# NILGAI MOVEMENT ECOLOGY: IMPLICATIONS FOR MANAGEMENT OF CATTLE FEVER TICKS IN SOUTH TEXAS

A Thesis

by

KATHRYN M. SLIWA

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Approved as to style and content by:

Randall W. DeYoung, Ph.D.
Committee Chair

Jeremy A. Baumgardt, Ph.D.
Committee Member

J. Alfonso Ortega-S., Ph.D.
Committee Member

David G. Hewitt, Ph.D.
Committee Member

John A. Goolsby, Ph.D.
Committee Member

Scott E. Henke, Ph.D.
Department Chair

George Allen Rasmussen, Ph.D.
Vice President for Research and Graduate Studies

May 2021

**ABSTRACT**

Nilgai Movement Ecology: Implications for Management of Cattle Fever Ticks in South Texas

May 2021

Kathryn M. Sliwa, Bachelor of Science, Delaware Valley University

Chairman of Advisory Committee: Dr. Randy W. DeYoung

One of the most significant vector-borne diseases of livestock worldwide is bovine babesiosis, spread by cattle fever ticks (CFT), *Rhipicephalus (=Boophilus) microplus* and *R. (B.) annulatus*. The disease and its one-host vector were introduced to the Americas on livestock in the $16^{th}$ century. Although CFT were eradicated from the U.S. by 1943, bovine babesiosis is endemic in Mexico. Periodic trans-border outbreaks of CFT still occur in parts of South Texas and pose an ongoing threat to the U.S. cattle industry. The U.S. government maintains a permanent quarantine zone along the southern border to prevent re-infestation from Mexico. Wildlife, including introduced nilgai antelope (*Boselaphus tragocamelus*), are suitable alternate hosts and can disperse CFT from infested areas. Nilgai are abundant (over 30,000 free-ranging individuals), and make long-distance movements. There are currently no methods to treat nilgai for CFT. Nilgai do not respond to traditional treatment options such as medicated feed; furthermore, little is known about nilgai ecology in South Texas or their native range in India and Pakistan. I monitored 30 GPS-collared nilgai (F=19, M=11) in Cameron County, Texas, USA, from April 2019–March 2020 to better understand: 1) nilgai movement and behaviors, 2) nilgai habitat selection in South Texas, and 3) fence-crossing behavior by nilgai. I observed movement patterns consistent with residency (56.7%), use of seasonal ranges (23.3%), nomadic movements (13.3%), and dispersal (6.7%). Overall, nilgai had large and highly variable home ranges. Annual median home range estimate were 593 ha (range = 105–1,545) and 937 ha (range

= 221–1,602) for females and males, respectively. Nilgai selected for woody and mixed cover habitats (suitable tick habitat) regardless of season or sex. Nilgai cross livestock fencing, which may move ticks onto adjacent properties, but crossing sites may be re-visited, presenting an opportunity for treatment via remote sprayers. Movement data suggested that during the year 17/30 nilgai crossed a fence > 1 time per month, 9/30 nilgai had ≥ 1 month with 0 fence crossings, and 4/30 nilgai left the study area. Using trail camera photos to identify crossing events at monitored sites, collared nilgai were captured crossing a fence 63 times, consisting of 17/30 individuals. The movement behaviors and ecology of nilgai challenge the sustainability of CFT eradication efforts in the U.S. Understanding how host species use the landscape can aid in the creation of a more effective cattle fever tick eradication plan for South Texas. This is key information the Cattle Fever Tick Eradication Program can use to adapt new technologies to treat infestations in nilgai.

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# CHAPTER I. MOVEMENT ECOLOGY OF NILGAI ANTELOPE IN SOUTH TEXAS

**ABSTRACT** Wildlife play an important role in the emergence of livestock diseases and can complicate disease management efforts. One of the most significant vector-borne diseases of livestock worldwide is bovine babesiosis, spread by cattle fever ticks (CFT), *Rhipicephalus (=Boophilus) microplus* (Cannestrini) and *R. (B.) annulatus* (Say). The disease and its one-host vector were introduced to the Americas on livestock in the 16$^{th}$ century. Although CFT were eradicated from the U.S. by 1943, bovine babesiosis and CFT are endemic in Mexico. Periodic trans-border outbreaks of CFT still occur in parts of South Texas and pose an ongoing threat to the U.S. cattle industry.  Recently, the management of CFT in the trans-border region has been complicated by the presence of a free-ranging exotic, the nilgai antelope (*Boselaphus tragocamelus*). Nilgai are abundant (over 30,000 free-ranging individuals), are a competent host for CFT, and make long-distance movements. Furthermore, little is known about nilgai ecology in South Texas or their native range in India and Pakistan. The goal of this study was to better understand nilgai movements and space use to inform CFT treatment strategies.  Specific objectives were to 1) relate individual movement patterns to nilgai behavior, 2) estimate home range sizes at different temporal scales (monthly, seasonally, and overall), and 3) calculate average movement metrics, activity patterns and space use. I analyzed hourly locations from 30 GPS-collared nilgai in Cameron County, TX from April 2019–March 2020. I observed movement patterns consistent with residency (56.7%), use of seasonal ranges (23.3%), nomadic movements (13.3%), and dispersal (6.7%). Two young females made long-distance movements resembling dispersal behavior, traveling ~40 km from their initial capture location. Female dispersal is uncommon in ungulates, and may result from the social structure of nilgai, in which

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some males are territorial. Overall, nilgai had large and highly variable home ranges: annual median home range estimate for females was 593 ha (range = 105–1,545) and for males 937 ha (range = 221–1,602). Peak nilgai activity occurred during crepuscular hours, and average hourly movement for females was 126 m/hr and for males 152 m/hr. Nilgai home range sizes and long-distance movements have the potential to overlap multiple ranches, as the typical ranch size in South Texas ranges from 250–6,000 ha. Therefore, CFT eradication efforts need to be broad-scale and consistent across ranches. Movement behaviors of nilgai challenge the sustainability of CFT eradication efforts in the U.S. and understanding these behaviors will help the Cattle Fever Tick Eradication Program develop new technologies to treat infestations in nilgai.

**KEY WORDS** Nilgai antelope, *Boselaphus tragocamelus*, cattle fever ticks, bovine babesiosis, movement behavior, home range, net squared displacement, female dispersal, wildlife disease

Wildlife play an important role in the emergence of livestock diseases and can interfere with disease management efforts (Miller et al. 2013). Because livestock sales are responsible for almost half of the U.S. agriculture industry's profits, disease management is an essential aspect of animal agriculture operations (Sumner et al. 2005). The growing interest to import exotic ungulate species for recreational hunting and marketing exotic meats (Pérez de León et al. 2012) has increased both the threat of foreign pathogens and the number of potential host species (Bram et al. 2002).

Bovine babesiosis is one of the most significant vector-borne diseases of livestock worldwide (Martinez et al. 2006, Miller et al. 2013). The disease is economically detrimental to the livestock industry due to production losses and cost of tick control efforts (Bock et al. 2004, Cardenas-Canales et al. 2011). The protozoan parasites responsible for bovine babesiosis are transmitted by the one-host cattle fever ticks (CFT), *Rhipicephalus (=Boophilus) microplus* (Cannestrini) and *R. (B.) annulatus* (Say; Pérez de León et al. 2012). The disease arrived in North America during the 1500s, as Spanish colonists brought CFT-infested cattle and horses to the New World (Pelzel 2005, USDA-APHIS 2010, Pérez de León et al. 2012). By the 1800s, bovine babesiosis and CFT were widely distributed throughout the southern U.S. and California (Pérez de León et al. 2012). In 1906, the Cattle Fever Tick Eradication Program was created and began eradication efforts for bovine babesiosis in the U.S. (Pérez de León et al. 2012, Giles et al. 2014). Treatment strategies included removal or treatment of cattle, the tick's preferred host. By 1943, CFT had been isolated in a permanent quarantine zone along the Texas-Mexico border, extending about 800 km from Del Rio, TX to Brownsville, TX (Pérez de León et al. 2012, Giles et al. 2014).

For a one-host tick, the livestock-focused strategies of the Cattle Fever Tick Eradication Program proved successful. However, control efforts encountered problems in the presence of wildlife species that served as competent alternative hosts, including white-tailed deer (*Odocoileus virginianus*), and recently nilgai antelope (*Boselaphus tragocamelus*; Pound et al. 2010, Busch et al. 2014). In 1931, white-tailed deer were discovered with CFT in Florida, threatening nearby livestock herds (Pound et al. 2010). After culling deer in multiple counties, Florida once again regained eradication status (Pound et al. 2010), with a loss of approximately 20,000 deer (Kistner and Hayes 1970). As a member of the family Bovidae, nilgai are more closely related to cattle than deer, and are a competent host for CFT (Goolsby et al. 2017, Singh et al. 2017). Native to India, Pakistan, Bangladesh, and Nepal, nilgai were first introduced as a game species to South Texas in 1924 (Sheffield et al. 1971). Since their introduction, nilgai have naturally dispersed throughout the region, ranging from Baffin Bay to Brownsville, TX, and in northern Mexico as far west as Durango (Sheffield et al. 1971, Olafson et al. 2018). After feral pigs (*Sus scrofa*), nilgai have become the second most abundant free-ranging exotic ungulate in the state (Lohmeyer et al. 2018), with current population estimates of over 36,000 in South Texas (Olafson et al. 2018).

As nilgai have expanded into the Texas-Mexico border region, the risk for the spread of CFT has become increasingly critical (Moczygemba et al. 2012). Recent, persistent infestations of CFT outside of the permanent quarantine zone led to the creation of a temporary preventative quarantine area in Cameron County, Texas, during 2014; the presence of nilgai greatly hindered the control of this outbreak (Fig. 1.1; Olafson et al. 2018). Management is difficult in part because nilgai home ranges (median = 4,665 and 1,606 ha for males and females, respectively) are much larger than home ranges of white-tailed deer (average = 182–922 ha for males), the other alternative host for CFT (Webb et al. 2007, Foley et al. 2017). Furthermore, individuals or groups of nilgai are capable of movements >30 km (Leslie 2008, Moczygemba et al. 2012, Foley et al. 2017).  Finally, white-tailed deer can be treated by medicated feed laced with acaricide (i.e., Ivermectin), whereas nilgai do not respond to feed or bait.

Understanding host movement patterns and behaviors can determine where to target host species for treatment. Disease ecology research often determines 'typical' movement patterns to gain population-level inferences from a study (Shaw 2020). This approach can overlook individual host variation, which can be a key aspect in the spread of parasites and disease (Boulinier et al. 2016, Shaw 2020). Furthermore, previous studies have observed high individual variation in home range and movements regardless of sex (Moczygemba et al. 2012, Foley et al. 2017). Foley et al. (2017) reported male nilgai home ranges spanning 571–20,809 ha, and female ranges of 848–29,909 ha. Previous studies estimated home ranges using minimum convex polygons, which may inflate home range sizes by including unused areas (Huck et al. 2008). It is unclear whether home range size and variation are an artifact of the estimation method. Regardless, large home ranges of at least some nilgai are concerning because they increase the risk of carrying ticks outside of the quarantine zones (Foley et al. 2017).

Relatively little is known about nilgai ecology, including the behavioral processes driving individual variation in movement patterns and behaviors among nilgai. Previous studies were limited and focused on the quantification of home range sizes, with little attention to individual movements. The large movements and home ranges of nilgai are critical in estimating how CFT can be spread (Moczygemba et al. 2012). A fine-scale analysis of nilgai movement ecology is needed to identify behavioral drivers of movements, key information for the development and testing of tick eradication methods to combat this disease (Foley et al. 2017). The objectives of this research were to: 1) investigate behavioral drivers of individual movement patterns, 2) quantify temporal variation in home range sizes, and 3) calculate movement metrics of nilgai to assess fine-scale activity patterns.

**STUDY AREA**

This study took place on privately owned properties in Cameron County, Texas, USA, all located within the temporary preventative quarantine area (Fig. 1.2). Wildlife and cattle are exposed to *R.* (*B.*) *microplus* in this area, and cattle are regularly treated. The Western sites are 2 ranches that have similar habitat structure and nilgai ranges can overlap both properties. The Western sites are located southeast of the community of Rio Hondo and border an 840-ha tract managed by the U.S. Fish and Wildlife Service. These ranches are managed mostly for hunting, although each has cattle. In total, the Western sites are 1,409-ha with clay, silty clay loam, and fine sandy loam soils (WSS 2019). During April 2019–March 2020, this area received 62 cm of rain, with a mean temperature ranging from 19.3 to 29.5 C during the year (Prism 2020). These properties are all located in the Lower Rio Grande Valley, Lower Rio Grande Alluvial Floodplain, and Gulf Coast Prairies and Marshes ecoregions (TPWD 2019). Characteristics of these ecoregions include arid grasslands and woody patches along the Gulf Coast (Bailey et al. 1994). Common vegetation included honey mesquite (*Prosopis glandulosa*) thornscrub, live oak (*Quercus virginiana* [Mill.]), Guinea grass (*Megathrysus maximus*), and prickly pear cactus (*Opuntia engelmannii*).

The Eastern site is a 2,063-ha property surrounded by the Laguna Atascosa National Wildlife Refuge (NWR), located along the Laguna Madre Bay. The Eastern site is a working cattle ranch and grows crops in some portions of the property. Soil types include silty clay, silty clay loam, sandy clay loam, and clay (WSS 2019). During April 2019–March 2020, the Eastern site received 61 cm of rain, with average temperatures ranging from 20.1 to 28.2 C during the year (Prism 2020). This property is in the Laguna Madre Coastal Marshes and Southern Gulf Prairies ecoregions. These ecoregions feature tidal mud flats, grassy meadows, and a hypersaline lagoon system (Bailey et al. 1994). Common plants include honey mesquite, live oak, gulf cordgrass (*Spartina spartinae* [Trin.]), and seacoast bluestem (*Schizachyrium scoparium* var. littorale).

## METHODS

### Nilgai Capture and Marking

In March 2019, 30 nilgai (20 F; 10 M) were captured at random using a net gun fired from a helicopter. This technique has proven to be a successful method to capture large mammals (Webb et al. 2008) and previous studies have used this method to capture nilgai (Moczygemba et al. 2012, Foley et al. 2017). Once a nilgai was netted, a ground crew blindfolded the individual, tied the legs, and removed the net. I met the ground crew at the capture location and deployed global positioning system (GPS) collars (VERTEX Lite-3D IRIDIUM, VECTRONIC Aerospace, Germany) on each nilgai. The collars weighed approximately 900 g. I deployed 19 collars on the Western sites and 11 on the Eastern site. The collars were programmed to collect locations at a 1-hr fix rate. I estimated age of a nilgai based on tooth replacement of the incisors for deciduous or adult teeth. Since there are no defined criteria to age a nilgai, I separated individuals into young (<2 years old) and adult (2+ years old). I kept handling time under 15 minutes, and nilgai were released immediately following data collection. In September 2019, collared nilgai were recaptured. I removed 3 collars from nilgai on the Western sites, and redeployed the collars on 3 (2 M; 1F) new nilgai on the Eastern site. Procedures and capture activities were consistent with recommendations by the American Society of Mammologists (Sikes et al. 2016) and approved by the Texas A&M University-Kingsville Institutional Animal Care and Use Committee, approval 2018-09-19.

**Data Processing**

I removed GPS locations collected during the first 3 days post-deployment to give the nilgai time to adjust after captures (Foley et. al 2017). Data analysis for this study began 01 April 2019 and ended 31 March 2020. I screened the collar data for unrealistic locations using methods outlined by Bjørneraas et al. (2010). I set the limiting parameters to: $\alpha$= 550 m/hr (velocity), $\theta$= – 0.719 (corresponds to turning angles between 136º and 224º), $\mu$= 10 km (distance nilgai could travel in 2 hr), and $\Delta$=100 km (distance nilgai could not travel in 2 hr; Bjørneraas et al. 2010, van Beest et al. 2011, Schweiger et al. 2015). I used the 95$^{th}$ percentile for average step lengths of the collared nilgai to get the value of $\alpha$=550 m/hr. I used the 75$^{th}$ percentile for average turning angles of the collared nilgai to get the value of $\theta$= –0.719. The velocity and turning angle needed to be able to eliminate erroneous points without removing true locations (Bjørneraas et al. 2010). After testing different combinations of velocity and turning angle, this pair was the most efficient at highlighting locations that appeared biologically unfeasible for the nilgai. This approach was based on moose (*Alces alces*) movement, which, like nilgai, are large ungulates with variable ranges. All final locations used also had a dilution of precision (DOP) value <10.

