 1 and sites highlighted in blue represent Group 2.

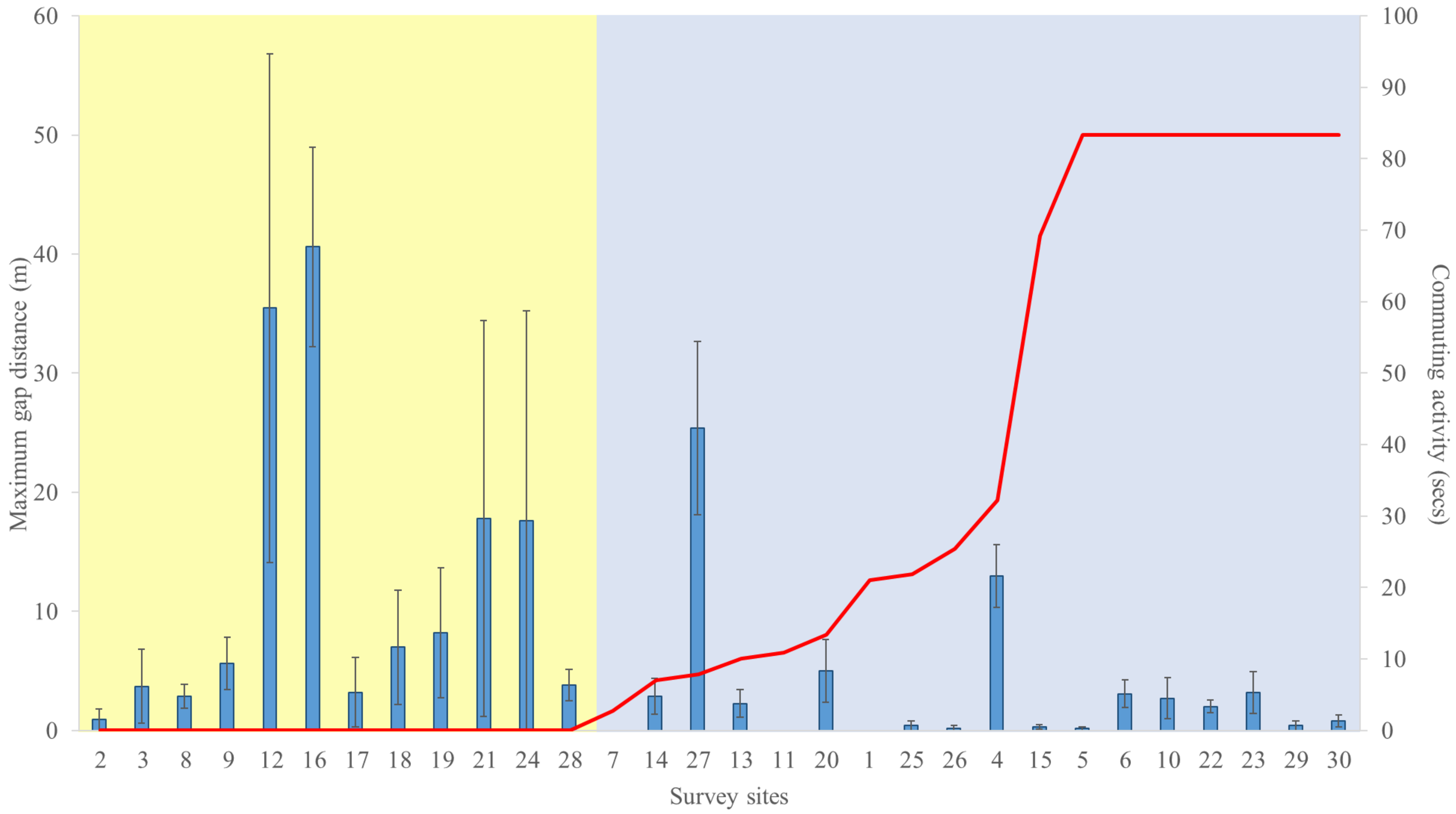


Figure 24: Average bat commuting activity per site (bars with ±SE) recorded in behavioral observation surveys at potential movement corridors with maximum gap distance (lines) measured along the 50 m section of the potential commuting route. Sites highlighted in yellow represent Group 1 and sites highlighted in blue represent Group 2.

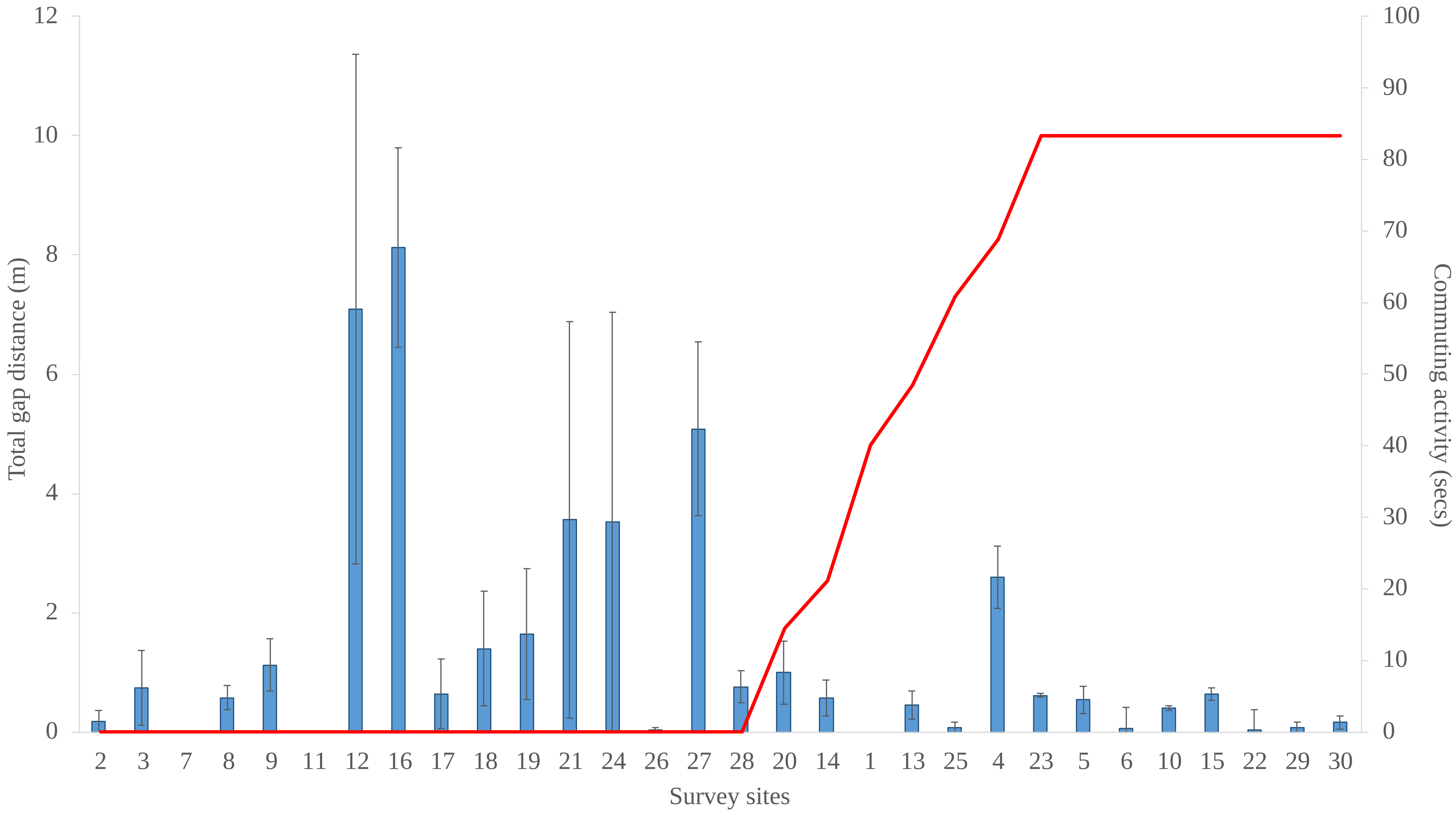


Figure 25: Average bat commuting activity per site (bars with ±SE) recorded in behavioral observation surveys at potential movement corridors with total gap distance (lines) measured along the 10 m section of the potential commuting route.