**Movement Patterns and Behavior**

Individual animals often display different movement patterns as a result of age-, sex-, and individual-specific factors. Little research has been done on the movement behaviors of nilgai. However, as a sexually dimorphic antelope species, nilgai behavior is comparable to species found in class C of Jarman's (1974) organization of African antelope. Class C characteristics include territorial males and female groupings, with only a portion of males mating (Jarman 1974). Male antelope in class C are only territorial during certain seasons, during which time they will defend their territory by fighting; non-territorial males (usually sub-adults) will form bachelor groups (Jarman 1974). Male nilgai show similar patterns, and adult males use latrine piles within their ranges, another class C characteristic (Jarman 1974, Zoromski 2019). Female antelope in class C will associate in groups based on physiological state and position their ranges based on resources not territories (Jarman 1974). Identifying movement behaviors of individual nilgai can be an important tool for implementing management plans within a highly variable population (Singh et al. 2016).

One method to classify behavioral drivers of patterns of movement is the net squared displacement (NSD; Bunnefeld et al. 2010). The NSD measures the square of the Euclidean distance between the starting location and subsequent locations on a movement path of an individual (Bunnefeld et al. 2010, Killeen et al. 2014, Bastille-Rousseau et al. 2016). I used the methods of Bastille-Rousseau et al. (2016), which incorporated a latent state model into the NSD statistic, to assess individual movement patterns using the *lsmnsd* package in R. The latent state model provides some flexibility and a higher accuracy of movement pattern classifications to the NSD metric (Bastille-Rousseau et al. 2016, Stears et al. 2019).

One challenging aspect of researching an exotic and understudied species is trying to fit them into a model comparable to similar species without muting their unique features. I chose NSD to help identify movement patterns of nilgai because it was based on predetermined guidelines and parameters that could be adjusted to fit the species. Net squared displacement has been used to describe movement patterns of large ungulates, such as elk (Killeen et al. 2014), moose (Singh et al. 2012), red deer (*Cercus elaphus*; Mysterud et al. 2011, Bischof et al. 2012), and Mongolian gazelle (*Procapra gutturosa*; Imai et al. 2019).

The starting location for a NSD model is critical, as this point will be compared against ensuing locations. If the starting location is outside of an individual's usual home range, the estimated movement behavior could be flawed (Singh et al. 2016). I examined locations of each nilgai to determine whether the starting date of 01 April 2019 or the individual's capture location was an appropriate starting point. Some individuals altered their behavior immediately after capture and did not return to their 'normal' movement patterns until after my analysis period began. If that was the case, I used the coordinates of the individual's capture location as the starting point, as it was often better situated within an individual's usual range.

I resampled the location data for each individual to a 13-hr interval to obtain 1 location each day. Resampling the data accounts for spatial autocorrelation, shortens computing time, and can provide a more accurate classification for movement datasets used for NSD analysis (Mysterud et al. 2011, Papworth et al. 2012, Bastille-Rousseau et al. 2016). I visually compared the NSD graphs with the respective GPS locations to make a final determination of movement behavior (Mysterud et al. 2011, Bischof et al. 2012, Singh et al. 2016, Walton et al. 2017). The visual inspection adds a subjective component to this process. However, the package cannot account for species- and site-specific space use (Mysterud et al. 2011, Bischof et al. 2012). For example, NSD is often used to distinguish migratory animals from resident individuals (Bunnefeld et al. 2010, Papworth et al. 2012). Nilgai are considered non-migratory, so for individuals labeled as migratory, I re-classified as using seasonal ranges.

I classified movement patterns into dispersal, use of seasonal ranges, resident, and nomadic movements. Nilgai that dispersed left their home range or point of origin without returning for the duration of the year (Killeen et al. 2014). Dispersal can be segmented into 3 phases: emigration, transfer to a new area, and immigration (Andreassen et al. 2002, Woodroffe 2003). The initial step of emigration is when an individual decides to leave its area of residence. This is followed by a transfer period where the individual seeks out a new area to settle. The final step is immigration, where the individual establishes themselves into a new place of residency (Andreassen et al. 2002). Use of seasonal ranges was defined as nilgai that appeared to have separate seasonal ranges spent most of the summer and winter in different areas. Resident nilgai were defined as displaying overlapping seasonal ranges with some periods of exploratory movements outside of their home ranges. Nomadic movements were defined as unpredictable or irregular movements regardless of season (Imai et al. 2019, Teitelbaum and Mueller 2019). The nomadic nilgai had irregular locations instead of general clustering like individuals classified as residents.

## Home Range Sizes and Temporal Variation

I calculated home range sizes for each month, season, and overall using a Brownian bridge movement model (BBMM; Horne et al. 2007). I selected the BBMM because the algorithm predicts paths of movement between each location to estimate home range size and accounts for high-frequency location data (Horne et al. 2007, Fischer et al. 2013). I calculated a 95% BBMM home range estimate and a 50% BBMM core range estimate (Fig. 1.3) for each individual at each temporal scale using the *BBMM* package in Program R (Nielson et al. 2013; R Core Team 2020). Seasonal analyses were based on biological time frames for nilgai: summer, April–July (gestation); autumn, August–November (birth, lactation); and winter, December–March (breeding; Sheffield et al. 1983, Foley et al. 2017). To compare with previous studies (Moczygemba et al. 2012, Foley et al. 2017), I also estimated the annual home range size of nilgai with 95% minimum convex polygons (MCP) using the *adehabitatHR* package in R (Calenge 2011). Although widely used and easy to implement, the MCP method can overestimate home range sizes by inclusion of unused areas and does not adjust for atypical movements (Huck et al. 2008). The MCP method is also sensitive to sampling intensity and outliers (Long and Nelson 2012). Location data for some individuals were incomplete due to mortalities and collar malfunctions; therefore, only nilgai that had >85% of the scheduled fixes for a given month were included in the monthly home range estimations. To be included in the seasonal home range, nilgai had to have been included in each of the 4 monthly home ranges for that period. I estimated an overall home range for nilgai that had fully functioning collars for the entire year.

I tested 3 fixed effects (sex, time period, and capture location) for interactions with home range sizes at the month and seasonal level using a linear mixed model with repeated measures implemented in SAS 9.4 (SAS Institute Incorporated, Cary, NC, USA). To account for temporal correlation between time periods, I compared variance-covariance structures using 9 different models and used the model with the lowest Akaike information criterion (AIC) value (Gann et al. 2019). The 9 models included first-order autoregressive, compound symmetry, and Toeplitz structures, as well as their heteroscedastic versions, variance-components, unstructured, and autoregressive moving average. I tested for normality of residuals using the Shapiro-Wilk test. Home range estimates were not normally distributed, and therefore the analysis was performed on the natural log-transformed scale. After the analysis was completed, I back-transformed the means and presented the results as median estimates (Jager and Looman 1987).

Due to differences in geographic boundaries and anthropogenic features (e.g., roads and fences) between sites, I tested if location influenced home range sizes between the Western and Eastern ranches. The Western sites have portions of 2.5-m net-wire game fence and access to major paved roads. The Eastern site has no game fence and is bordered by the Laguna Atascosa NWR land and the Laguna Madre. Nilgai that made long-distance movements were excluded from the home range analysis if these individuals relocated outside the vicinity of the study area.

**Movement Metrics**

I assessed total distance traveled and maximum axial distance traveled by each nilgai at 4 temporal scales: daily, monthly, seasonally, and overall (Fig. 1.4). I calculated step lengths between fixes using the *amt* package in R, which accounts for gaps in the location data (Signer et al. 2019). I calculated the total distance a nilgai moved by summing the step lengths individual nilgai traveled during each temporal scale. I calculated the maximum axial distance an individual traveled using the 2 farthest locations within each time frame (Foley et al. 2017, Kay et al. 2017). I included the same number of individuals at each temporal scale that were used in the home range analysis. Once again, individuals that moved beyond the study sites were excluded from the overall analysis, however it is important to summarize nilgai dispersal movements to highlight this behavior from a management perspective. Therefore, movement metrics for nilgai that dispersed were calculated separately to document how far they traveled.

I tested 3 fixed effects (sex, time period, and capture location) for interactions with total distance traveled and maximum axial distance at the month and seasonal level using a linear mixed model in SAS. I accounted for temporal correlation between time periods using the same models as described above. After testing for normality of residuals, I performed the analysis on the log scale for each metric, except the total distance traveled at the seasonal level, which I analyzed on the observed scale.

**Peak Hours of Activity**

I downloaded sunrise and sunset times for (lat/long) from the National Oceanic and Atmospheric Administration (NOAA) Global Monitoring Laboratory website (https://www.esrl.noaa.gov/gmd/grad/solcalc). I used the sunrise and sunset times for the 15$^{th}$ day of each month as an average to separate each month into time periods. Time periods included: dawn crepuscular (1 hr before and after sunrise), diurnal (1 hr after sunrise until 1 hr before sunset), dusk crepuscular (1 hr before and after sunset), and nocturnal (1 hr after sunset until 1 hr before sunrise; Morse et al. 2009, Webb et al. 2010). Since GPS locations were collected on the hour, locations were assigned dawn and dusk if the hours fell within the given window for that month. For example, if sunrise time was 0707 the dawn period would be 0607 to 0807. Locations on the 0700 and 0800 hour would be classified as dawn for this month. I calculated average velocity/hr for each individual nilgai. I averaged the step lengths by hour to get a rate of how far a nilgai traveled each hour within each time frame for both sexes. I used these time periods and the average velocity of nilgai to determine peak hours of activity for each month, season, and overall.

## RESULTS

I monitored 30 (19 F, 11 M) collared nilgai during 01 April 2019–31 March 2020. Out of the 30 deployed collars, 18 (15 F, 3 M) collars collected >95% of scheduled fixes during the year. An additional 3 collars on adult males remained on the same nilgai for the year, but the full set of locations was not retrievable due to collar malfunction. Six collars were deployed <1 year: 2 mortalities attributed to capture-related trauma, 2 nilgai were harvested or wounded during hunting activities, and 2 collars dislodged from the animals, 1 damaged by a gunshot during a harvest attempt and the other by wear and tear on the device. The collars used in this analysis collected 215,925 reliable locations throughout the year. In total, only 0.3% (<1% per individual) of locations were removed as outliers.

### Movement Patterns and Behaviors

The preliminary results of the NSD model had a 43% accuracy rate using all hourly fixes and a 57% accuracy rate after resampling to a 13-hr fix rate. After my visual inspection and reclassification, nilgai movement patterns included dispersal (2/30), seasonal ranges (7/30), nomadic (4/30), and resident (17/30; Fig. 1.5). Some nilgai were affected by capture-related activities (i.e., handling, helicopter activities), and displayed abnormal movements coincident with capture events (capture-related excursions). For starting locations, 13 nilgai were analyzed starting on 01 April 2019 and 17 nilgai started at their capture location coordinates on 28–29 March 2019.

There were 2 nilgai that dispersed, both young females (Fig. 1.6). All 4 nilgai that exhibited nomadic behavior were adult males. Out of the resident nilgai, 2 had capture-related excursions, 10 had periods of exploratory movements, and 5 exhibited both capture-related excursions and exploratory movements. There were only 2 young nilgai that were categorized as residents, the other 15 were adult animals. Nilgai with distinct seasonal ranges showed 3 individuals with summer and winter ranges with no overlap and 4 individuals that had slightly overlapping summer and winter ranges. There were 2 adult females and 1 young male nilgai with a seasonal range, the remaining were young females.

**Home Range Sizes and Temporal Variation**

Home range sizes (95% BBMM) per month (n=19–27) differed between sexes (*P*=0.030), where male home range sizes (298 ha, range = 252–352) were 1.6 times greater than females (185 ha, range = 164–210). There was an interaction between location and month (Fig. 1.7). After holding location constant, home range sizes on the Eastern site exhibited more month-to-month variation (*P*<0.001; range = 163–539 ha) than at the Western study area (*P*=0.087; range = 165–291 ha). At the seasonal level (n=19–26), there was a sex and season interaction among home range sizes (*P*=0.012; Table 1.1). During autumn and winter, males had 49% and 42% larger home ranges than females, respectively.

The yearly median core area estimate (50% BBMM) for females was 108 ha (range = 23–225) and for males 205 ha (range = 46–219). There was no sex effect on monthly core ranges with an estimate of 32 ha (range = 29–36) for females and 46 ha (range = 39–53) for males. Core range sizes showed an interaction between location and month (*P*<0.001), again with more variation between months on the Eastern site (range = 27–69 ha) than the Western sites (range = 26–52 ha). At the seasonal level, there was a sex and season interaction (*P*=0.012; Table 1.1). The core range for females did not significantly fluctuate between seasons. Males had 58% and 56% larger core ranges than females in autumn and winter, respectively.

There were 16 (13 F, 3 M) individual nilgai that had year-round locations, not including individuals that dispersed, to estimate overall home and core range size. The yearly median home range estimate (95% BBMM) for females was 593 ha (range = 105–1,545) and for males 937 ha (range = 221–1,602). The MCP method produced yearly estimates of 969 ha (range = 126–7,529) for females and 1,707 ha (range = 464–5,265) for males.

**Movement Metrics**

Nilgai traveled <500 m/hr 95% of the time throughout the year (Fig. 1.8). The median distance traveled per hr was 58 m/hr for females and 69 m/hr for males. Only 1% of distances were >1 km traveled in 1 hr; the maximum axial distance covered in 1 hr by a female was 2.8 km and by a male was 4.8 km.

Nilgai had a daily maximum axial distance of 0.5–1.5 km ~60% of the time (Fig. 1.8). The median daily maximum axial distance traveled for females was 1 km and for males 1.2 km. For females, the greatest daily maximum axial distance traveled was 10.2 km and for males was 9.3 km. Maximum axial distance at the monthly level exhibited both a location ($P$=0.029) and sex effect ($P$=0.045). Nilgai on the Eastern site had a greater monthly maximum axial distance by >1 km than individuals on the Western sites. Males (4.8 km, range = 4.4–5.3) had a greater monthly maximum axial distance than females (3.8 km, range = 3.6–4.1). At the seasonal level, maximum axial distance had a location effect ($P$=0.008), where nilgai the Eastern site traveled >2 km further seasonally than on the Western sites. The overall maximum axial distances for nilgai with a full year of locations ranged from 4.76–40.16 km (Table 1.2).

Nilgai traveled a total daily distance of <5 km 90% of the time (Fig. 1.8). The median total daily distance for females was 2.7 km and for males 3.3 km. The greatest total daily distance traveled by a female was 12.7 km and for a male 16.1 km. There was a sex effect

(*P*=0.004) on total distance at the monthly level, where males (112 km, range = 106–119) moved a greater total monthly distance than females (90 km, range = 87–94). Total distance at the monthly level had an interaction of location and month (*P*<0.001) with more variation across months on the Eastern site (range = 85–148 km) than the Western sites (range = 83–111 km). Male nilgai had the greatest space use during the winter months and on average always had greater space use per month than females (Fig. 1.9). Total distance at the seasonal level exhibited a 3-way interaction of location, sex, and season (*P*=0.022). After holding location constant, sex and season interacted at the Eastern site (*P*=0.007; Fig. 1.10); there was no interaction (*P*=0.341) at the Western study sites. Total distance traveled per season differed between females and males. During autumn, males traveled 560 km (range = 519–602) while females traveled 390 km (range = 368–413). In winter, males traveled 581 km (range = 546–616) and females traveled 355 km (range = 333–377).

Resident nilgai had an overall maximum axial distance of 4.76–13.36 km. Nilgai that used seasonal ranges had a maximum yearly distance of 6.89–18.60 km. Nilgai that left the study area traveled a maximum axial distance of 38.91–40.16 km during the year. The first nilgai to disperse (ID 35123), had its transfer phase in April and May; this individual had a maximum axial distance moved of 20.3 km in April and 34.7 km in May. Comparatively, the other female nilgai had a maximum axial distance ranging from 1.4–13.3 km in April and 2.2–7.5 km in May. Nilgai 35123's greatest 1-day distances were 12.11 km maximum axial distance and 20.13 km total daily distance, occurring on separate days in May. The other disperser (ID 35130) transitioned 3 times between ranges during August, September, and November, where this individual moved a maximum axial distance of 24.18 km, 16.56 km, and 10.58 km, respectively. Nilgai 35130 had a maximum axial distance ranging from 1.7–15.9 km in August, 2.4–11.7 km in September, and 2.2–5.9 km in November. Nilgai 35130's greatest 1-day distances were 14.6 km maximum axial distance and 19.1 km total daily distance, occurring on the same day in August.