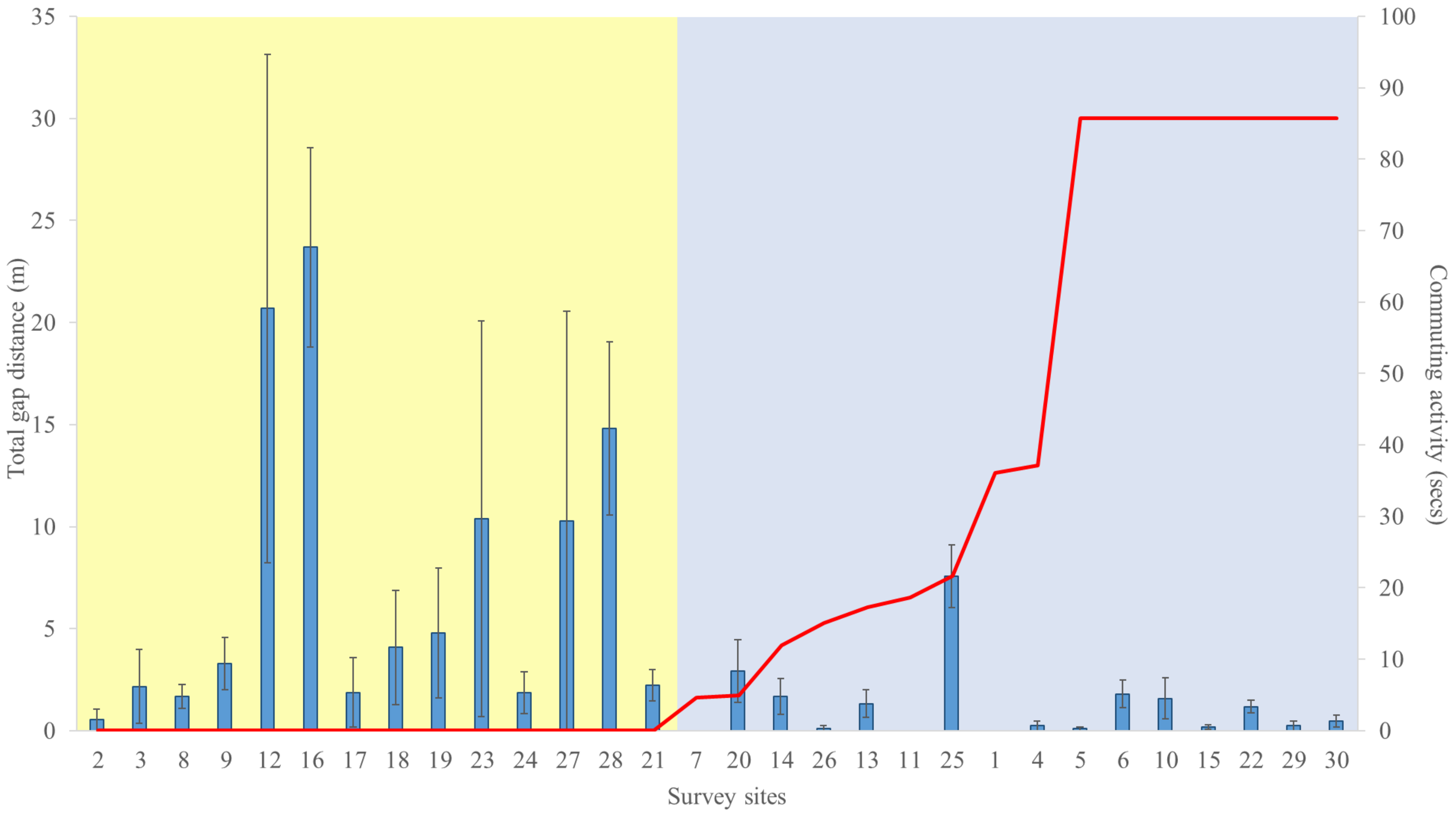


Figure 26: Average bat commuting activity per site (bars with ±SE) recorded in behavioral observation surveys at potential movement corridors with total gap distance (lines) measured along the 30 m section of the potential commuting route. Sites highlighted in yellow represent Group 1 and sites highlighted in blue represent Group 2.

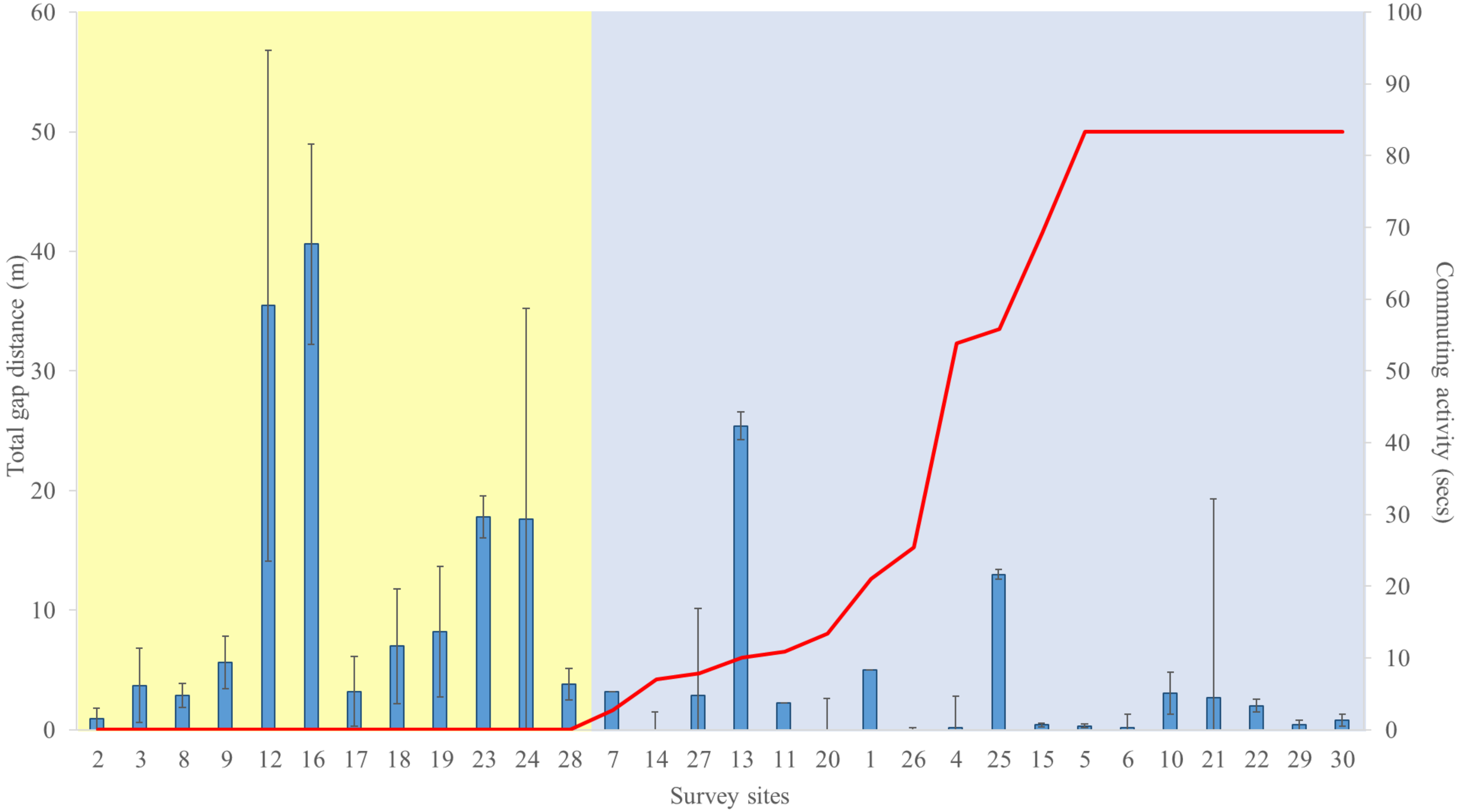


Figure 27: Average bat commuting activity per site (bars with ±SE) recorded in behavioral observation surveys at potential movement corridors with total gap distance (lines) measured along the 50 m section of the potential commuting route. Sites highlighted in yellow represent Group 1 and sites highlighted in blue represent Group 2.