### Peak Hours of Activity

Nilgai were most active during crepuscular periods, with an additional spike in movement during the early morning hours (Fig. 1.11). These 2 primary peaks closely corresponded to sunrise and sunset times. Peak hours of activity during the summer for both sexes were 0100–0300, 0600–0800, and 1900–2100. Female movement ranged from a high of 290 m at 2000 to a low of 70 m at 2300. Male movement was also highest at 2000, with an average of 314 m moved and a low of 80 m at 1200. Primary peak hours during the autumn for both sexes were 0600–0800, and 1800–2000. Secondary peaks differed between sexes, with females peaking from 0000–0200 and males peaking from 0100–0300. Female movement peaked at 1900, with an average of 192 m moved and was lowest at 1400 with 91 m moved. Male movement was at a high of 262 m at 0700 and at a low of 78 m at 1400. In the winter, both sexes had peak hours of activity from 0000–0200, 0700–0900, and 1700–1900. Peak in female movement was greatest at 1800, with an average of 231 m moved and at a low of 54 m at 0500. Male movement peaked at 320 m at 1800 and was lowest at 0500 and 0600, with an average of 102 m moved.

## DISCUSSION

Host movements can be significant in the management of vector-borne diseases. Relatively little is known about nilgai antelope in their native or introduced ranges. Recent studies reported large and variable ranges, but the behavioral and environmental drivers of space use were not quantified, making it difficult to integrate into management decisions (Moczygemba et al. 2012, Foley et al. 2017). My study revealed insights into nilgai movement behavior and patterns, including female dispersal events and the influence of estimation methods on home ranges.

**Movement Patterns and Behaviors**

Two collared females left their area of residence, each doing so in a unique way. Nilgai 35123 immediately left the study area after capture, and spent April exploring. In early May, it transitioned to resident behavior in a new area. This individual traveled roughly 180 km in 2 months, and crossed into Willacy County, outside of the temporary preventive quarantine area. Nilgai 35130 remained in the area of capture for the entirety of the summer season before dispersing in 3 movement segments in the duration of the year. In August, 35130 traveled ~24 km from the Eastern site to a new area in roughly 3 days. Six weeks later, 35130 traveled ~17 km further south in less than 2 days. In late November, 35130 made one last move ~9 km further south, where it remained in a wildlife refuge area just north of the Texas-Mexico border. With only 2 individuals dispersing in different seasons, it is difficult to pinpoint what the typical dispersal period looks like for this population. From a management standpoint, the lack of information makes it hard to anticipate when young nilgai will be on the move.

Previous studies suspected female dispersal in nilgai after reporting females with a maximum monthly distance of 24.4–37 km (Foley et al. 2017). Other mammal species that display female dispersal include the white-lined bat (*Saccopteryx bilineata*), chimpanzee (*Pan troglodytes*), pika (*Ochotona princeps*), mountain gorilla (*Gorilla gorilla*), and African wild dog (*Lycaon pictus*; Greenwood 1980). A common driver of female dispersal is that it allows subordinate females to breed and raise young without interference from dominant females (Clutton-Brock and Lukas 2012). There were 19 collared females (7 young and 12 adult) in this study, and 2 young females dispersed. The dispersers were categorized as young, but an exact age or sexual status is unknown. In South Texas, females reach sexual maturity at 2 years of age, but typically do not produce offspring until a year later (Leslie 2008). Females can demonstrate intrasexual agonistic behavior by neck fighting and showing aggression towards other females (Leslie 2008). This type of behavior could result in the dispersal of subordinate females.

Another driver of female dispersal is to avoid competition with kin (Clutton-Brock and Lukas 2012). Class C female antelopes will form groups based on shared home ranges or similar physiological states, but groupings are not a result of kinship (Jarman 1974). Female nilgai exhibit grouping behavior where adults with calves and yearling cows are often seen together in groups of 4–20 (Fall 1972, Sankar et al. 2004, Leslie 2008). In Texas, biological seasons are not strictly defined, resulting in calves being present throughout the year (Sheffield et al. 1983, Leslie 2008). Undefined seasons could result in differing dispersal timings between individuals. Female dispersal could result in the protection of their young from predators or male infanticide (Clutton-Brock and Lukas 2012). To my knowledge, there has been no documented case of male aggression toward young offspring. Nilgai in South Texas lack natural predators, with most mortalities linked to human activities (Leslie 2008, Goolsby et al. 2018).

Dispersal in animals is a complex process that is difficult to understand. When an individual leaves its natal area, venturing into the unknown can be costly with no guarantee of reproductive success (Greenwood 1980). In most mammal species, dispersal is male-biased (Coulon et al. 2006), especially for species that are polygynous (Greenwood 1980). Female-biased dispersal is common in birds, where a male defends a resource to acquire a receptive female (Greenwood 1980). A common trait of class C antelopes is the defecation markings by territorial males (Jarman 1974). Adult male nilgai will defend a territory that is marked by latrines, where individuals repeatedly defecates in the same location (Fall 1972, Bayani and

Watve 2016, Goolsby et al. 2017, Zoromski 2019). Latrines are mostly visited by older adult males, with increasing usage during breeding season (Zoromski 2019). Male nilgai aged ≥4–6 years old make up most breeders (Lochmiller and Sheffield 1989). Therefore, it is likely that these resident males defend a territory and do most of the breeding.

Although female nilgai appear more prone to disperse, males also moved considerable distances. During rut, some males that do not maintain a defined territory may use a system termed ‘roving territoriality,’ where bulls travel in search of a female (Sankar et al. 2004, Sheffield et al. 1983). This roving behavior could explain why only adult males were found to be nomadic within the parameters of this study. In March, an adult male nilgai (ID 35110B) that exhibited nomadic behavior moved ~12 km in 2 days from the Eastern site to north of the Western sites, where the individual spent 12 days until returning to the Eastern site. Three days later, the nilgai traveled the same path back to north of the Western sites for a day before returning to the Eastern site yet again. Irregular movements like this example can make it difficult to predict when and where nilgai are moving.

When a host species leaves its area of origin 1 of 2 things can occur: 1) the host can carry parasites to novel areas, or 2) the host could bypass parasites by moving away from highly infested areas (Peacock et al. 2018). In South Texas, tick populations are generally highest during June–August, corresponding with high rainfall events (Pérez de León et al. 2012, Foley et al. 2017). Therefore, nilgai using seasonal ranges may be a more susceptible host during certain times of the year. The individuals that dispersed made movements in April, May, August, September, and November, all of which could have resulted in the movement of ticks. Over half of the nilgai in this study exhibited movement representative of resident behavior, which could maintain local infestations. However, non-resident nilgai appear to pose the greatest risk of moving CFT across ranches throughout South Texas. Similar movement behaviors were observed in elk, where resident, migratory, and dispersal events all occurred within the same population (Killeen et al. 2014).

Collecting more than a year of data for each animal would have been beneficial in determining if movement patterns such as the seasonal ranges were consistent over multiple years or just a 1-time occurrence. The nilgai captures and timing of collar deployment may have affected the conclusions. In addition to the initial capture, the nilgai were recaptured in September, resulting in capture-related movements midway through the study. Some nilgai altered their normal movement patterns for multiple days or a week after the 2$^{nd}$ capture. Due to hunter harvest, relocation of collars, and collar malfunctions, there were 12 individuals that did not have a full year of data. The insufficient amount of data for these individuals made it hard to determine patterns when only a season or 2 was available. Nilgai with separate seasonal ranges could have dispersed or done a small-scale migration, however I only monitored these specific nilgai for a year. Although nilgai are considered a non-migratory species, they could be shifting their ranges based on seasonal changes. However, without enough information to support dispersal, I classified these individuals as having seasonal ranges based on their movement patterns during the year. Future studies should consider monitoring the same individuals for >1 year to gain a better understanding of nilgai behaviors over time.

**Home Range Sizes and Temporal Variation**

Similar to previous studies, I observed that nilgai home range sizes have high individual variation regardless of sex (Moczygemba et al. 2012, Foley et al. 2017). However, the method of estimation used in home ranges had a dramatic effect on home range size. Previous home range estimates were produced using MCP, which can inflate estimates (Huck et al. 2008), and included individuals that left the study area and traveled 9–37 km in a given month (Foley et al. 2017). Compared to the BBMM home ranges, the previous estimates were 1.7 and 2.7 times greater for females and males, respectively. I found that males had a significantly larger home range size than females during the autumn and winter seasons, contrary to previous reports (Foley et al. 2017). During the summer, males and females had similar home range estimates.

Ranch location influenced the size of 50% and 95% BBMM estimates of nilgai at the monthly level. Movement behaviors differed between individuals collared on each site. There were 13 nilgai monitored on the Eastern site and 5 of those individuals were considered resident animals. There were 17 nilgai monitored at the Western sites and 12 individuals were considered resident animals. The location effect could also be a result of other site-specific factors, such as game fence and paved roads. With a higher number of resident individuals and the influence of game fencing, nilgai at the Western sites had less variation among months than at the Eastern site. The Eastern site had more individuals with unpredictable movements, which resulted in higher variation between months.

Previous studies did not deconstruct long-distance movements into a transitional phase between an individual’s origin and new area of residency; by doing so, I was able to depict more accurate home range sizes for nilgai. The BBMM method overall provided a better estimate of nilgai space use than previously used MCP. In this study, the median MCP estimates were 1.6 and 1.8 times greater than the median BBMM estimates for females and males respectively. The BBMM also revealed travel routes outside of an individual’s home range during dispersal and excursion events without including excess areas in the estimate.

**Movement Metrics**

Previously, females were reported to have greater space use, especially during the summer months when tick counts are highest in South Texas (Pérez de León et al. 2012, Foley et al. 2017). By removing the transitional stage of dispersal from the analysis, I was able to determine that males typically moved farther each month than females. Males always had the greatest space use, with rates highest during the winter/breeding months. Although females in this study did have dispersal events during summer months, females in general moved and occupied less space than males. When nilgai that dispersed are included in the population average, it can falsely inflate the average values.

**Peak Hours**

In the previous literature, there have been conflicting accounts of when nilgai are most active. Nilgai are reported to be nocturnal (Singh et al. 2017), diurnal (Sheffield et al 1983, Sankar et al. 2004), and crepuscular (Dinerstein 1979, Chakraborty 1991, Sankar et al. 2004). My study showed nilgai were strongly crepuscular, with increased activity at night during summer and autumn. During the summer months, both sexes followed the same activity pattern, peaking during the same hours. Calving season begins in August, and female activity patterns decreased during the autumn months. Nilgai cows typically keep their calves hidden for about a month before they will be seen together (Sankar et al. 2004). On average, mating season begins in December, where males will begin searching for a receptive female, increasing their daily activity levels during the winter months. Nilgai are valued game animals and activity patterns may be influenced by hunting pressure. Other ungulate species, like elk (*Cercus elaphus*), alter their behavior during hunting season (Amor et al. 2019).

## MANAGEMENT IMPLICATIONS

Wildlife hosts species can threaten livestock health and the livelihood of U.S. ranchers. The movement behaviors and space use of nilgai limits treatment options for CFT. This study demonstrates how nilgai space use can impact CFT eradication efforts on ranches in South Texas. The combination of long-distance movements, seasonal movements, and large home range sizes of nilgai means that nilgai use the landscape at a scale larger than the average property size of 250–6,000 ha in South Texas (Webb et al. 2007). Not only do nilgai cross multiple property boundaries, they have the potential to travel across international and county borders, where management practices differ. With no current treatment option for nilgai within their North American range, CFT is at risk of spreading further outside of the permanent quarantine zone.

The lack of research on basic ecology of nilgai antelope hinders the development of management strategies. My study produced more realistic home range and space use estimates and revealed behavioral drivers behind nilgai movements. Understanding nilgai movement can help better prepare targeted treatment options for nilgai. Identifying movement patterns (female dispersal, use of seasonal ranges, and nomadic behavior), how far an individual can travel, and primary periods of activity are important considerations when creating a disease management plan. This information can be used to model the potential spread of ticks and assess potential treatment strategies. With no current definitive solution to treat nilgai, preventive and supplementary methods may be most effective. An integrated approach may be needed to reduce tick loads in South Texas.

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**Table 1.1.** Seasonal home range (HR) estimates for each sex at the 95% and 50% density level using a Brownian bridge movement model (BBMM) and associated standard errors (SE) of GPS-collared nilgai antelope (1-hr fix rate) in Cameron County, TX, USA, from April 2019–March 2020. Home range estimates were back-transformed from the log-scale, resulting in an upper and lower standard error estimate. Males had larger seasonal home range sizes than females during fall and winter at both the 95% and 50% density levels.

| | | | Female | | | Male | | |
|---|---|---|---|---|---|---|---|---|
| BBMM Level | Season | *P* value | HR Estimate | SE (Lower) | SE (Upper) | HR Estimate | SE (Lower) | SE (Upper) |
| 95% | Summer | 0.766 | 340 | 290 | 400 | 371 | 293 | 469 |
| | Autumn | 0.023 | 366 | 310 | 433 | 752 | 583 | 969 |
| | Winter | 0.006 | 289 | 245 | 341 | 688 | 537 | 880 |
| 50% | Summer | 0.957 | 59 | 51 | 69 | 58 | 47 | 73 |
| | Autumn | 0.050 | 63 | 54 | 73 | 108 | 87 | 135 |
| | Winter | 0.039 | 51 | 44 | 59 | 91 | 73 | 115 |

**Table 1.2.** Overall metrics for 18 GPS-collared nilgai antelope (1-hr fix rate) that had >95% of fixes during April 2019–March 2020 in Cameron County, TX, USA. Home range estimates and maximum axial distance reference nilgai space use throughout the year for each movement behavior. Nilgai that dispersed do not have an overall home range estimate since they transitioned between home ranges during the year. Nomadic nilgai were not included since these individuals did not have >95% of fixes during April 2019–March 2020. Minimum convex polygon (MCP) estimates are provided to demonstrate the difference in size compared to Brownian bridge movement model estimates (BBMM). (M=male, F=female, A=adult, Y=young, WS=Western Sites, ES=Eastern Site)

| Collar ID | Movement Strategy | Sex | Age | Location | 95% MCP (ha) | 95% BBMM (ha) | 50% BBMM (ha) | Max Axial Distance[1] (km) |
|---|---|---|---|---|---|---|---|---|
| **35107** | Resident | M | A | WS | 464 | 221 | 46 | 4.76 |
| **35113** | Resident | F | A | WS | 340 | 232 | 42 | 5.21 |
| **35117** | Resident | F | A | ES | 312 | 179 | 28 | 13.36 |
| **35119** | Resident | F | Y | WS | 1077 | 593 | 93 | 6.59 |
| **35121** | Resident | F | A | WS | 695 | 441 | 108 | 5.93 |
| **35125** | Resident | F | A | WS | 969 | 675 | 149 | 6.59 |
| **35126** | Resident | F | A | ES | 126 | 105 | 23 | 5.10 |
| **35131** | Resident | M | Y | WS | 1707 | 937 | 205 | 8.61 |
| **35133** | Resident | F | A | WS | 827 | 621 | 125 | 7.85 |
| **35108** | Seasonal | F | Y | WS | 1429 | 1015 | 225 | 7.29 |
| **35109** | Seasonal | M | Y | ES | 5265 | 1602 | 219 | 15.57 |
| **35111** | Seasonal | F | A | ES | 909 | 308 | 60 | 6.89 |
| **35112** | Seasonal | F | A | ES | 5543 | 1331 | 204 | 13.59 |
| **35116** | Seasonal | F | Y | WS | 2052 | 532 | 96 | 10.02 |
| **35128** | Seasonal | F | Y | ES | 7529 | 1545 | 170 | 18.60 |
| **35129** | Seasonal | F | Y | ES | 3754 | 1103 | 157 | 12.96 |
| **35123** | Dispersal | F | Y | WS | - | - | - | 38.91 |
| **35130** | Dispersal | F | Y | ES | - | - | - | 40.16 |

[1]=Maximum axial distance is the greatest distance between 2 points during the year.