Finally, for maximum tree height we found that bat commuting activity was significantly different among sites within the 30 and 50 m sections (Fig. 28; Appendix B Table B1). More specifically, for the 30 m section we determined there to be three distinct groups; Group 1 had sites with no trees, Group 2 had sites with maximum tree height between 2.9 m and 11.6 m, and Group 3 with values >11.6 m (Fig. 29). We identified significantly more bats at sites in Group 3 with a maximum tree height greater than 11.6 m (Groups 1 and 2: W=446, P=0.63; Groups 1 and 3: W=320, P=0.018, Groups 2 and 3: W=619.5, P=0.052). Three groups were identified in the 50 m section for maximum tree height; sites with heights less than 3.4 m were in Group 1, sites with heights between 3.4 and 11.6 were in Group 2, and sites with heights greater than 11.6 m were in group 3 (Fig. 30). Sites with tree height greater than 11.6 m had significantly more bat commuting activity (Groups 1 and 2: W=310, P=0).

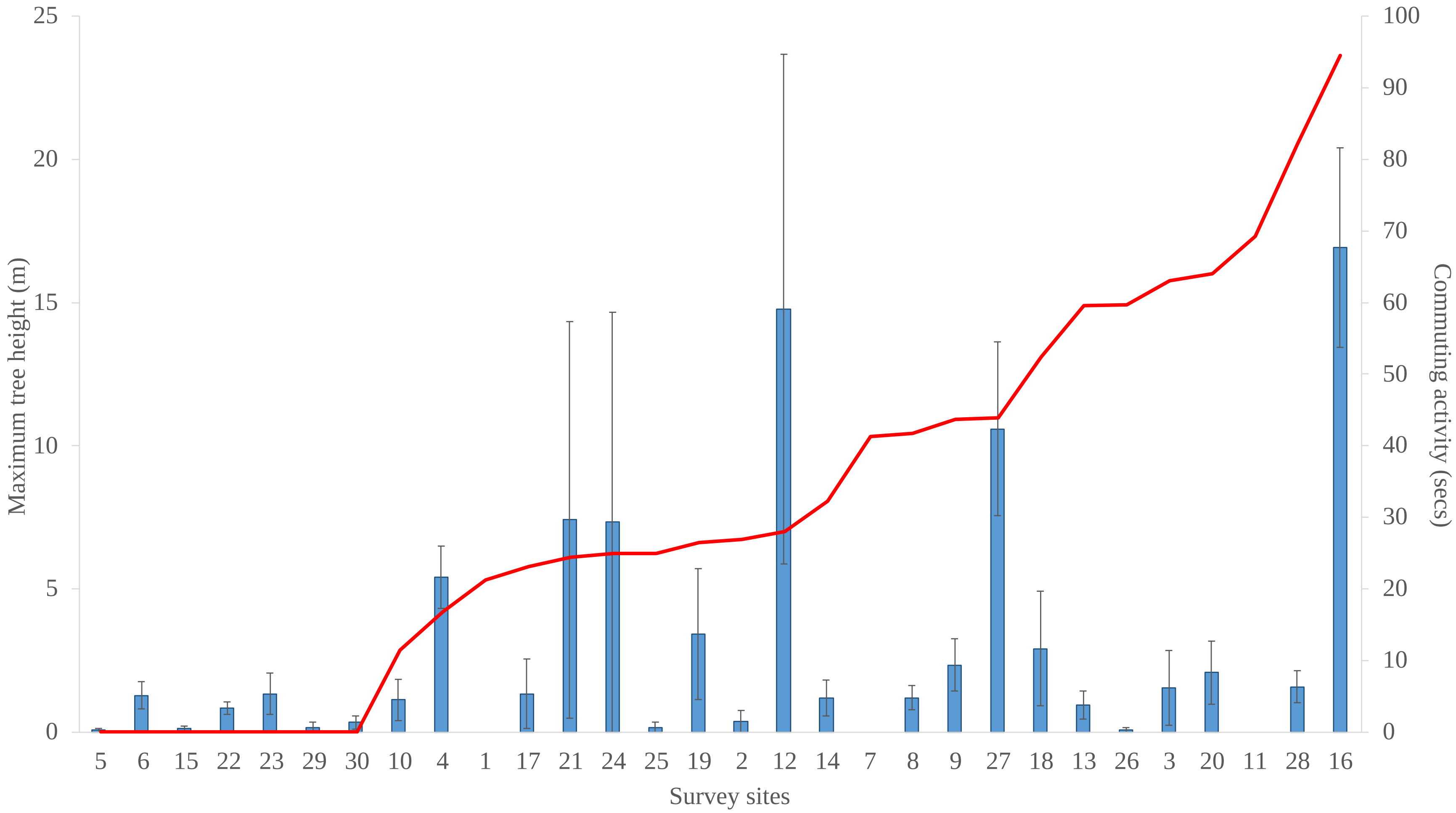


Figure 28: Average bat commuting activity per site (bars with ±SE) recorded in behavioral observation surveys at potential movement corridors with maximum tree height (lines) measured along the 10 m section of the potential commuting route.

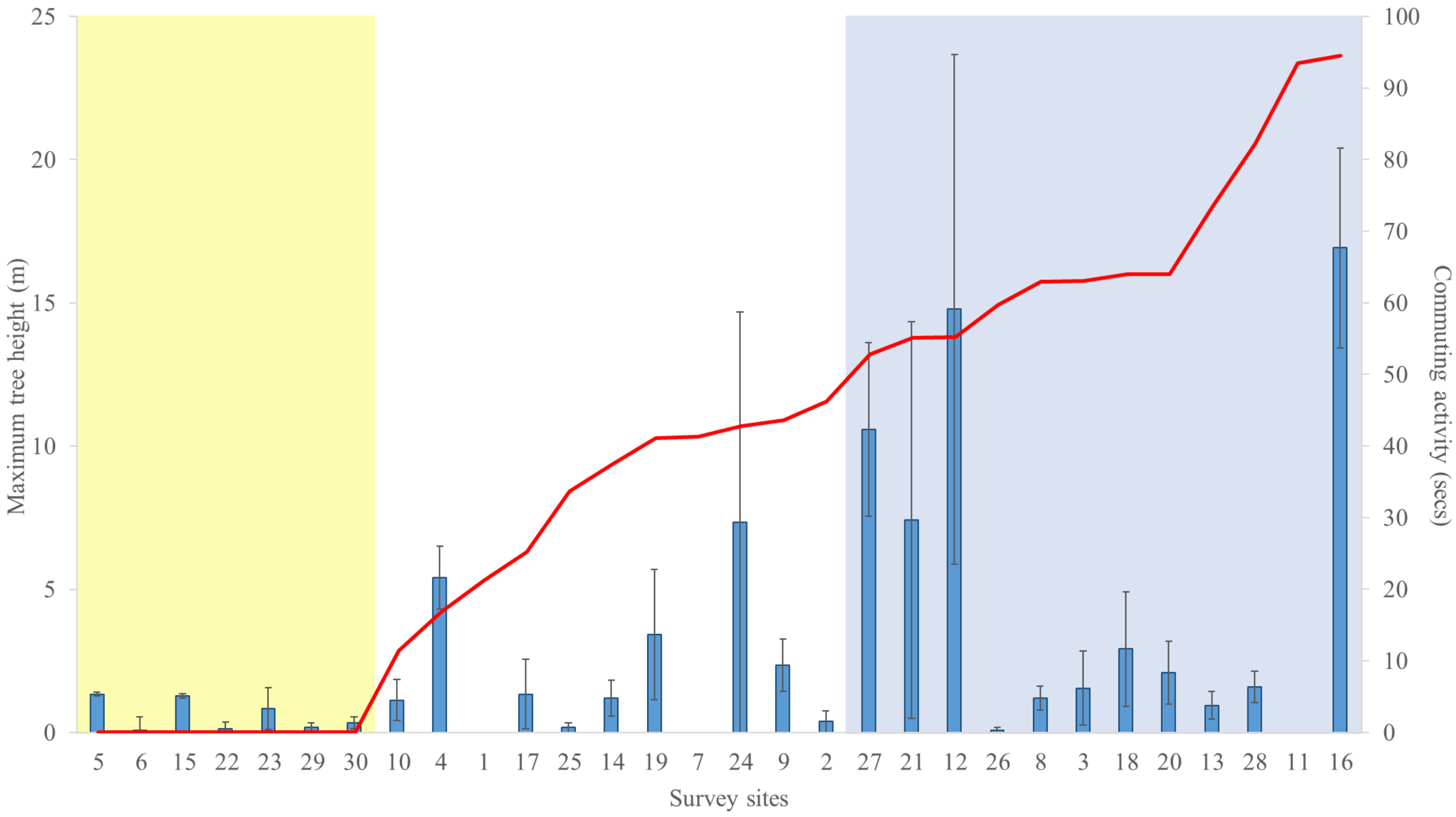


Figure 29: Average bat commuting activity per site (bars with ±SE) recorded in behavioral observation surveys at potential movement corridors with maximum tree height (lines) measured along the 30 m section of the potential commuting route. Sites highlighted in yellow represent Group 1 (tree height =0m), sites in white show Group 2 (2.9-11.6 m), and sites shaded in blue represent Group 3 (>11.6 m).

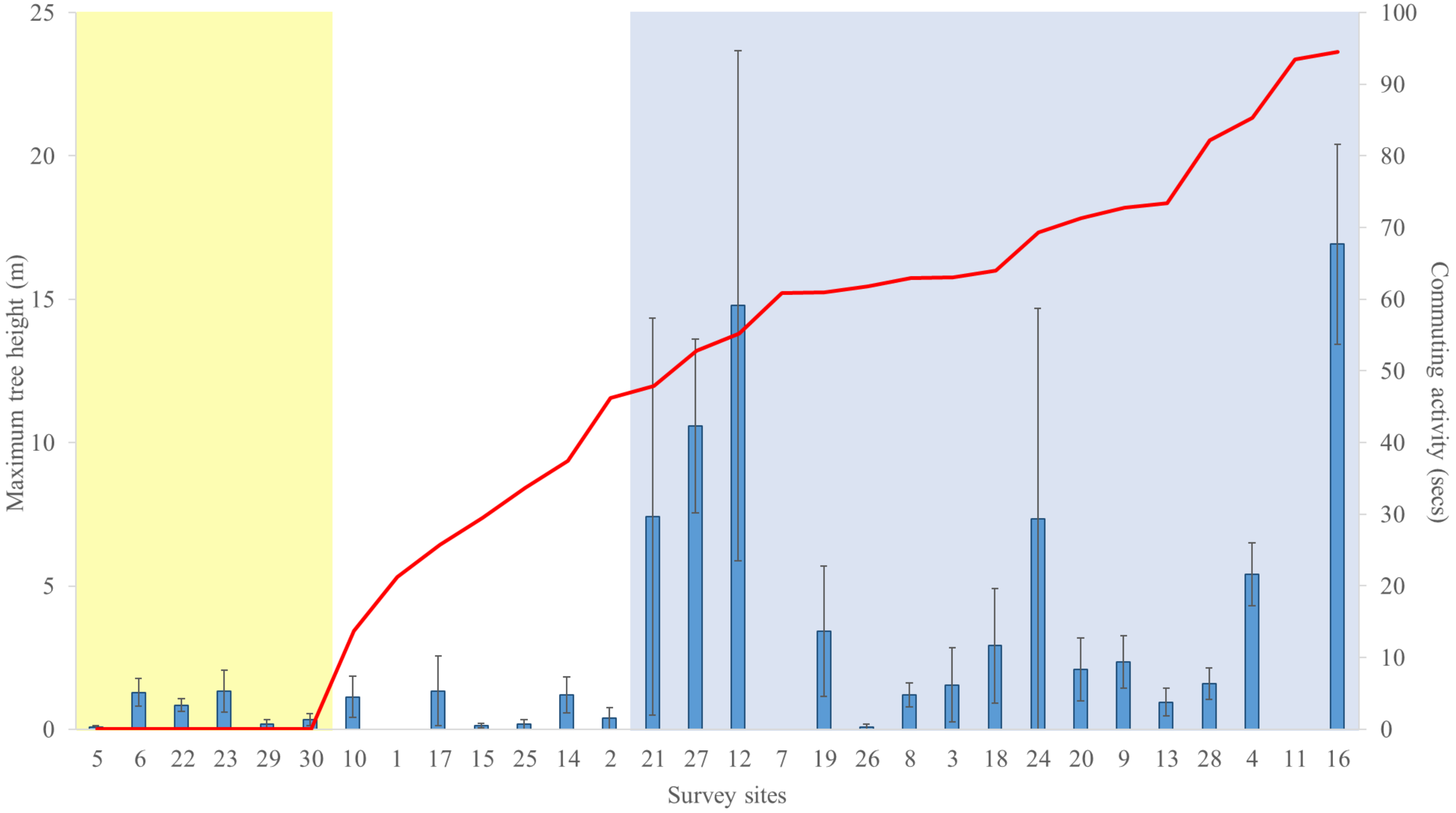


Figure 30: Average bat commuting activity per site (bars with ±SE) recorded in behavioral observation surveys at potential movement corridors with maximum tree height (lines) measured along the 50 m section of the potential commuting route. Sites highlighted in yellow represent Group 1 (tree height <3.4 m), sites in white show Group 2 (3.4-11.6 m), and sites shaded in blue represent Group 3 (>11.6 m).

From the CART analysis we found that bat commuting activity was influenced by the combination of two or more tree metrics (Fig. 30). Total gap distance was the only tree metric that did not appear to have a combined effect on bat commuting activity. The regression tree for the 10 m section indicated that the factors that produced the least bat activity were sites with maximum tree height less than or equal to 22.1 m, maximum gap distance greater than 7 m, and canopies with a rugosity value less than 1.2 (Fig. 31). The most commuting activity at the 10 m section occurred at sites with a maximum tree height of greater than 22.1 m.

For the 30 m section we found that the least amount of commuting activity occurred at sites with a maximum gap distance greater than 0.8 m and a canopy with rugosity values greater than 1.5 (Fig. 32). The sites with the most bat commuting activity in the 30 m section had a maximum gap distance less than or equal to 0.8 m, percent canopy cover less than or equal to 56.7, and rugosity values less than or equal to 1.5.

At the 50 m section, the regression tree showed that at sites with maximum tree height greater than 11.8 m, the least amount of bat commuting activity occurred at sites with rugosity values less than or equal to 1.4 and maximum gap distance less than 0.8 (Fig. 33). For sites with a maximum tree height greater than 11.8, the most bat commuting activity occurred at sites with a rugosity value greater than 1.4, percent canopy cover less than or equal to 63.6, and maximum gap distance less than or equal to 6.4.