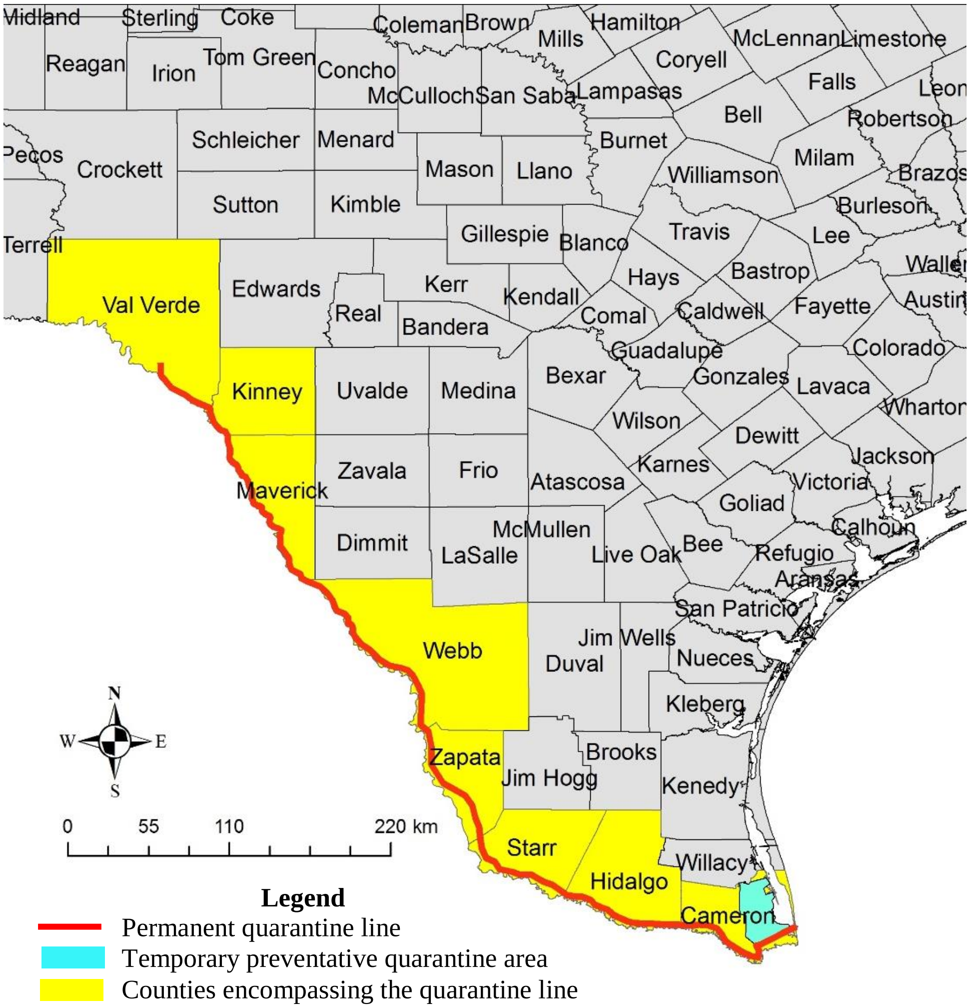



**Figure 1.1.** The location of the permanent quarantine zone and temporary preventative quarantine area in Texas, USA. The permanent quarantine zone acts as a buffer to prevent the re-infestation of cattle fever ticks in the U.S. The temporary preventative quarantine area was created in 2014 after wildlife were implicated in cattle fever tick outbreaks.

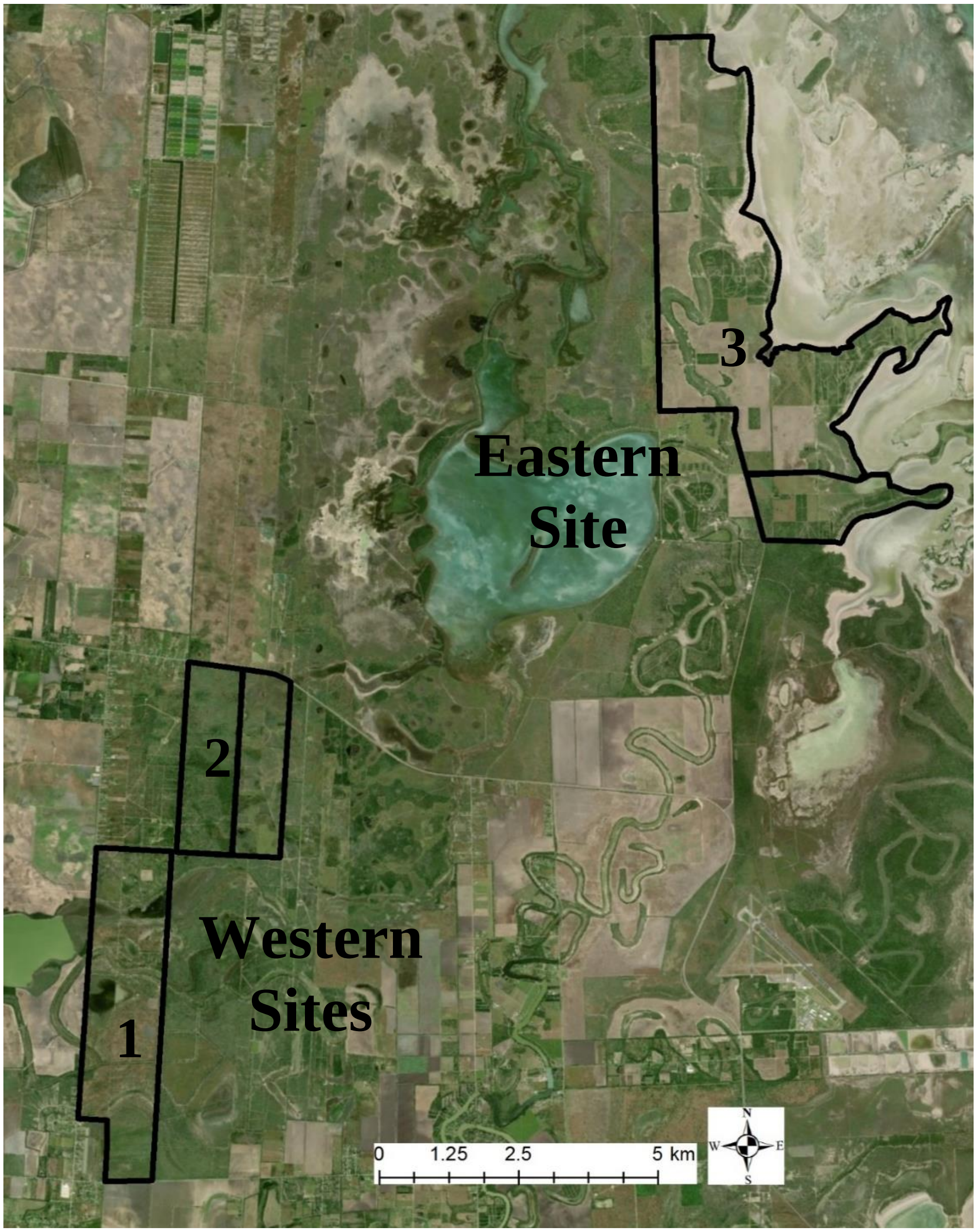



**Figure 1.2.** Study sites in Cameron County, TX, USA, where 30 nilgai antelope were fitted with GPS-collars during April 2019–March 2020. Ranches 1 and 2 were grouped together to form the 'Western sites' because nilgai home ranges were larger than the property boundaries.

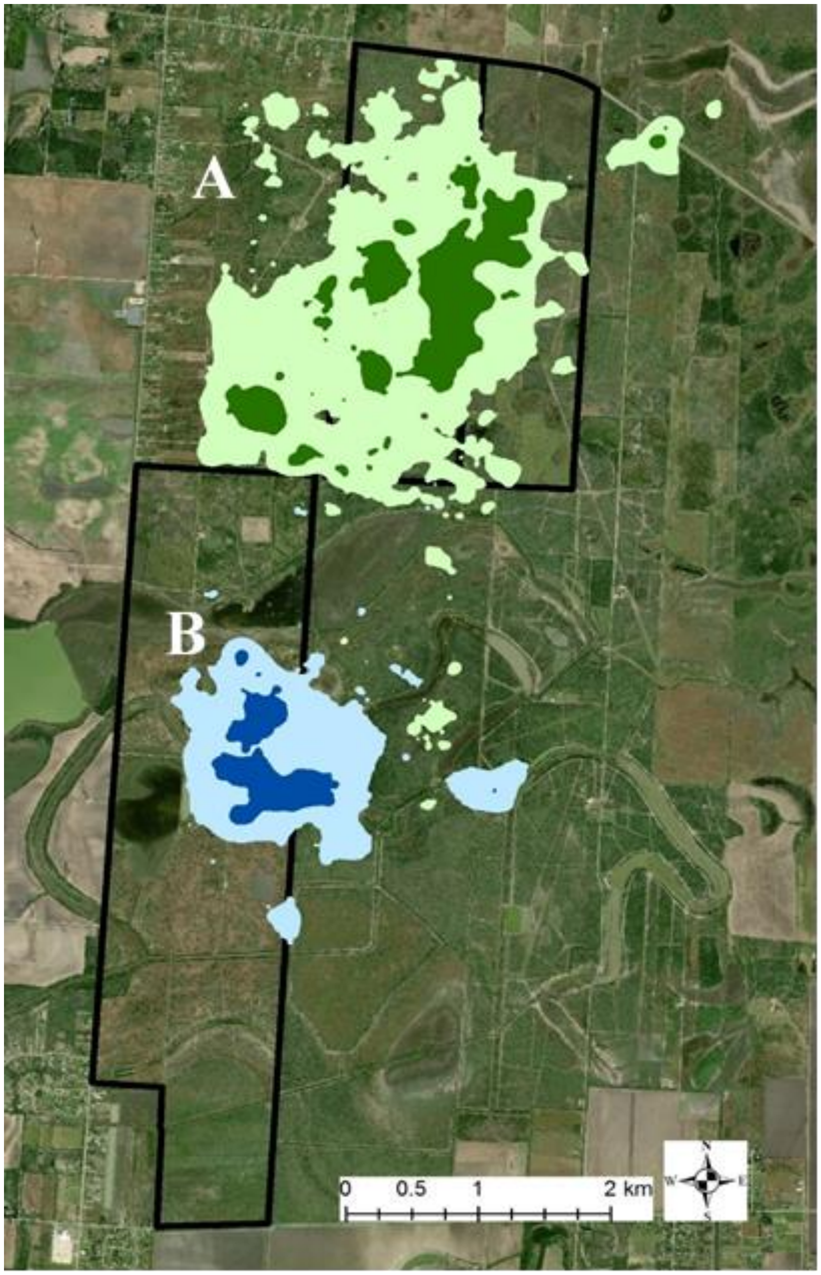
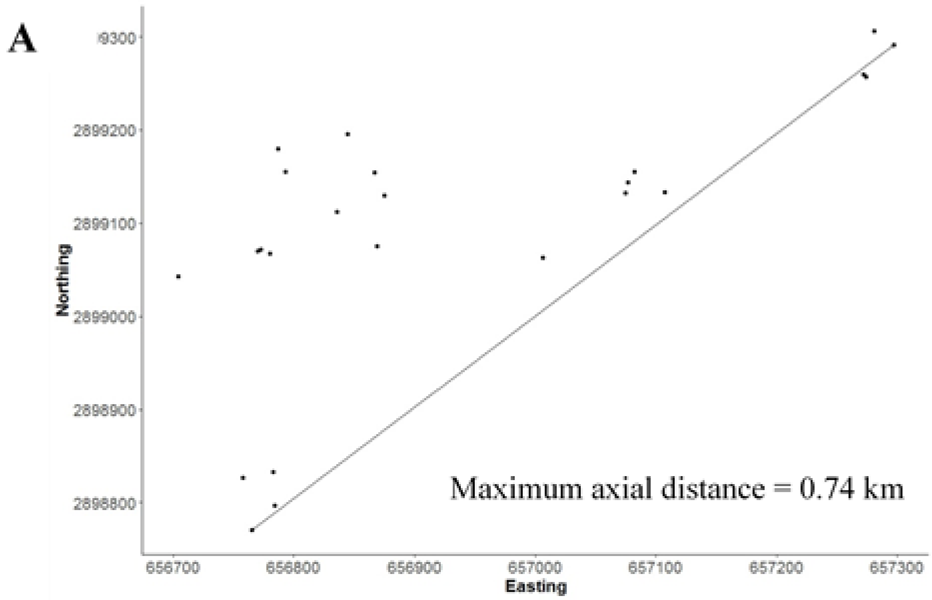



**Figure 1.3.** Examples of the Brownian bridge movement model (BBMM) home range estimates for (A) a female and (B) a male nilgai antelope at the Western sites in Cameron County, TX, USA, from April 2019–March 2020. The BBMM were estimated using GPS locations collected at a 1-hr fix rate. The 95% BBMM are represented by the lighter outer polygons and the 50% BBMM are the darker inner polygons.



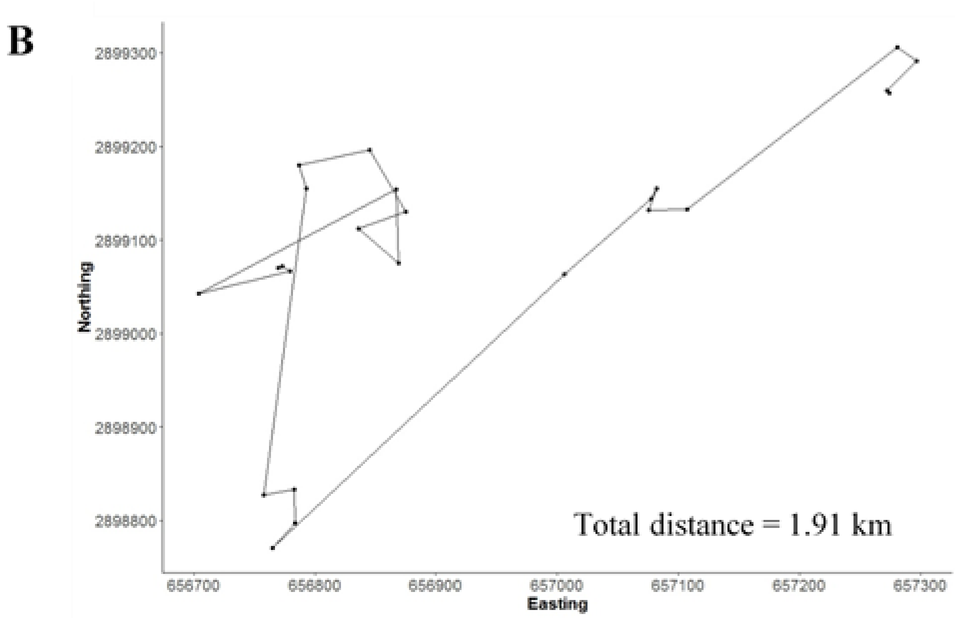




**Figure 1.4.** Illustration of how to calculate maximum axial distance and total distance using 1 day of locations derived from hourly GPS locations from a collared female nilgai antelope in Cameron County, TX, USA, on 27 June 2019. (A) An example of maximum axial distance between points traveled in 1 day. (B) An example of total cumulative distance an animal traveled between subsequent points in 1 day.