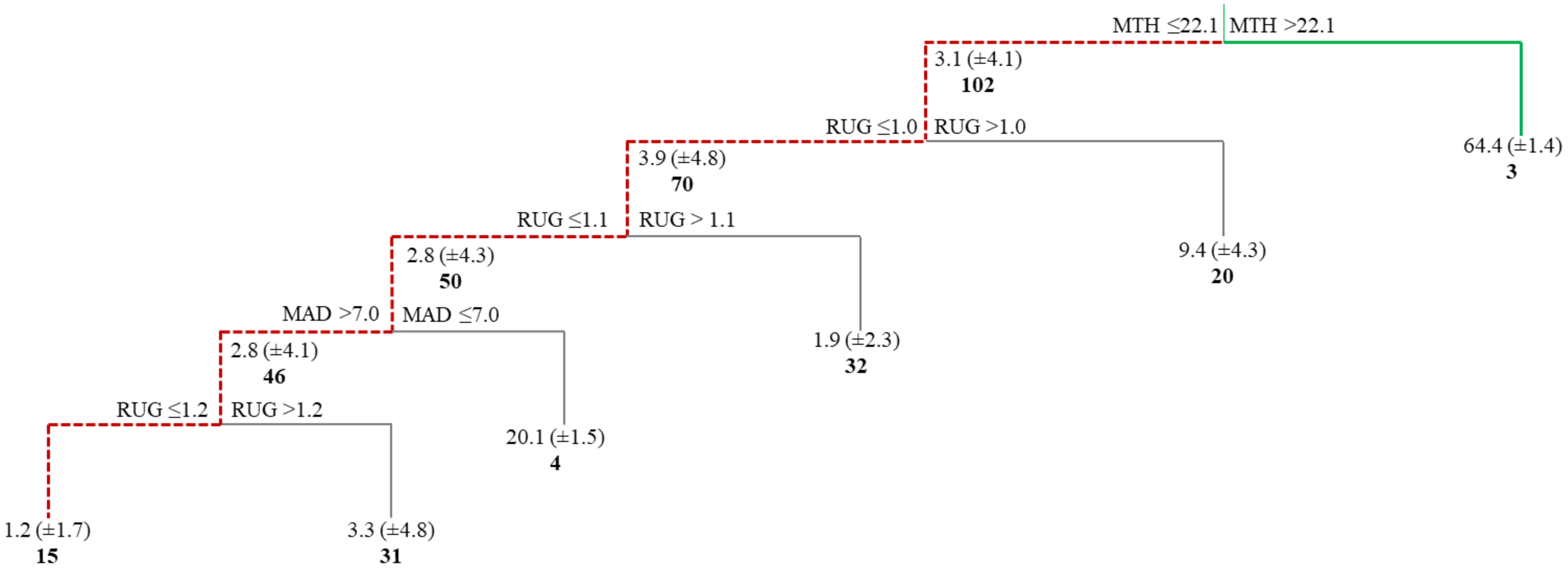


Figure 31: Regression trees comparing the tree metrics using average bat commuting activity per site per night for the 10 m sections at potential movement corridors in Tarrant County, Texas recorded from June to September 2022 and March to May 2023. The variable predictors that create a split are labeled at each branch split. Below each node values represent the mean (± SD) and total number of responses considered in bold. Red dotted line shows the combination of independent variables which resulted in the least bat activity; while the solid green line shows the variables that led to the most activity. Abbreviations are as follows: percent canopy cover (PPC), rugosity value (RUG), maximum gap distance (MAD), total gap distance (TGD), and maximum tree height (MTH). R^2 (training = 0.375, test = 0.136) and Mean Square Error (MSE; training = 0.261, test = 0.361) values were used to optimally prune the tree.

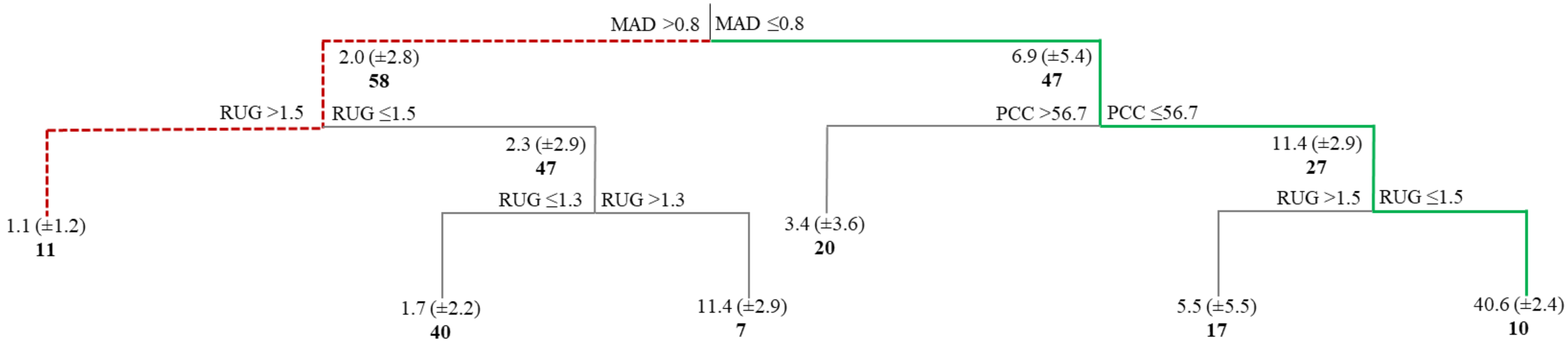


Figure 32: Regression trees comparing the tree metrics using average bat commuting activity per site per night for the 30 m sections at potential movement corridors in Tarrant County, Texas recorded from June to September 2022 and March to May 2023. The variable predictors that create a split are labeled at each branch split. Below each node values represent the mean (± SD) and total number of responses considered in bold. Red dotted line shows the combination of independent variables which resulted in the least bat activity; while the solid green line shows the variables that led to the most activity. Abbreviations are as follows: percent canopy cover (PPC), rugosity value (RUG), maximum gap distance (MAD), total gap distance (TGD), and maximum tree height (MTH). R^2 (training = 0.473, test = 0.149) and Mean Square Error (MSE; training = 0.220, test = 0.355) values were used to optimally prune the tree.

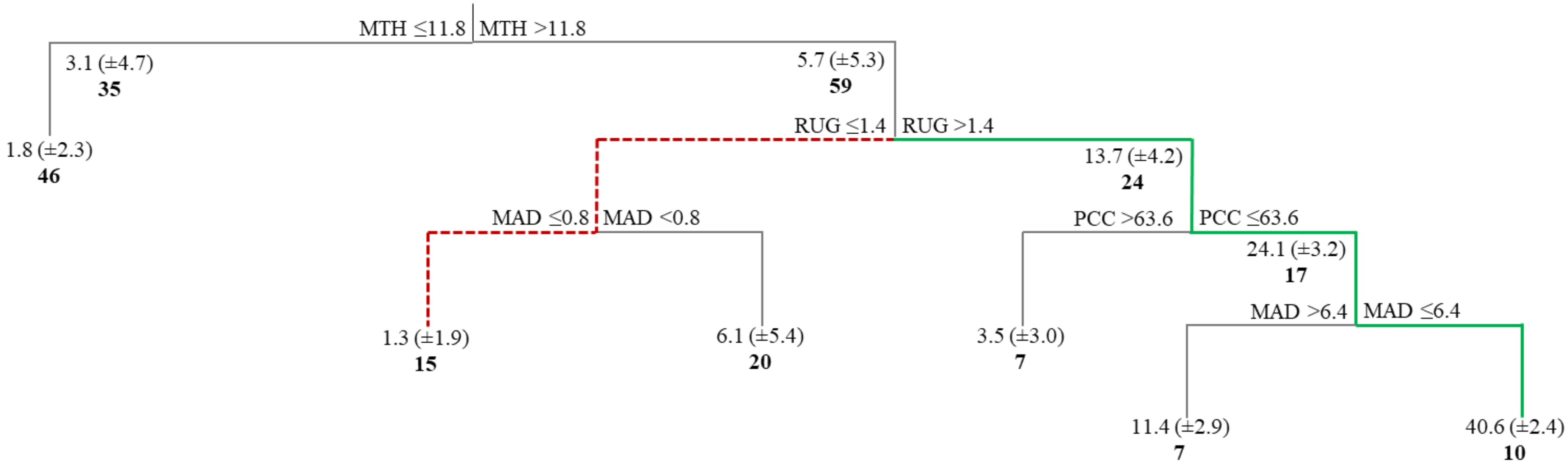


Figure 33: Regression trees comparing the tree metrics using average bat commuting activity per site per night for the 50 m section at potential movement corridors in Tarrant County, Texas recorded from June to September 2022 and March to May 2023. The variable predictors that create a split are labeled at each branch split. Below each node values represent the mean (± SD) and total number of responses considered in bold. Red dotted line shows the combination of independent variables which resulted in the least bat activity; while the solid green line shows the variables that led to the most activity. Abbreviations are as follows: percent canopy cover (PPC), rugosity value (RUG), maximum gap distance (MAD), total gap distance (TGD), and maximum tree height (MTH). R^2 (training = 0.480, test = 0.216) and Mean Square Error (MSE; training = 0.217, test = 0.327) values were used to optimally prune the tree.

DISCUSSION

In our study, we determined that the structure of the urban forest, in terms of tree characteristics, could benefit or hinder the movement of bats across the urban environment. More specifically, we found that all five tree metrics measured affected bat commuting activity along potential commuting routes. Metrics, such as increasing tree height, were positively correlated with bat commuting activity, while increasing percent canopy cover, rugosity, maximum gap distance, and total gap distance appeared to negatively influence commuting. Moreover, the impact each tree metric had on bat activity varied by the length of the potential community route examined (i.e., spatial scale mattered). Along a 10 m length, we found that, alone, increasing percent canopy cover and rugosity affected bat commuting activity, but maximum gap distance, total gap distance, and maximum tree height did not have an effect. However, in combination increasing rugosity and maximum gap distance negatively influenced bat commuting activity. In contrast, we found that all five of the tree metrics alone impacted bat commuting activity along potential commuting routes at 30 and 50 m lengths. We determined that increasing maximum gap distance and rugosity, in combination, negatively affected commuting, but the combination of decreasing maximum gap distance, percent canopy cover, and rugosity positively influenced commuting. These results support our proposed hypothesis that bats would commute regularly along corridors with tall trees and less undulating interconnected canopies.

More specifically, for percent canopy cover we recorded a ~5-fold increase in bat activity simply due to the presence of trees. With trees present, we found that if the percent canopy cover exceeded 16% then the amount of activity decreased by 39%. This result contradicts previous studies that have shown that canopy cover percentage increases bat activity by offering cover from predation and providing structural complexity (Bailey et al. 2019, Moretto et al. 2019, Tena et al. 2020). The difference between these studies and our study is that they focused on bat presence rather than on a specific activity, such as commuting. Thus. their results may have been influenced by the inclusion of other activities. Foraging and commuting activities, for instance, are behaviors that involve taking different levels of risk, as they have very different costs and gains (e.g., foraging gains energy, while commuting loses energy; Bennett and Zurcher 2013). Based on this, we hypothesize that the optimal percent canopy cover required for commuting may be different from that of foraging.

Similarly, for rugosity we recorded a ~5-fold increase in bat activity due to the presence of trees. With trees present, we found that if the rugosity exceeded a value of 1.1 then the amount of activity decreased by 66%. These results are similar to other studies that found that canopy rugosity negatively affected bat activity and support our rationale that increases in clutter created by the canopy can hinder bat activity and, in the case of commuting, can influence how efficiently bats move across the landscape (Heim et al. 2018, Suarez-Rubio et al. 2018). For percent canopy cover at 30 m and 50 m lengths, we recorded a ~5-fold increase in bat activity due to the presence of trees. With trees present, along the 30 m sections we found that if the percent canopy cover exceeded 43% then the amount of activity decreased by 76%. With trees present along the 50 m sections, we found that bat commuting activity was over six times higher when percent canopy cover exceeded 51% and 73% lower with canopy exceeding 62%. These results suggest that too much canopy cover in the surrounding area increases clutter, which deters bats from commuting through the area efficiently (Blakey et al. 2017, Suarez-Rubio et al. 2018). While too little canopy cover may reduce landscape connectivity, preventing bats from accessing certain areas (Bailey et al. 2019, Lewanzik et al. 2022). Other studies support these findings by also suggesting that the presence of intact canopies in urban areas can reduce the negative effects of light pollution at night, as well as traffic noise, as these factors are known to interfere with bat commuting and foraging activity (Hooton et al. 2022, Moretto et al. 2022).

For rugosity in the 30 m and 50 m lengths, we recorded a ~5-fold increase in bat activity due to the presence of trees. With trees present, we found that if the rugosity exceeded a value of 1.3 then the amount of activity increased ~2.5 times. Along 50 m lengths, activity increased ~4-fold when the rugosity value was greater than 1.4. These results contradict the decrease in bat activity with increasing rugosity identified along the 10 m lengths and may be related to scale and direct observation (i.e., the distance included in the surveys). For instance, we directly observed bats along 10 m by 10 m field-of-view, which did not necessarily consider other aspects of the potential commuting route that bats could be utilizing, such as above the canopy and the other side of these linear features. Studies, for example, show that bats can adjust their flight height and position along commuting routes to attain the straightest route (Fujioka et al. 2011, Tsoar et al. 2011, O'Mara et al. 2019). While other studies have shown that bats will select sheltered areas and adjust their flight height and commuting path to avoid windy conditions (Verboom and Huitema 1997, Cryan et al. 2014, Salinas et al. 2014). Thus, it is possible that our direct observations of bats did not record these adjustments in flight location and we underestimated bat activity at this scale.

Overall, these results emphasize the importance of trees in an urban landscape for commuting bats (Moretto et al. 2019) and also validate our hypothesis that bats would prefer to commute along straighter less undulating tree lines, as it is more efficient to maneuver straight flight paths (Heim et al. 2018). Furthermore, an increase in canopy cover, as well as variations in the size and shape of individual trees canopies, can increase rugosity. In other words, fuller canopies create more clutter and obstacles for bats to maneuver. Our findings are supported by Blakey et al. (2017) that revealed a similar decrease in bat foraging activity with increasing clutter (in this case a measure of foliage cover).

For maximum and total gap distance, we recorded an 80% increase in bat activity due to the absence of gaps in the tree canopy along the 30 m lengths, and an 71% increase in the 50 m lengths. These findings indicate that any gaps present can deter bats from commuting. Other studies have also shown similar results with commuting bats avoiding using tree-lines with gaps, suggesting this may be an anti-predator response (Zurcher et al. 2010). Roads, for example, can hinder movement along commuting corridors as bats have been shown to not cross roads greater than 4 lanes wide, but if tree canopies connected over a road or the gap between the canopies is <5 m wide, many species of bat can cross them (Berthinussen and Altringham 2012, Bennett and Zurcher 2013, Abbott et al. 2015, Hooton et al. 2022). More importantly on a larger scale, studies have shown that trees connect habitats across the landscape (Hale et al. 2012, Threlfall et al. 2012, Heim et al. 2015). Thus, the more interconnected the urban forest the greater the abundance of bats in an area is likely to be.

Similarly, we found that tree height represented an important metric at both 30 and 50 m lengths, as the present of trees >2.9 m in height lead to a ~6-fold and ~5-fold increase in bat commuting activity, respectively. Furthermore, bat commuting activity increased a further ~3-fold and ~7-fold, respectively, when maximum tree height exceeded 11.6 m. Other studies support our findings, suggesting that taller mature trees have a positive effect on bat presence, although this is dependent on species and perceived risk of predation (Fern et al. 2018, O'Mara et al. 2019).

Focusing on the diversity of bat species along the potential commuting routes, 13% of our sites had all six species, 33% had five species, 17.5% had four, 17.5% had 3, 17.5% had 2 species, 1.5% had 1, and <1% had no species recorded. The least recorded species was the Mexican free-tailed bats representing <1% of the acoustic calls recorded. This result is not surprising given this species is not known to use tree lines to commute, instead they are open air flyers and forage at heights above 400 m preying on swarms of invertebrates (Ammerman et al. 2012). In contrast, evening bats were the most common species observed, accounting for 71% of observations, and the eastern red bat was the second most recorded species comprising 13% of observations. These results are congruent with the actual abundance of local species because the evening and eastern red bats are the most common bats in the study area (Bienz 2016, Hall and Bennett 2021). Furthermore, based on their ecology evening bats are likely to be the most abundant as they are communal, living in colonies of up to 950 individuals, while eastern reds are solitary and territorial with home ranges >1 km^2 (Walters et al. 2007, Ammerman et al. 2012). Similarly, we would expect to record lower numbers of silver-haired (11%) and hoary (3%) bat activity at our sites because these species are also solitary and territorial (Klug and Barclay 2013, Kurta et al. 2018). For our tricolored bat, only 1.3% of calls were from this species. Again this is not surprising as this species is not often recorded in the area and population declines across North America due to a disease known as white-nose syndrome resulted in this species being proposed to be federally listed as endangered in September 2022 (Bienz 2016, USFWS 2022). As a result of this listing, our study highlights the importance of improving the urban forest for bats. We also noted that there was gradual increase in the number of species across our study sites, however, the sites with the least species, included those in heavily manicured areas, with potentially lots of lighting and limited tree canopy cover (such as an athletics field, tennis court, and manicured lawn next to a retention pond), while the most species were recorded at sites with the straightest mature tree-lines with intact canopies. These trends further support our hypothesis that bats commute regularly along corridors with tall trees and less undulating interconnected canopies.