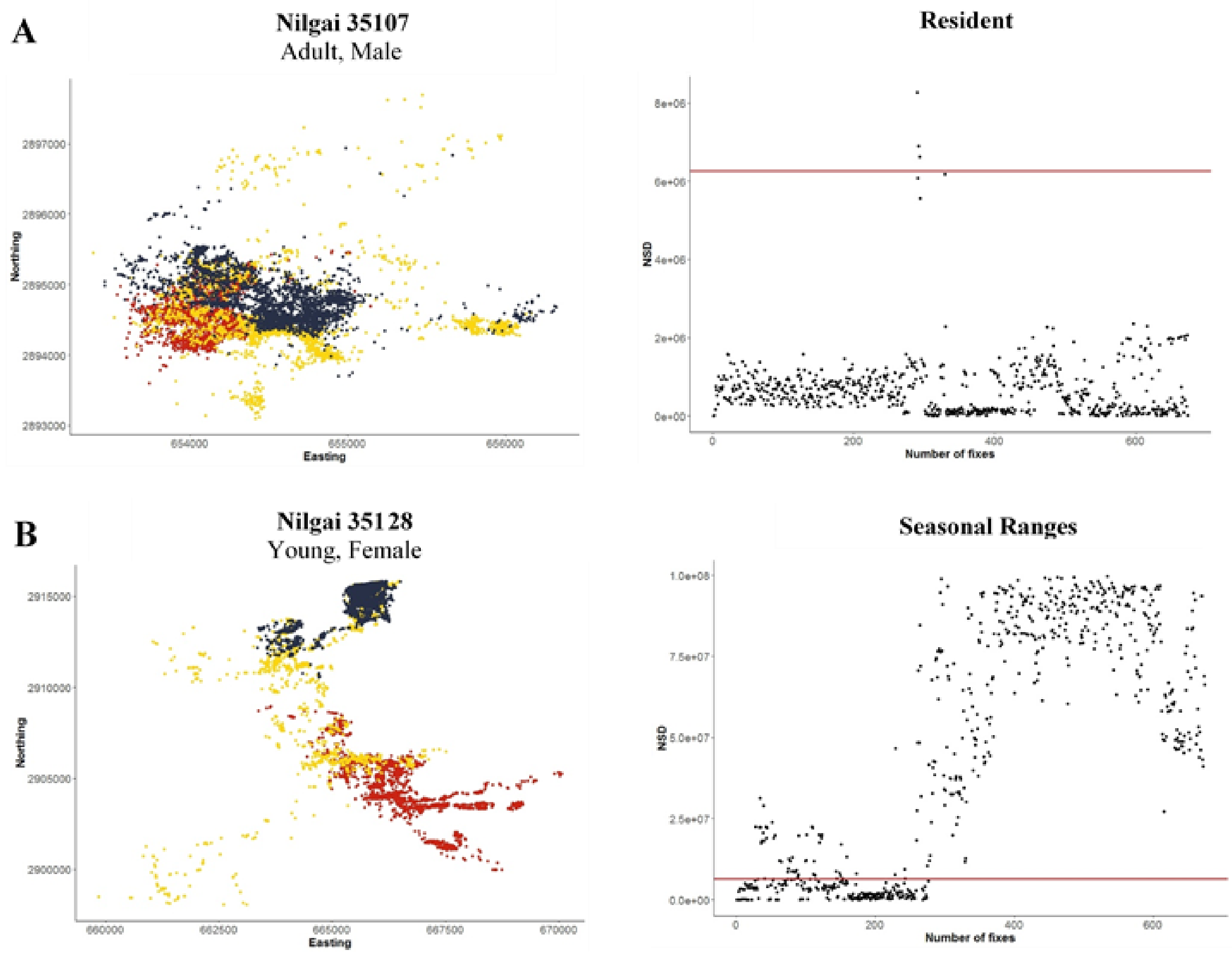



**Figure 1.5.** Movement patterns of GPS-collared nilgai antelope (1-hr fix rate) in Cameron County, TX, USA, from April 2019–March 2020. The left column illustrates the geographic locations of a nilgai from each of the 4 movement pattern classifications: (A) resident, (B) seasonal ranges, (C) nomadic, and (D) dispersal. The locations are color coded by season: summer (red), autumn (yellow), and winter (blue). The right column contains the net squared displacement (NSD) graphs that corresponds to the locations to the left. The red horizontal line on the NSD graphs is a uniform marker across all 4 rows that marks 2.5 km from the starting location of each individual.

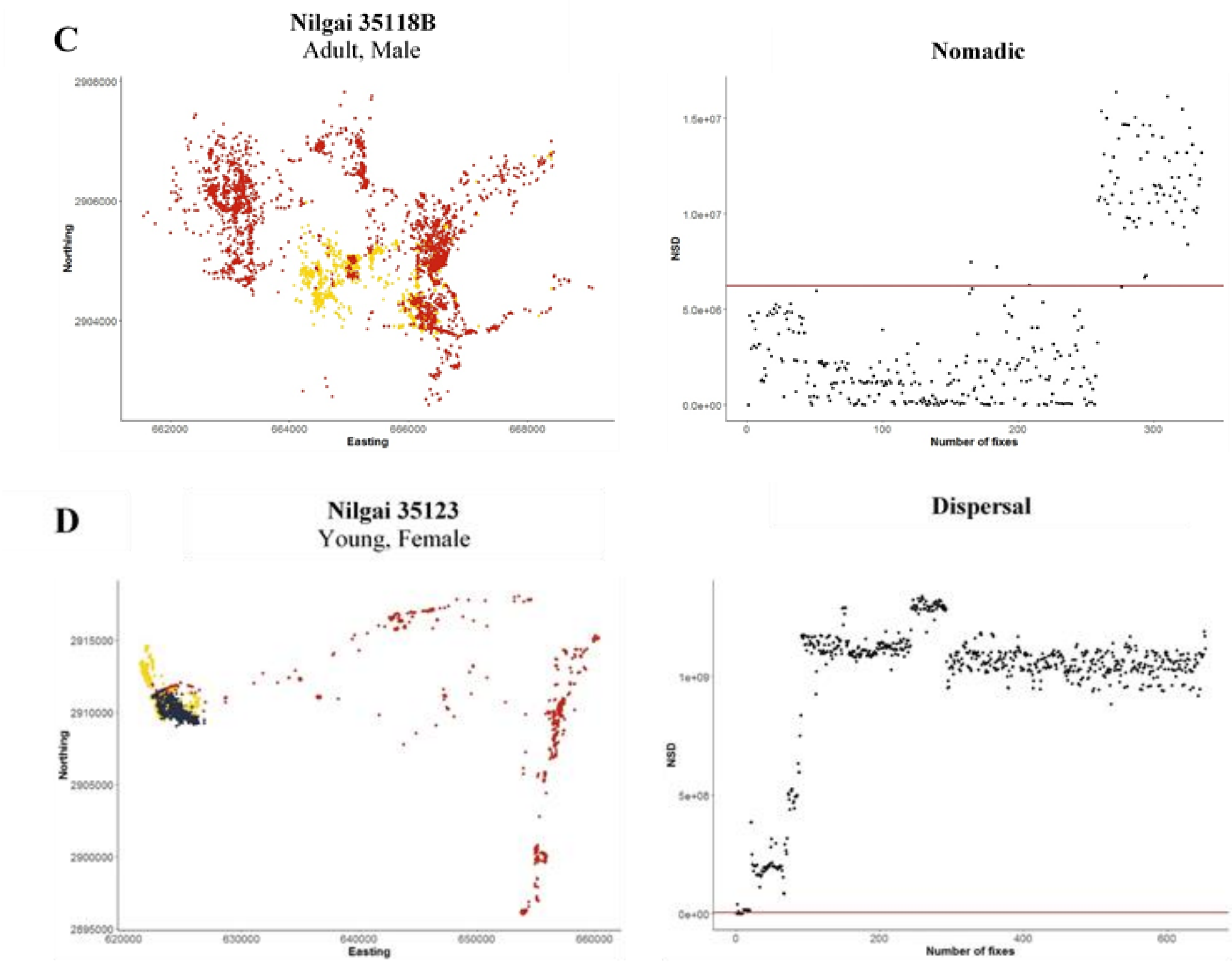



Figure 1.5 continued.

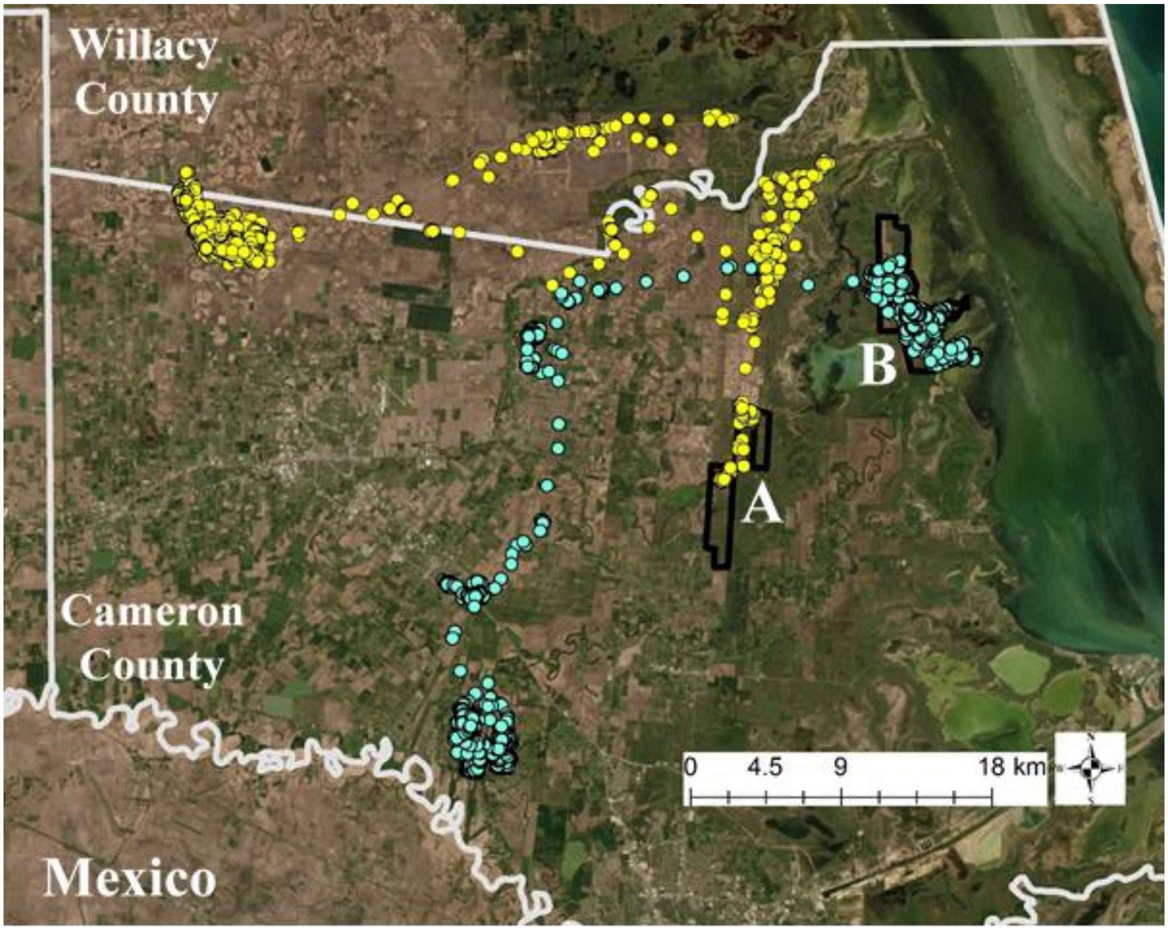



**Figure 1.6.** GPS locations (1-hr fix rate) for the 2 young female nilgai that dispersed in Cameron County, TX, USA, during April 2019–March 2020. (A) Nilgai 35123 (yellow) was captured on the Western sites and (B) nilgai 35130 (blue) was captured on the Eastern site.

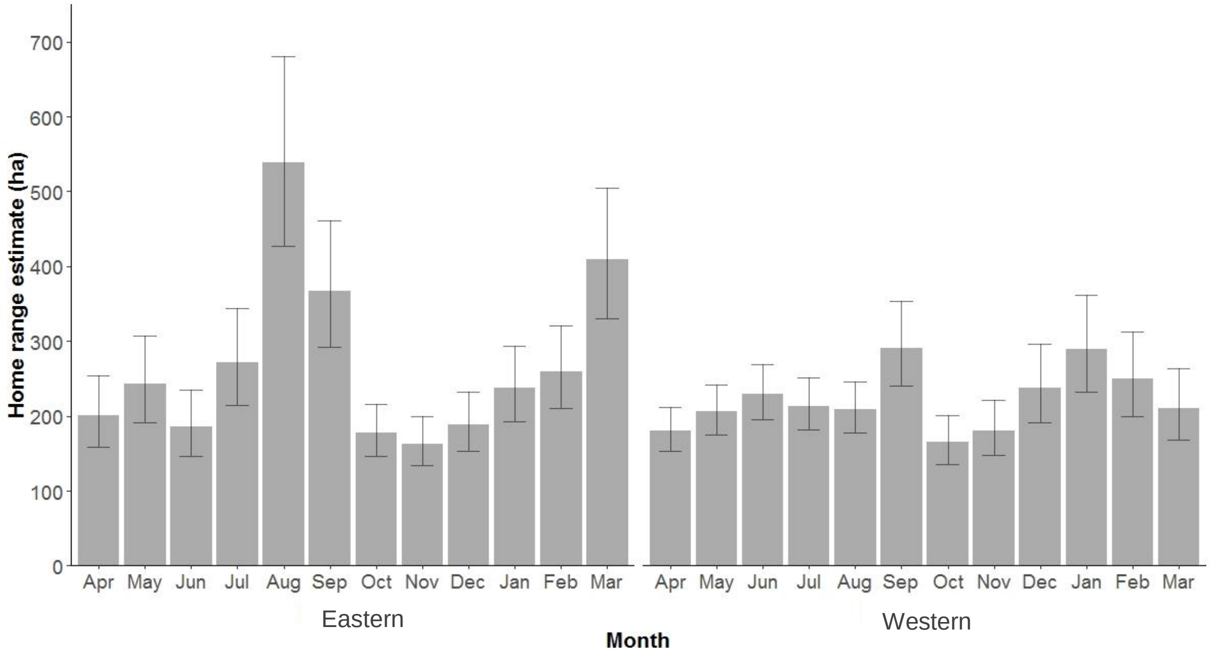



**Figure 1.7.** Monthly Brownian bridge movement model home range estimates derived from GPS-collar data (1-hr fix rate) at the 95% density level and associated standard errors of 19–27 nilgai antelope in Cameron County, TX, USA, from April 2019–March 2020. Home range sizes varied among months at the Eastern site. Nilgai on the Western sites displayed less variation in size over time.

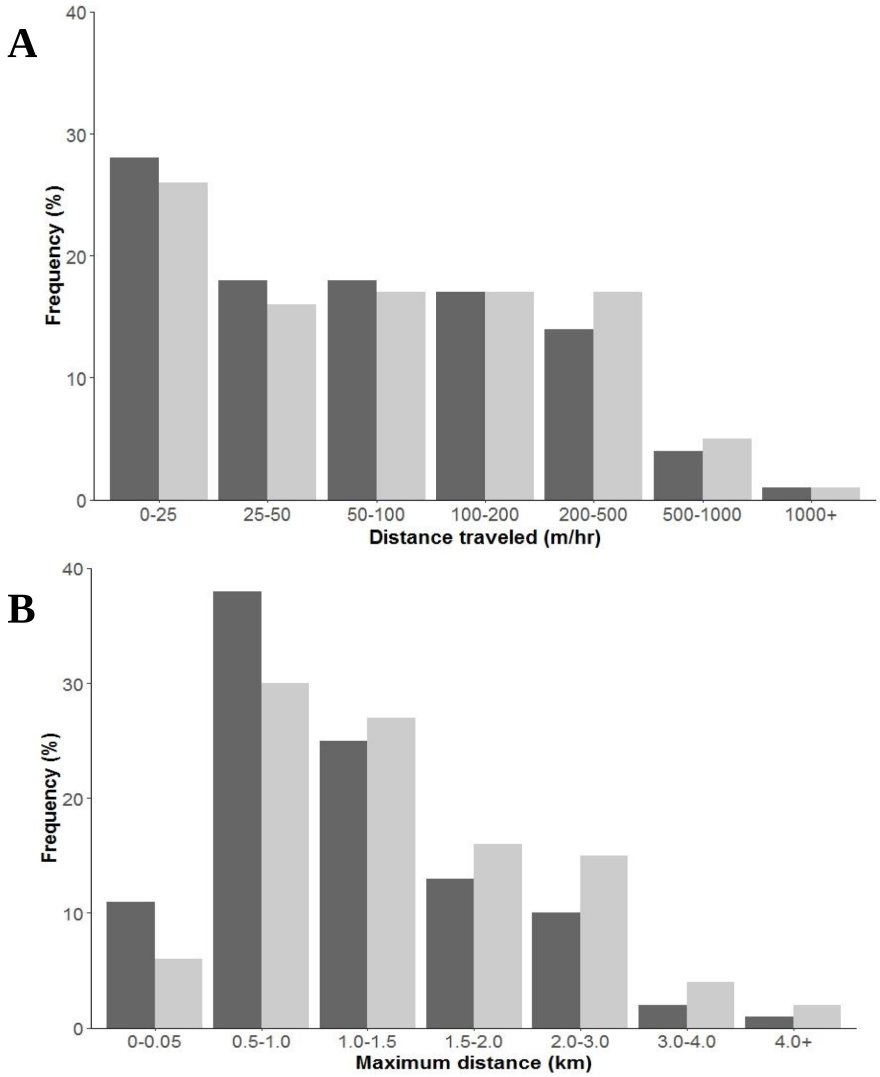



Figure 1.8. The frequency of daily movement metrics of nilgai antelope in Cameron County, TX, USA, from April 2019–March 2020. Daily movement metrics were calculated for distance traveled per hour, maximum distance traveled in a day, and total distance traveled in a day using GPS locations collected every hour. (A) Using all collected nilgai locations (female=19, male=11), the distance traveled during each hour was summarized for both sexes. (B) The maximum axial distance traveled each day by each individual was calculated and summarized for both sexes. (C) The total distance each nilgai traveled each day was cumulated and summarized for both sexes.