We acknowledge, that there may be other tree metrics that we could have utilized in this study, such as diameter at breast height (DBH) and the species of trees present at each site. DBH could be an important indicator of tree maturity, while tree species may dictate canopy structure and height, as well as the bat species are likely to be present (Vasko et al. 2020, Novella-Fernandez et al. 2022). Additionally, the structure of the individual trees can change over time, both seasonally and yearly, as trees grow and mature. These changes can subsequently influence the effectiveness of a potential commuting route for bats. For example, increasing canopy cover can improve connectivity by connecting canopies together, however, with time as the canopy continues to grow, they can become more cluttered hindering bat movement. Therefore, active management of the urban forest should be undertaken by urban practitioners to maintain straighter tree lines that will encourage bats to use these as commuting routes. Consequently, pruning trees to reduce clutter will be necessary to maintain tree line suitability. Again, it is likely that the use of any tree line will be species dependent, as well as be dependent on the local bat community, as some bat species will be more tolerant to clutter and disturbance, while other will not (Suarez-Rubio et al. 2018, Weier et al. 2018). Managers, therefore, should maintain a variety of commuting routes with varying levels of clutter and canopy cover. For example, some species may utilize tree-lined roads to forage around street lights, and other more sensitive species will only use green spaces and parks with low levels of human activity and disturbance (Moretto et al. 2022). In some cases, urban managers will need to increase the number of trees present to enable canopies to become interconnected. Moreover, managers should prioritize areas with low tree densities to increase connectivity across the urban landscape.

Another consideration is that this study was specific to north central Texas, but the species we found in this study are common throughout Texas and the eastern United States, which implies that our conclusions may only be applied to urban areas throughout this region (Ammerman et al. 2012). However, tree lines and woodland edges are used by many bat species all over the world to commute, and therefore the tree metrics we analyzed in this study are likely to influence bats in other urban areas (Blakey et al. 2017, Suarez-Rubio et al. 2018, Moretto et al. 2019). Finally, we recommend that these tree metrics be used to create a suitability model to identify areas in the urban landscape to increase bat commuting activity. These areas can then be conserved and managed to keep trees with characteristics favorable for bats, but also, a suitability model could identify key areas where urban forest management can be used to create movement corridors that will connect previously disconnected habitats. Conservation work based on a suitability model could improve landscape connectivity for many species and increase the biodiversity of wildlife in urban habitats. The model could pinpoint where there is potential functional connectivity in the urban landscape, that would be beneficial for bats, but could also be advantageous for birds and other wildlife as bats are indicators of functional connectivity in the urban forests.

CONCLUSION

Our study revealed that bat commuting activity can be increased within an urban area if the urban forest comprises mature trees with straight contiguous interconnected canopies. More specifically, the urban forest should be managed to 1) increase the interconnectedness of tree canopies along tree lines and woodland edges, 2) prune tree canopies to make tree-lines straighter and reduce clutter, and 3) plant trees wherever there are gaps present in the canopy and in areas with a low density of trees (i.e., along the side of roads, parking lots, and greenspaces). We demonstrate that the urban forest is vital for bats to exist in urban settings. It can and should be managed by planners and wildlife practitioners, especially in cities that are rapidly expanding and transforming the landscape, to establish conditions that promote landscape permeability for bats and subsequently aid their conservation in urban areas.

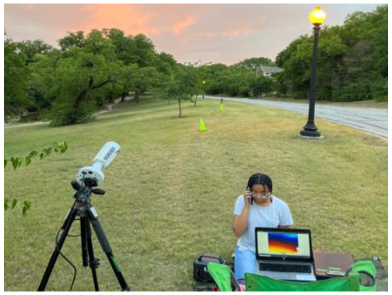
APPENDIX

Appendix A:

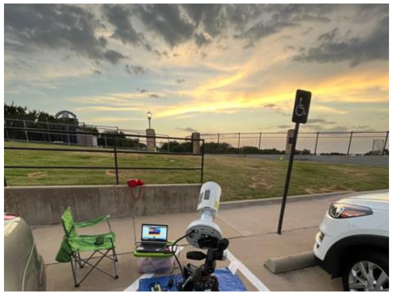
Table A1: Side and front-facing field-of-views for each of the 15 study sites surveyed in behavioral observation surveys.

Site	**Side-facing field-of-view**	**Front-facing field-of-view**	**Site**	**Side-facing field-of-view**	**Front-facing field-of-view**
1			3		
	Along park trail with a mix of tall and short trees. Running along a small creek.			Along drainage ditch with trail in the middle of site. Several tall trees in the middle of site.	
2			4		
	Dense tree line with several large trees along small creek.			Along park trail with few scattered trees.	

Site	Side-facing field-of-view	Front-facing field-of-view	Site	Side-facing field-of-view	Front-facing field-of-view
5			7		
	No trees present; along bank of trinity river.			Site on edge of drainage ditch with tree line along road edge.	
6			8		
	Along brick wall serving as linear feature.			Along park trail and tree line with drainage ditch running parallel.	

Site	**Side-facing field-of-view**	**Front-facing field-of-view**	**Site**	**Side-facing field-of-view**	**Front-facing field-of-view**
9			11		
	Along interconnected tree line with a mix of small and tall trees. Open grass area along site.			Site between road and drainage ditch with several large trees completely covering site.	
10			12		
	Site next to road with a couple of small trees and a streetlamp.			Large, mature trees scattered around potential commuting route with large gaps dispersed between canopies.	

Dense tree line with several large trees along small creek.	No trees present; along bank of trinity river.

Site	**Side-facing field-of-view**	**Front-facing field-of-view**	**Site**	**Side-facing field-of-view**	**Front-facing field-of-view**
13			15		
Open grassy park area with a couple large mature trees.			Site is between parking lot and fence along soccer field.		
14			16		
In park with large grass area with medium sized trees along drainage ditch.			Tree line of tall, mature trees in campground and large creek parallel to tree line.		

Dense tree line with several large trees along small creek.			No trees present; along bank of trinity river.		
Site	**Side-facing field-of-view**	**Front-facing field-of-view**	**Site**	**Side-facing field-of-view**	**Front-facing field-of-view**
17			19		
Tree line of medium to small trees along park road.			Tree line next to creek on the edge of a large grass area in a park.		
18			20		
Interconnected tree line along street.			Several medium to large trees next to playground in park.		

	Dense tree line with several large trees along small creek.			No trees present; along bank of trinity river.	
Site	**Side-facing field-of-view**	**Front-facing field-of-view**	**Site**	**Side-facing field-of-view**	**Front-facing field-of-view**
21			23		
	Tree line of a couple large trees at edge of large grassy area in park.			Open grassy area in park along street with no trees.	
22			24		
	Tennis court fence in large, open grass covered park.			Tree line of large trees between street and grassy area.	

	Dense tree line with several large trees along small creek.			No trees present; along bank of trinity river.	
Site	**Side-facing field-of-view**	**Front-facing field-of-view**	**Site**	**Side-facing field-of-view**	**Front-facing field-of-view**
25			27		
	Line of small trees next to fence on edge of soccer field.			Interconnected tree line with tall and short trees. Parallel to riparian area.	
26			28		
	Several large, isolated trees between parking lot and street.			Tree line in between TCU property and houses.	

Dense tree line with several large trees along small creek.			No trees present; along bank of trinity river.		
Site	**Side-facing field-of-view**	**Front-facing field-of-view**	**Site**	**Side-facing field-of-view**	**Front-facing field-of-view**
29			30		
Open grassy area along edge of pond.			Along bank of reservoir next to street with no trees.		

Appendix B:

Table B1: Pairwise Comparison of Bat Commuting Times between Sites: Dunn's Test Results.

	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13	S14	S15	S16	S17	S18	S19	S20	S21	S22	S23	S24	S25	S26	S27	S28	S29	S30
S1		0.426	0.207	0.018	0.468	0.142	0.502	0.145	0.073	0.194	0.500	0.015	0.207	0.201	0.410	0.027	0.229	0.174	0.162	0.183	0.170	0.184	0.204	0.243	0.439	0.458	0.027	0.150	0.442	0.307
S2			0.301	0.043	0.474	0.204	0.429	0.208	0.173	0.269	0.208	0.046	0.309	0.286	0.490	0.030	0.342	0.231	0.208	0.227	0.231	0.244	0.286	0.386	0.501	0.489	0.041	0.202	0.502	0.443
S3				0.170	0.241	0.420	0.210	0.429	0.311	0.493	0.208	0.172	0.500	0.492	0.320	0.146	0.490	0.439	0.428	0.442	0.445	0.463	0.487	0.481	0.312	0.286	0.172	0.404	0.314	0.439
S4					0.030	0.245	0.023	0.240	0.327	0.193	0.021	0.498	0.173	0.181	0.046	0.444	0.179	0.240	0.268	0.243	0.240	0.227	0.208	0.185	0.055	0.046	0.475	0.295	0.057	0.151
S5						0.185	0.471	0.174	0.146	0.224	0.469	0.031	0.243	0.230	0.459	0.017	0.286	0.205	0.187	0.204	0.204	0.210	0.236	0.310	0.477	0.492	0.029	0.172	0.478	0.392
S6							0.148	0.492	0.462	0.440	0.145	0.252	0.408	0.433	0.208	0.204	0.410	0.490	0.502	0.491	0.489	0.475	0.446	0.369	0.206	0.204	0.227	0.494	0.208	0.293
S7								0.151	0.077	0.198	0.503	0.018	0.210	0.205	0.413	0.082	0.233	0.181	0.167	0.188	0.174	0.188	0.207	0.245	0.445	0.460	0.041	0.156	0.446	0.309
S8									0.448	0.446	0.148	0.242	0.425	0.442	0.218	0.206	0.423	0.494	0.494	0.497	0.492	0.485	0.458	0.394	0.220	0.203	0.218	0.488	0.221	0.309
S9										0.353	0.075	0.337	0.309	0.339	0.175	0.243	0.309	0.442	0.463	0.443	0.442	0.430	0.389	0.286	0.172	0.174	0.284	0.481	0.174	0.229
S10											0.196	0.195	0.487	0.496	0.292	0.166	0.481	0.463	0.442	0.461	0.471	0.482	0.499	0.461	0.287	0.249	0.170	0.429	0.288	0.423
S11												0.017	0.209	0.203	0.411	0.041	0.230	0.177	0.164	0.185	0.172	0.186	0.206	0.244	0.441	0.459	0.033	0.153	0.443	0.308
S12													0.172	0.189	0.049	0.441	0.182	0.242	0.278	0.244	0.240	0.232	0.212	0.179	0.057	0.048	0.470	0.301	0.058	0.146
S13														0.492	0.331	0.149	0.496	0.442	0.422	0.441	0.443	0.459	0.484	0.489	0.321	0.291	0.164	0.393	0.322	0.443
S14															0.299	0.152	0.488	0.461	0.440	0.456	0.462	0.478	0.491	0.469	0.296	0.261	0.183	0.423	0.298	0.429
S15																0.034	0.369	0.240	0.226	0.240	0.240	0.260	0.301	0.409	0.493	0.477	0.045	0.207	0.494	0.457
S16																	0.148	0.209	0.212	0.203	0.205	0.194	0.175	0.150	0.043	0.033	0.488	0.228	0.045	0.082
S17																		0.442	0.422	0.447	0.441	0.458	0.478	0.492	0.354	0.313	0.186	0.394	0.355	0.457
S18																			0.492	0.500	0.501	0.491	0.473	0.423	0.241	0.223	0.225	0.479	0.242	0.340
S19																				0.493	0.492	0.476	0.456	0.390	0.223	0.208	0.240	0.493	0.226	0.309
S20																					0.499	0.491	0.469	0.420	0.242	0.220	0.225	0.481	0.243	0.337
S21																						0.493	0.477	0.424	0.244	0.225	0.219	0.478	0.245	0.347
S22																							0.487	0.443	0.257	0.241	0.209	0.461	0.258	0.380
S23																								0.462	0.297	0.262	0.193	0.440	0.298	0.423
S24																									0.391	0.349	0.163	0.354	0.393	0.475
S25																										0.491	0.048	0.206	0.501	0.439
S26																											0.045	0.200	0.492	0.426
S27																												0.250	0.050	0.127
S28																													0.207	0.288
S29																														0.441
S30																														

Table B2: Results of Kruskal-Wallis test examining percent canopy cover (PCC), rugosity (RUG), and maximum tree height (MTH) in the 10, 30, and 50 m section of the commuting route.

Kruskal-Wallis				
metric	length	chi2	df	p-value
PCC	10	6.5568	2	0.0377
PCC	30	12.283	2	0.00215
PCC	50	13.12	3	0.00439
RUG	10	7.9545	2	0.0187
RUG	30	6.6937	2	0.0352
RUG	50	9.9642	2	0.0069
MTH	10	2.350	2	0.309
MTH	30	6.6981	2	0.0351
MTH	50	11.015	2	0.00406

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VITA

Personal Background

Manuel de Oyarzabal Barba
Coppell, Texas

Education

2017	Diploma, Jesuit College Preparatory School of Dallas, Dallas, Texas
2021	Bachelor of Science, Environmental Science, Santa Clara University
2023	Master of Science, Environmental Science, Texas Christian University

Experience

2022-2023	Teaching Assistant, Texas Christian University
2021	Temporary Field Technician, National Ecological Observatory Network
2019	Intern, Zoológico Guadalajara
2019	Research Intern, Romero Institute

Presentations

de Oyarzabal Barba, M, Lavy, BL, Bennett, VJ. Improving Urban Flyways for Bats: The Importance of Tree Canopy Structure. Southwest Division of the American Association of Geographers, Laredo, Texas.

de Oyarzabal Barba, M, Lavy, BL, Bennett, VJ. 2023. TCU Research and Creative Activities Week Poster Session. Texas Christian University. Fort Worth, TX.

de Oyarzabal Barba, M, Lavy, BL, Bennett, VJ. 2023. Student Research Symposium. Texas Christian University. Fort Worth, TX.

Awards

2022	$3,000 - ENSC graduate research grant award, Department of Environmental Sciences, Texas Christian University
2022	$1,600- SERC graduate research grant award, College of Science and Engineering, Texas Christian University
2023	$400 - Graduate Student Travel Grant, College of Science and Engineering, Texas Christian University

ABSTRACT

IMPROVING URBAN FLYWAYS FOR BATS: THE IMPORTANCE OF THE TREE CANOPY STRUCTURE.

By Manuel de Oyarzabal Barba, M.S., 2023
School of Science and Engineering
Texas Christian University

Thesis Advisors:	Dr. Brendan Lavy, Assistant Professor of Environmental Science
	Dr. Victoria J. Bennett, Associate Professor of Environmental Science
Committee Member:	Dr. Gehendra Kharel, Assistant Professor of Environmental Science

Movement corridors represent an important resource, allowing wildlife to access resources (Jones et al. 2018, Scharf et al. 2018, Gregory et al. 2021). In this study, we examined five tree metrics that could influence connectivity: percent canopy cover, rugosity (straightness of the canopy edge), maximum gap distance, total gap distance, and maximum tree height. The results show that all five independent variables influenced bat commuting activity. We found that the presence of trees is essential for bat commuting activity. This study demonstrated that there are specific characteristics of trees that influence the ability of bats to commute through the urban forest and use the resources available. From our results, we suggest that professionals, where feasible, prune tree lines straight and remove clutter to allow bats to move easily along tree lines. Trees should also be planted wherever gaps are present in the canopy and the tallest trees should be conserved.