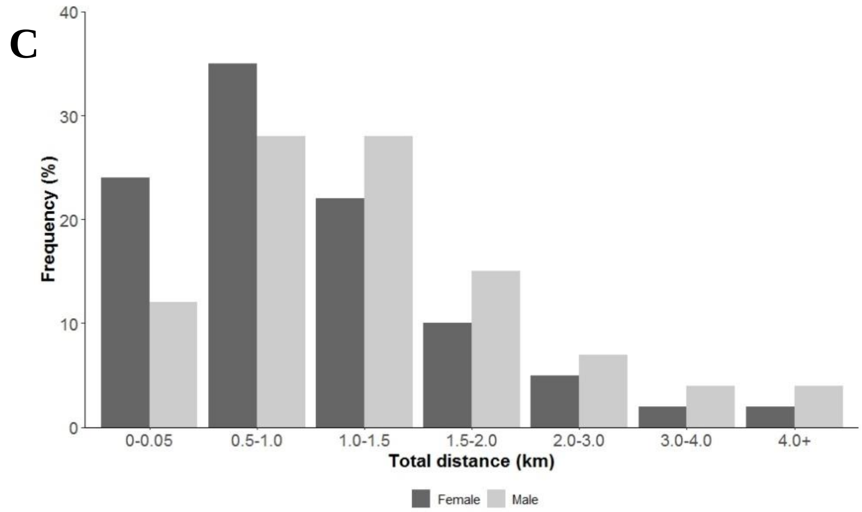



Figure 1.8 continued.

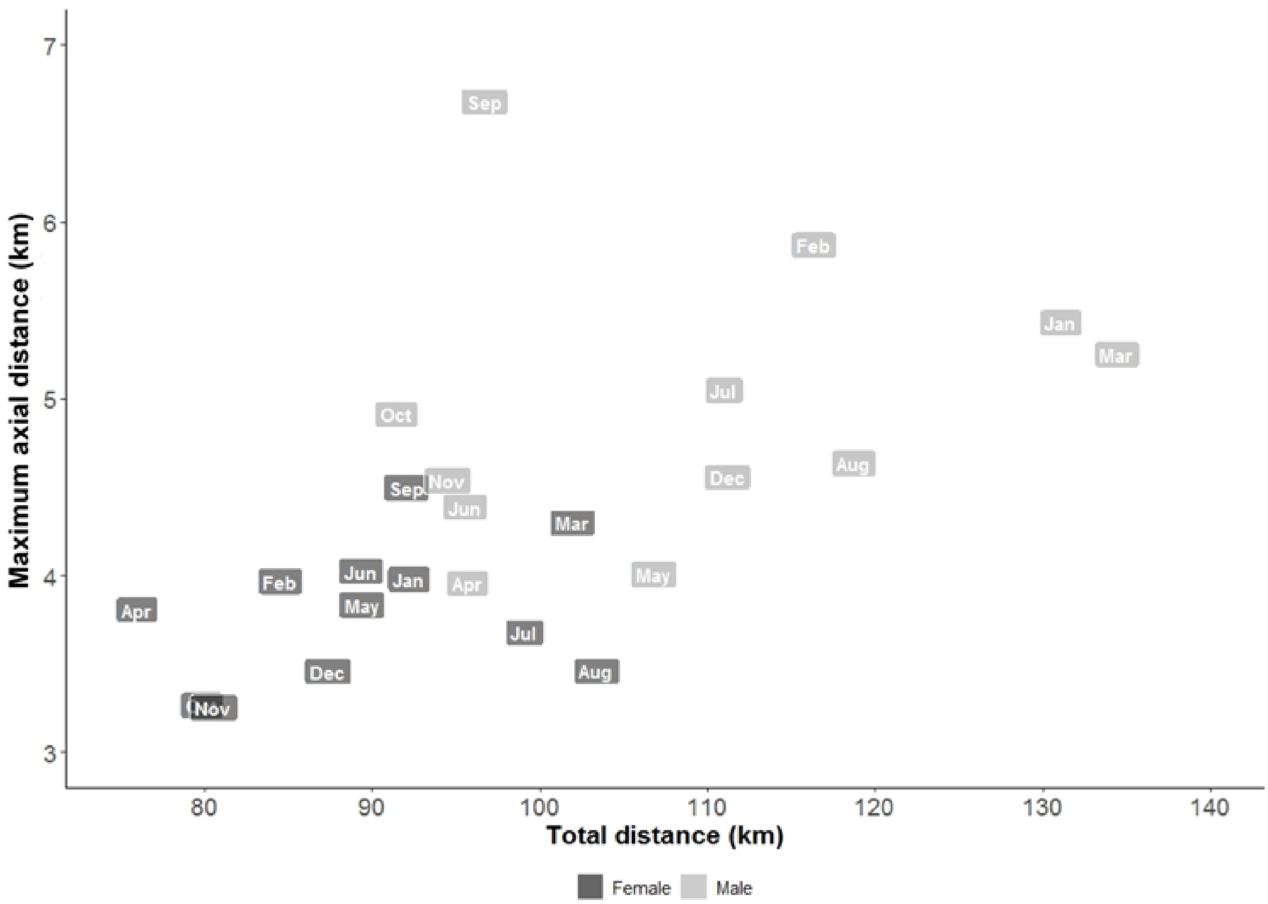



**Figure 1.9.** Observed monthly space use between sexes of GPS-collared nilgai antelope (1-hr fix rate) in Cameron County, TX, USA, during April 2019–March 2020. Maximum axial distance (km) was defined as the farthest distance between 2 points within a month for each sex. Total distance (km) was the cumulative sum of all step lengths during a month for each sex. The bottom-left portion of the graph indicates nilgai were more sedentary whereas the top-right portion indicates nilgai were more mobile.

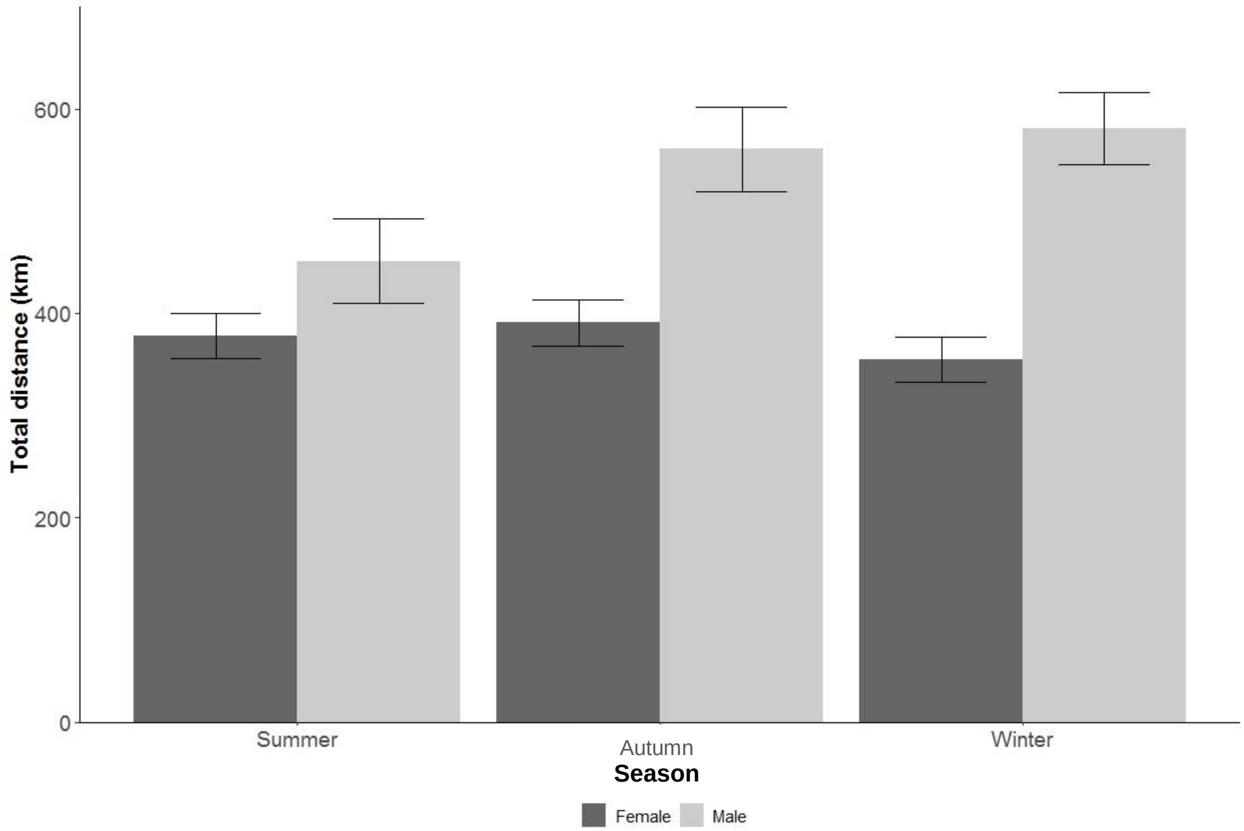



**Figure 1.10.** Median total distance and standard error traveled by GPS-collared nilgai antelope (1-hr fix rate) for each season and sex on the Eastern site in Cameron County, TX, USA, from April 2019–March 2020. Males traveled more than females during the autumn and winter on the Eastern site.

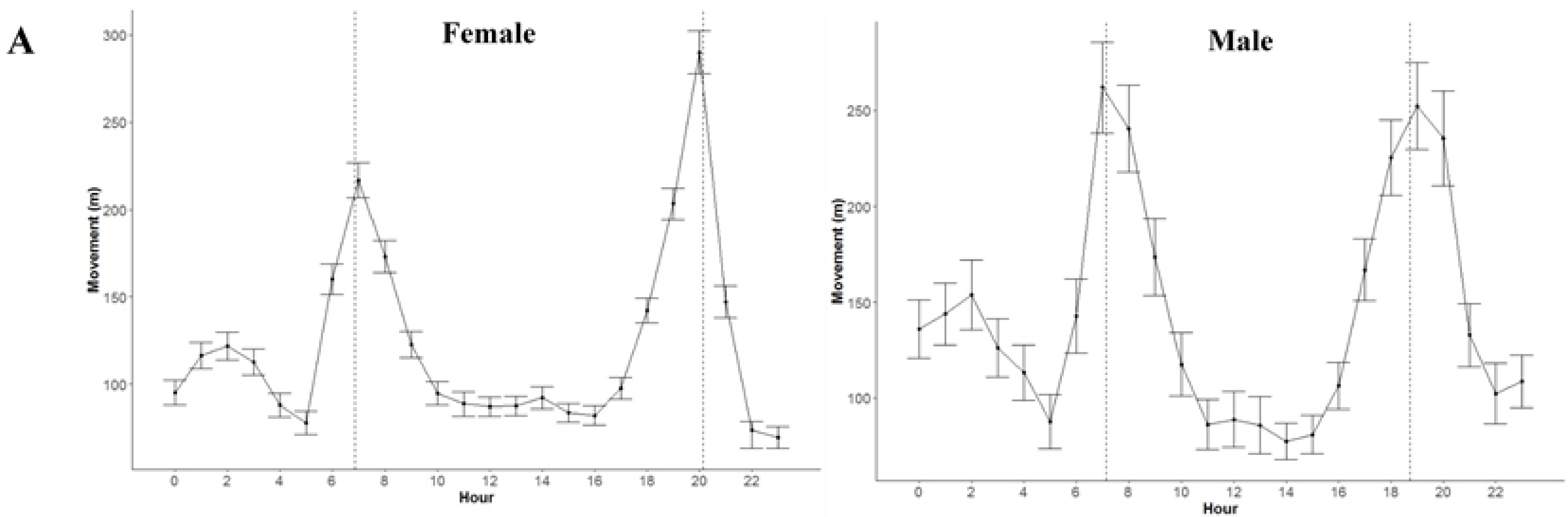



**Figure 1.11.** Seasonal variation in peak hours of activity (95% CI) for GPS-collared nilgai (1-hr fix rate) in Cameron County, TX, USA, from April 2019–March 2020: (A) summer (April-July), (B) autumn (August-November), and (C) winter (December-March). The vertical dashed lines represent average sunrise and sunset times during each season.

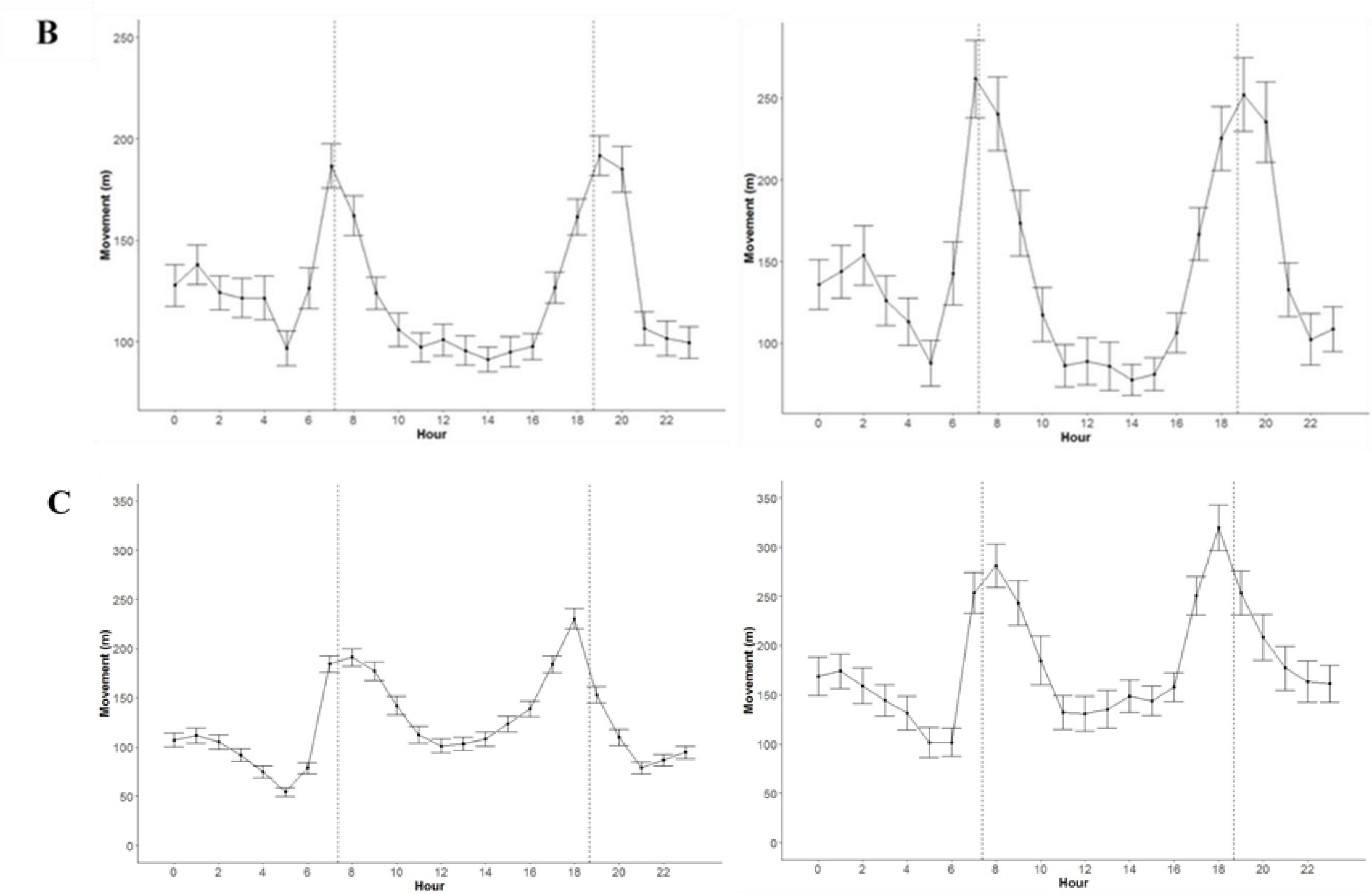



Figure 1.11 continued.

# CHAPTER II. HABITAT SELECTION OF NILGAI ANTELOPE IN SOUTH TEXAS

**ABSTRACT** Foraging activities and resource availability can influence the home range size and movement of animals. Understanding how a species selects habitat features across a landscape can provide managers information for wildlife and disease management. Nilgai antelope (*Boselaphus tragocamelus*) are an exotic ungulate species that has naturalized in South Texas, USA. Nilgai are a suitable host for cattle fever ticks (CFT), *Rhipicephalus (=Boophilus) microplus* (Cannestrini) and *R. (B.) annulatus* (Say), which can transmit bovine babesiosis. Bovine babesiosis can be deadly in cattle and is a major concern for livestock producers. Nilgai are a large, intermediate feeder whose diets overlap with both white-tailed deer (*Odocoileus virginianus*) and cattle, depending on the time of year and range condition. Although nilgai have been in Texas for almost a century, there is very little information on nilgai ecology and habitat selection. With the threat of re-infestation of cattle fever ticks throughout the region, research on nilgai movement and habitat selection is needed. In this study, I evaluated habitat selection of exotic nilgai antelope in South Texas based on global positioning systems (GPS) locations from 30 collared animals during 2019–2020. Nilgai selected for woody and mixed cover regardless of season or sex. Nilgai had similar patterns of selection and avoidance each season regardless of whether individuals were resident or displayed seasonal movements. There were 79 road-crossing events by 9 individual nilgai within the year. Most collared nilgai did not have access to a paved road due to ranch location or restriction by impermeable game fence. Eradication efforts use treated cattle to remove ticks from the landscape. However, nilgai select for areas with greater brush cover which is also suitable tick habitat. These areas are not frequented by cattle and can act as a source of re-infestation. Understanding how host species use the landscape can aid in the creation of a better cattle fever tick eradication plan for South Texas.

**KEYWORDS** Nilgai antelope, *Boselaphus tragocamelus*, cattle fever ticks, step-selection function, habitat selection, wildlife disease management

Animal movements and home range size are influenced by resource availability, and must support foraging, mate selection, caring for offspring, and predator avoidance (Burt 1943, Beyer et al. 2010, Allen and Singh 2016). Individuals will select habitat to best suit their needs, which will vary based on sex, season, and age (Burt 1943). Habitat selection analyses can help identify how the distribution of resources on the landscape affects animal movements (Beyer et al. 2010). Understanding how a species selects habitat features across a landscape can provide information for conservation as well as management of diseases transmitted by wildlife (Allen and Singh 2016).

Diseases transmitted by wildlife present a serious challenge to management because treatment of wildlife is often difficult or impossible. In the case of vector-borne diseases, habitat selection analyses can identify the spatial overlap of vulnerable hosts. The cattle fever ticks (CFT), *Rhipicephalus (=Boophilus) microplus* (Cannestrini) and *R. (B.) annulatus* (Say), can transmit bovine babesiosis, which is a major concern for livestock producers in the trans-border region of South Texas (Bock et al. 2004, Gohil et al. 2013). A permanent quarantine zone was established along the Texas and Mexico border to prevent re-infestation of CFT from endemic areas in Mexico. Wildlife are suitable alternative hosts for CFT, including the exotic nilgai antelope (*Boselaphus tragocamelus*; Goolsby et al. 2017, Singh et al. 2017).

Nilgai were first introduced as a game species to South Texas in 1924 on the King Ranch's Norias Division, and have successfully colonized much of coastal South Texas (Sheffield et al. 1971). Free-ranging populations of nilgai range from Baffin Bay to Brownsville, TX, and in northern Mexico as far west as Durango; current population estimates report over 36,000 nilgai in southern Texas (Olafson et al. 2018). Native to India, Pakistan, Bangladesh, and Nepal, nilgai are Asia's largest antelope (Sankar et al. 2004). Most nilgai in their native range are located in India, where populations are estimated at 100,000–150,000 (Sankar et al. 2004, Leslie 2008). In India, nilgai are habitat generalists and occupy a mix of thin brush, open grassy plains, areas with dispersed low trees, and occasionally rolling hills (Sankar et al. 2004).

South Texas lies at similar latitudes (10–31º N) to the native range of nilgai, with similar climatic conditions (Sheffield et al. 1971). Nilgai in Texas display similar habitat patterns as in India, frequenting areas with sparse live oak (*Quercus virginiana* [Mill.]), open pastures, coastal prairies, and mixed brush (Tamaulipan thornscrub; Sheffield 1983, Leslie 2008). In Texas, their diet includes 85% grass and herbaceous species and 15% browse species, including mesquite (*Prosopis* spp.), Guinea grass (*Megathrysus maximus*), Lovegrass (*Eragrostis* spp.), crowngrass (*Paspalum* spp.), buffelgrass (*Cenchrus ciliaris*), spikerush (*Eleocharis* spp.), partridge pea (*Cassia fasciculata*), snoutbean (*Rhynchosia* spp.), and live oak (Sheffield 1983). As a large, intermediate feeder, nilgai can compete with both native white-tailed deer (*Odocoileus virginianus*) and cattle, depending on the time of year and range condition (Hines 2016).

Although nilgai have been present on South Texas rangelands for almost a century, there is little information on nilgai ecology and habitat selection. With the threat of CFT re-infestations throughout the region, research on nilgai movement and habitat selection is needed. Cattle are regularly treated within the quarantine zone and can be effective at removing ticks from the landscape. However, ranches without cattle and areas not frequented by cattle have the potential to maintain tick populations via wildlife hosts. Nilgai are a competent host for CFT and there is no effective treatment for nilgai. Nilgai habitat selection may reveal how ticks can be maintained on the landscape. In this study, I evaluated habitat selection of exotic nilgai antelope in South Texas. The goals of this study were to: 1) investigate seasonal habitat selection by nilgai, 2) assess habitat selection based on movement behaviors, and 3) evaluate paved roads as a barrier to nilgai movement.

**STUDY AREA**

This study took place on privately owned properties in Cameron County, Texas, all located within the temporary preventative quarantine area (Fig. 2.1). Wildlife and cattle are exposed to *R.* (*B.*) *microplus* in this area, and cattle are regularly treated. The Western sites include 2 ranches (Ranch 1 and Ranch 2) that are similar in habitat type and nilgai often overlap the 2 properties. The Western sites are located southeast of the community of Rio Hondo and border an 840-ha tract managed by the U.S. Fish and Wildlife Service. These ranches are managed primarily for hunting, although each ranch has cattle. Ranch 1 is 777-ha property with clay, silty clay loam, and fine sandy loam soils (WSS 2019). Ranch 2 is a 632-ha property with a soil composition of fine sandy loam and clay soils (WSS 2019). During April 2019–March 2020, this area experienced an annual rainfall of 62 cm, with a mean temperature ranging from 19.3 to 29.5 C (Prism 2020). These properties are all located in the Lower Rio Grande Valley, Lower Rio Grande Alluvial Floodplain, and Gulf Coast Prairies and Marshes ecoregions (TPWD 2019). Characteristics of these ecoregions include arid grasslands and woody patches along the Gulf Coast (Bailey et al. 1994). This is consistent with the common vegetation found on these properties, including honey mesquite thornscrub (*Prosopis glandulosa*), live oak, Guinea grass, and prickly pear cactus (*Opuntia engelmannii*).

The Eastern site is a 2,063-ha property bordered by the Laguna Atascosa National Wildlife Refuge and the Gulf Coast. This ranch differs from other properties used in this study in that, in addition to cattle ranching, it is also used to produce agricultural crops, primarily sorghum. Soil types include silty clay, silty clay loam, sandy clay loam, and clay (WSS 2019). During April 2019–March 2020, the Eastern site experienced an annual rainfall of 61 cm, with average temperatures ranging from 20.1 to 28.2 C (Prism 2020). This property is in the Laguna Madre Coastal Marshes and Southern Gulf Prairies ecoregions. These ecoregions feature tidal mud flats, grassy meadows, and a hypersaline lagoon system (Bailey et al. 1994). Common plants found in these regions include honey mesquite, live oak, gulf cordgrass (*Spartina spartinae* [Trin.]), and seacoast bluestem (*Schizachyrium scoparium* var. littorale).

## METHODS

### Nilgai Capture and Marking

In March 2019, 30 nilgai (20 F; 10 M) were captured as encountered using a net gun fired from a helicopter. This has proven to be a successful method to capture large mammals (Webb et al. 2008) and previous studies have used this method to capture nilgai (Moczygemba et al. 2012, Foley et al. 2017). Once a nilgai was netted, a ground crew blindfolded the individual, tied the legs, and removed the net. I met the ground crew at the capture location and deployed GPS collars (VERTEX Lite-3D IRIDIUM, VECTRONIC Aerospace, Germany) on each nilgai. I deployed 19 collars on the Western sites and 11 on the Eastern site. The collars were programmed to collect locations at a 1-hr fix rate. Handling time was generally kept under 15 minutes, with nilgai released immediately following data collection. In September 2019, collared nilgai were recaptured, and I removed 3 collars from nilgai the Western sites and I redeployed collars on 3 (2 M; 1F) new nilgai on the Eastern site. Procedures and capture activities were consistent with recommendations by the American Society of Mammologists (Sikes et al. 2016) and approved by the Texas A&M–Kingsville Institutional Animal Care and Use Committee, approval 2018-09-19.

**Explanatory Variables**

I used land cover classifications derived from 10×10-m spatial resolution Sentinel-2 Multi Spectral Instrument images taken on 27 April 2019 downloaded from the USGS Glovis website (https://glovis.usgs.gov/). I used an unsupervised classification method in ERDAS Imagine 2020 (Hexagon Geospatial; Norcross, GA) to classify the images. I separated the satellite imagery into 180 initial classes that were merged into 8 categories. I digitized agriculture land in ArcMap 10.8 (ESRI; Redlands, CA) that was then merged with the final mosaic image. I performed a desk accuracy assessment using 313 randomly generated points. I used a confusion matrix to get an overall accuracy assessment of 87% for the final images (Congalton 1991).

For this study, I focused on woody, herbaceous, mixed cover, and agriculture cover types because those were the most biologically meaningful cover classes for nilgai. Woody cover included areas of woodland, forest, or shrubland. This cover class has canopy cover >95% and is dominated by species such as honey mesquite, huisache (*Vachellia farnesiana*), spiny hackberry (*Celtis tala*), colima (*Zanthoxylum fagara)*, and brasil (*Condalia hookeri*; Elliott 2014). Herbaceous cover included areas of grassland with minimum shrub encroachment. Dominant grassland species included Guinea grass, buffelgrass, old world bluestem spp., and coastal species such as Gulf cordgrass (Elliott 2014**)**. Mixed cover included areas that were a combination of woody patches and open grasslands. This included woody areas with a sparse canopy cover and grasslands with emergent shrub cover (Elliott 2014). Agriculture land within the study area included row crops such as sorghum, cotton, corn, hay (non-alfalfa), sugarcane, and fallow land (USDA-NASS 2021). Since I only used imagery taken on 1 day during the year, agriculture land was determined by land use regardless of growing stage on that particular day.

**Data Analysis**

I removed locations collected during the first 3 days of post-collar deployment to give the nilgai time to adjust after captures (Foley et. al 2017). Data analysis for this study began starting 01 April 2019 and ended 31 March 2020. I screened the collar data for unrealistic locations using methods outlined by Bjørneraas et al. (2010), removing 0.27% (<1% per individual) of locations (see 'Chapter 1: Data Processing' for more details).

Based on available literature, I hypothesized that nilgai will select habitat based on seasonal foraging opportunities and changes in biological needs. Seasons were divided based on biological time frames for nilgai: summer, April–July (gestation); autumn, August–November (birth, lactation); and winter, December–March (breeding; Sheffield et al. 1983, Foley et al. 2017). My second hypothesis was nilgai movement behavior would influence habitat selection. Previous analyses (Chapter 1) have observed nilgai movement behaviors consistent with resident, use of seasonal ranges, nomadic behaviors, and dispersal. Nilgai that altered their home ranges seasonally or left their area of residence could have been influenced by availability of resources. I predicted that habitat selection varied among movement behaviors. Also, I predicted that summer and winter habitat selection would vary between resident nilgai and nilgai that had different seasonal ranges.

To determine the land cover composition of the study area, I created a 100% minimum convex polygon around all used locations for 28 nilgai during the year using the package *adehabitatHR* in Program R (Calenge 2011; R Core Team 2021). The MCP was strictly used to identify the major land cover classes within the study area. I did not include 2 individuals that dispersed since they moved outside the study area.

I assessed nilgai habitat selection at the 3rd order (Johnson 1980) using a step-selection function (SSF; Fortin et al. 2005). Third-order selection focuses on how individuals select or avoid resources within their home ranges (Johnson 1980). A SSF uses step length and turning angle between consecutive fixes to discern behaviors from the movement patterns (Fig. 2.2; Fortin et al. 2005, Thurfjell et al. 2014). Step lengths are the straight-line distance between consecutive locations and turning angles are the directional shift between 2 consecutive step lengths (Latham et al. 2011). Since SSF incorporate an individual's movement, this approach is better suited to model habitat selection than traditional resource selection functions at the 3rd order (Killeen et al. 2014, Thurfjell et al. 2014).

For each individual, I calculated step lengths and the turning angles using the *amt* package in R (Signer et al. 2019, Richter et al 2020). Locations were resampled at a 1-hr interval to remove gaps in collection from the analysis (Signer et al. 2019). I generated 3 random locations per used step that were based on observed distributions of step length and turn angle (Long et al. 2009, Signer et al. 2019, Hinton et al. 2020). I used a distance-based approach to analyze habitat covariates, which uses continuous rather than categorical variables (Conner and Plowman 2001, Benson et al. 2016). I created a raster layer for each of the 4 land cover types using the Euclidean distance tool in ArcMap (Benson 2013, Hinton et al. 2020). The Euclidean distance tool uses the 10-m pixels from the classified imagery to calculate the distance to the nearest pixel of the specified land cover type (Benson 2013, Hinton et al. 2020). I extracted the covariate values for both used and random end points from the raster stack I created with all 4 cover types (Signer et al. 2019). To analyze distance-based variables, I scaled and centered the extracted covariate values (Viana et al. 2018, Hinton et al. 2020). Centering was performed by subtracting the mean of the habitat variable from each extracted habitat value. Scaling was done by dividing the centered values by the standard deviation. Before running the models, I tested for collinearity among habitat variables using the Pearson correlation coefficients (Killeen et al. 2014). All covariates had correlation coefficients <0.70 and were therefore all included in the model (Viana et al. 2018).

I created 22 models with a combination of season, sex, movement behavior, and the overall year. Since I was only interested in 4 land cover classes (woody, mixed, herbaceous, and agricultural land), all were included in each model. I used conditional logistic regression to analyze the models (Fortin et al. 2005) using the *survival* package in R (Therneau et al. 2021, Viana et al. 2018). For each model, I combined all nilgai used and random locations. To account for individual variation and repeated measures I considered each nilgai as a stratified variable in the model (Long et al. 2009). Therefore, each used location was only compared to its corresponding random points. Model output was interpreted based on the sign of the beta coefficients that corresponded to the following equation: $w(x) = exp(\beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_i x_i)$ (Latham et al. 2011, Benz et al. 2016). I used a distance-based approach so negative coefficients infer selection and positive coefficients infer avoidance.

**Road Crossings**

I assessed nilgai road-crossing events by taking the straight-line distance between step lengths and intersecting the step lengths with the 2019 Texas Department of Transportation roadway inventory GIS layer (www.gis-txdot.opendata.arcgis.com; Prokopenko et al. 2017). Crossings that only had 1 location on the opposite side of the road with a subsequent return to the previous side may be erroneous. Therefore, I defined a road crossing as having at least 2 locations on either side of the paved road (Lewis et al. 2011). Road-crossing events were summarized by type of road and time of crossing. Roads were categorized by volume grouping based on the annual average daily traffic metric.

## RESULTS

### Habitat Analysis

In total, 192,159 used nilgai locations were collected for 28 individuals between 01 April 2019 and 31 March 2020 (Fig. 2.3). The 100% MCP around the used points produced a study area of 27,006 ha. The study area was comprised of 29.2% herbaceous cover, 21.2% woody cover, 13.3% agricultural fields, 13% water and tidal flats, 12.8% bare ground, 10.1% mixed cover, and 0.4% infrastructure (Fig. 2.3). The 4 land cover classes used in the model comprised >90% of used point classifications (Table 2.1).

In general, all the locations of collared nilgai for the year showed nilgai selected for woody cover, mixed cover, and agricultural lands, and neither selected nor avoided herbaceous cover (Table 2.2). When broken down by season, nilgai selected for woody cover, mixed cover, and agricultural lands, and did not select for areas close to herbaceous cover in both summer and autumn. In winter, nilgai selected for all 4 land cover classes.

During the year, females (n=19) selected for all land cover classes except herbaceous cover (Fig. 2.5). In the summer and autumn, females selected for areas farther from herbaceous cover. Females in the winter did not select for agricultural lands and selected for woody, mixed, and herbaceous cover. Female nilgai always selected for woody and mixed cover, and selection was highest during the autumn.

Male nilgai (n=11) selected for covered areas, agricultural land, and areas farther away from herbaceous cover during the year (Fig. 2.5). In the summer, males selected for woody and mixed cover, did not select for areas close to herbaceous cover, and agricultural land was not a driver of nilgai selection. In the autumn, male nilgai avoided herbaceous cover and selected for the other 3 land cover classes. In the winter, males selected for all 4 cover classes.

During the year, there were 17 resident nilgai, 7 nilgai that had seasonal ranges, 4 with nomadic behavior, and 2 that dispersed. Resident nilgai selected for woody cover, mixed cover, and agricultural land, and areas away from herbaceous cover. Nilgai with seasonal ranges selected for all 4 cover classes. Nomadic nilgai selected for woody cover, mixed cover, and agricultural land, and did not select or avoid herbaceous cover. Individuals that dispersed, selected for woody, mixed, and herbaceous cover, and did not select for agricultural land.

After breaking the year into seasons, nilgai that had seasonal ranges and resident individuals showed the same patterns of use and avoidance (Fig. 2.6). In the summer, both groups of nilgai selected for woody cover, mixed cover, and agricultural land, and neither selected nor avoided herbaceous cover. Resident nilgai had a much stronger selection towards mixed cover than individuals with separate ranges in the summer. In the autumn, woody cover, mixed cover, and agricultural land was selected for, and herbaceous cover was not selected. In the winter, both groups selected for all 4 cover classes. Nilgai with seasonal ranges showed stronger selection for mixed and herbaceous cover during winter than resident individuals.

**Road Crossings**

I documented 79 road-crossing events made by 9 individual nilgai (Fig. 2.7). Two adult male nilgai had their home ranges bisected by a paved road and were responsible for 73.4% of total crossing events. The other 7 nilgai made short excursions across a road with 2-4 road crossings per individual for the year. Out of the 79 road-crossing events, 96.2% occurred on a road that had 500-1,999 vehicles per day on average in 2019. The remainder of road-crossing events took place on roads with <500 vehicles per day on average in 2019. Road-crossing events occurred at night (84%), 13% during crepuscular periods, and 4% during the day.

**DISCUSSION**

As a host species for CFT, understanding nilgai habitat selection could aid tick eradication efforts in South Texas. There has been relatively little research done on nilgai in either of their introduced or native ranges. My study revealed insights into nilgai habitat selection which can help identify areas on the landscape where nilgai could maintain CFT.

This is the first study of nilgai habitat selection in their introduced range in South Texas. My hypothesis was that nilgai would select habitat based on seasonal foraging opportunities. Nilgai are a sexually dimorphic species and biological needs vary throughout the year for each sex (Leslie 2008). Overall, I found few seasonal trends in nilgai habitat selection, indicating that similar habitat was selected throughout the year. Nilgai appeared to always select woody and mixed cover regardless of sex or season.

In India, deforestation has led to increased occurrences of nilgai in developed areas (Shambhulingappa et al. 2014). Habitat loss and reduction in predators has caused nilgai to move into agriculture land (Chauhan 2011, Gautam and Bissa 2016). In their native range, crop-raiding by nilgai at night has resulted in a large human-nilgai conflict (Chauhan 2011, Bayani and Watve 2016, Gautam and Bissa 2016). Throughout the night, nilgai are often found in open agricultural land and in covered forest during daylight hours (Chauhan 2011, Bayani and Watve 2016). My study revealed that generally nilgai selected for agricultural land, except for females during the winter. On average, females will calve during the autumn or early winter. This could lead to an avoidance of open areas during these seasons. Females will typically keep their calves hidden for the first month (Leslie 2008).

Herbaceous cover was the only land cover class that was typically not selected. Although there are no natural predators of nilgai in Texas, avoidance of open areas could be instinctual. As an exotic species, nilgai can be hunted year-round, with no season or bag limits, which could contribute to nilgai selection for woody cover (Leslie 2008, Goolsby et al. 2018, TPWD 2020). Hunting pressures and protecting young offspring could contribute to the avoidance of open herbaceous cover for nilgai. Hunted species, such as elk, alter their habitat selection in response to hunting pressures (Amor et al. 2019).

Although analyses indicated that nilgai generally did not select for areas with large amounts of herbaceous cover, used locations were commonly identified in herbaceous areas. A nilgai's diet includes grasses and forbs found in these areas. As seasonal changes occur, a nilgai's diet will shift throughout the year. Nilgai diets in Texas consisted of 48–74% grasses, 21–31% forbs, and 5–26% browse (Sheffield 1983). Although nilgai consume a large portion of grasses throughout the year, nilgai require a more diverse diet than cattle to fulfill their nutrient requirement (Sheffield 1983). Nilgai are most likely foraging in herbaceous areas near areas of cover. Areas with canopy cover could also provide nilgai a respite from the high temperatures in South Texas. Deer will use areas with cover more during the summer to avoid the heat and cover adds protection against predators (Wiemers et al. 2014). The overlap between cattle and CFT-host species is critical in determining an effective solution to eradicate ticks from South Texas.

Nilgai did use herbaceous areas, however they tended to select woody, mixed, and agriculture areas over large areas of herbaceous cover. Tick eradication efforts use treated cattle to remove ticks from the landscape. Cattle primarily select for herbaceous grassland over woody cover (Agudelo et al. 2021). However, areas with canopy cover and mixed-brush areas provide suitable habitat for CFT populations, which overlap with cover types used by nilgai and deer habitat (Agudelo et al. 2021). When properties within the quarantine zone do not have a cattle herd, CFT populations can be sustained by nilgai moving across ranches.

It is poorly understood what factors drive home range size and movement behaviors in ungulates. My second hypothesis was nilgai movement behavior would influence habitat selection. I analyzed habitat selection based on movement behaviors of nilgai to determine if resource availability was driving movement. I was primarily interested in seasonal difference between resident nilgai and individuals that used seasonal ranges. Nilgai that had separate seasonal ranges could have dispersed or migrated; which I could not determine because this study was limited to 1 year of locations. Given the available data, some nilgai remained in the same area while other nilgai had non-overlapping summer and winter ranges. Both groups had the same pattern of selection for each season. More information is still needed to determine if nilgai with seasonal ranges are moving based on seasonal variation in resources or other behavioral drivers.

There were only 2 nilgai that dispersed, each traversing the landscape in a unique way. Throughout the year, the dispersers avoided agriculture land. Much of Cameron County, Texas, is made up of agriculture land that is often fence-free, making agriculture land an easy cover type to move through. Since nilgai in general selected for areas with woody cover, it is reasonable that the nilgai moving through unfamiliar areas might avoid open areas. In a future analysis, habitat selection for the dispersers could be dissected further to see what factors may have influenced their choices.

Land cover classes not included in the analyses might have influenced habitat selection by nilgai. Other classes included bare ground, water/tidal flats, and infrastructure. Most bare ground within the study area contained caliche roads and coastal areas. Nilgai form latrine piles, where individuals repeatedly defecate in the same location (Fall 1972, Bayani and Watve 2016, Goolsby et al. 2017, Zoromski 2019). Nilgai will often place latrines on bare ground and ranch roads (Zoromski 2019). Access to water may be a factor in placement of home ranges, but salt and fresh water were not delineated in the land cover classification and water was provided for livestock on these ranches. There was an unequal balance of water between the ranches, with half of the nilgai ranges bordered by the Laguna Madre and the other half had access to a variety of water sources.

Nilgai on Ranch 1 had restricted access to paved roads due to an impermeable game fence on the Western external fence line. Most individuals on Ranch 2 that crossed a paved road used the same area to access the road. This section of Ranch 2 was free from physical barriers and was located in between a section of game fence and urban development, limiting potential crossing opportunities in other areas of the ranch. Since the Eastern site is surrounded by the Laguna Atascosa National Wildlife Refuge and the Laguna Madre, most nilgai on this ranch did not have access to paved roads. Unpaved roads throughout the refuge did allow vehicle traffic, but access was restricted at night. Nilgai primarily crossed roads during the night, possibly providing more cover and less human activity.

## MANAGEMENT IMPLICATIONS

Cattle fever tick larvae are the size of a grain of sand (USDA-APHIS 2010, Pérez de León et al. 2012). During the egg and larval stages, ticks spend their first several months living on vegetation, waiting to latch onto a host (Pérez de León et al. 2012). With changing climate and increased rainfall amounts, the numbers of CFT will continue to rise as suitable habitat increases and expands (Estrada-Pena 2001). As the density and distribution of wildlife hosts increase across South Texas, eradication efforts need to include control on all suitable hosts, especially highly dispersive animals such as nilgai. Information on nilgai habitat selection will allow managers to create more focused CFT eradication measures to target nilgai. As nilgai host CFT and overlap with areas used by cattle, the tick cycle will persist in the environment.

Management efforts focused entirely on cattle may no longer be effective at keeping the U.S. free of CFT. Areas frequented by cattle have the opportunity to reduce tick numbers as cattle are regularly treated with acaracides within the permanent quarantine zone. However, nilgai habitat that is not accessible by cattle provide areas for ticks to thrive without risk. Information on how nilgai select habitat and move throughout the landscape enables managers to identify areas also used by cattle. Understanding how nilgai select habitat features is a significant factor in CFT-eradication. As an alternative host species, nilgai have the ability to maintain populations of ticks in areas where treatment efforts may not reach. Therefore, it is imperative for CFT-eradication efforts to understand wildlife habitat selection in order reduce the risk of CFT re-infestations in the U.S.

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**Table 2.1.** The average distance to a habitat type (m) of used points from each modeled land cover class and the proportion of used points within each land cover type are presented by season, where summer = April–July, autumn = August–November, and winter = December–March. Descriptive statistics (mean±SD) of used locations of 28 GPS-collared nilgai antelope (1-hr fix) in Cameron County, TX, USA, from April 2019–March 2020. The proportion of each cover type used was based on the pixel classification of where that point was located. The distance to a habitat feature was how far on average locations were from a specific habitat feature.

| | Year (n= 28) | | Summer (n=26) | | Autumn (n=18) | | Winter (n=19) | |
|---|---|---|---|---|---|---|---|---|
| Distance to habitat type | mean±SD | Used | mean±SD | Used | mean±SD | Used | mean±SD | Used |
| Woody | 25 ± 42 | 36.6% | 23 ± 42 | 38.2% | 26 ± 46 | 37.1% | 25 ± 37 | 33.9% |
| Herbaceous | 26 ± 40 | 33.4% | 25 ± 38 | 32.4% | 28 ± 44 | 30.5% | 24 ± 37 | 38.2% |
| Mixed | 31 ± 42 | 20.9% | 29 ± 38 | 21% | 33 ± 47 | 21.2% | 31 ± 39 | 20.4% |
| Agriculture | 491 ± 465 | 2.6% | 474 ± 405 | 2.6% | 487 ± 472 | 3.6% | 521 ± 527 | 1.5% |
| **Total locations** | | **192,159** | | **72,809** | | **65,241** | | **54,109** |

**Table 2.2.** Regression coefficients (β) and standard errors (SE) for land cover types by sex and behavioral category for the step selection function models of GPS-collared nilgai antelope (1-hr fix rate) in Cameron County, TX, USA, from April 2019–March 2020.

| Model[1] | Woody | | Herbaceous | | Mixed | | Agriculture | |
|---|---|---|---|---|---|---|---|---|
| | β | SE | β | SE | β | SE | β | SE |
| **General (n=28)** | -0.397 | 0.008 | 0.010 | 0.006 | -0.208 | 0.006 | -0.168 | 0.012 |
| Summer | -0.438 | 0.013 | 0.028 | 0.009 | -0.246 | 0.011 | -0.148 | 0.020 |
| Autumn | -0.423 | 0.013 | 0.094 | 0.010 | -0.209 | 0.011 | -0.189 | 0.020 |
| Winter | -0.321 | 0.015 | -0.109 | 0.011 | -0.174 | 0.011 | -0.163 | 0.021 |
| **Female (n=17)** | -0.436 | 0.010 | -0.006 | 0.007 | -0.189 | 0.008 | -0.166 | 0.015 |
| Summer | -0.482 | 0.017 | 0.023 | 0.012 | -0.178 | 0.013 | -0.224 | 0.025 |
| Autumn | -0.501 | 0.018 | 0.085 | 0.012 | -0.229 | 0.014 | -0.139 | 0.025 |
| Winter | -0.320 | 0.019 | -0.135 | 0.013 | -0.170 | 0.014 | 0.134 | 0.026 |
| **Male (n=11)** | -0.342 | 0.012 | 0.042 | 0.010 | -0.239 | 0.011 | -0.170 | 0.019 |
| Summer | -0.370 | 0.022 | 0.035 | 0.016 | -0.377 | 0.019 | -0.032 | 0.031 |
| Autumn | -0.341 | 0.018 | 0.103 | 0.017 | -0.174 | 0.017 | -0.255 | 0.032 |
| Winter | -0.327 | 0.024 | -0.055 | 0.019 | -0.187 | 0.021 | -0.211 | 0.034 |
| **Resident (n=17)** | -0.477 | 0.012 | 0.035 | 0.008 | -0.238 | 0.009 | -0.181 | 0.016 |
| Summer | -0.531 | 0.020 | 0.021 | 0.013 | -0.379 | 0.015 | -0.198 | 0.026 |
| Autumn | -0.510 | 0.019 | 0.122 | 0.012 | -0.230 | 0.014 | -0.192 | 0.027 |
| Winter | -0.332 | 0.023 | -0.065 | 0.014 | -0.107 | 0.015 | -0.156 | 0.034 |
| **Seasonal (n=7)** | -0.369 | 0.013 | -0.035 | 0.010 | -0.171 | 0.011 | -0.121 | 0.019 |
| Summer | -0.437 | 0.021 | -0.004 | 0.017 | -0.107 | 0.018 | -0.145 | 0.033 |
| Autumn | -0.387 | 0.022 | 0.086 | 0.019 | -0.238 | 0.021 | -0.131 | 0.033 |
| Winter | -0.267 | 0.024 | -0.252 | 0.020 | -0.248 | 0.020 | -0.100 | 0.033 |
| **Dispersal (n=2)** | -0.036 | 0.010 | -0.061 | 0.015 | -0.039 | 0.016 | 0.283 | 0.038 |
| **Nomadic (n=4)** | -0.272 | 0.017 | -0.017 | 0.016 | -0.138 | 0.018 | -0.225 | 0.031 |

Note: Underlined β values denote coefficients that were not significant at α=0.05 level.
[1]=Resident nilgai had overlapping seasonal ranges, seasonal nilgai had separate summer and winter ranges, nilgai that dispersed left their area of origin and established a new residency, and nomadic nilgai had irregular and unpredictable ranges.

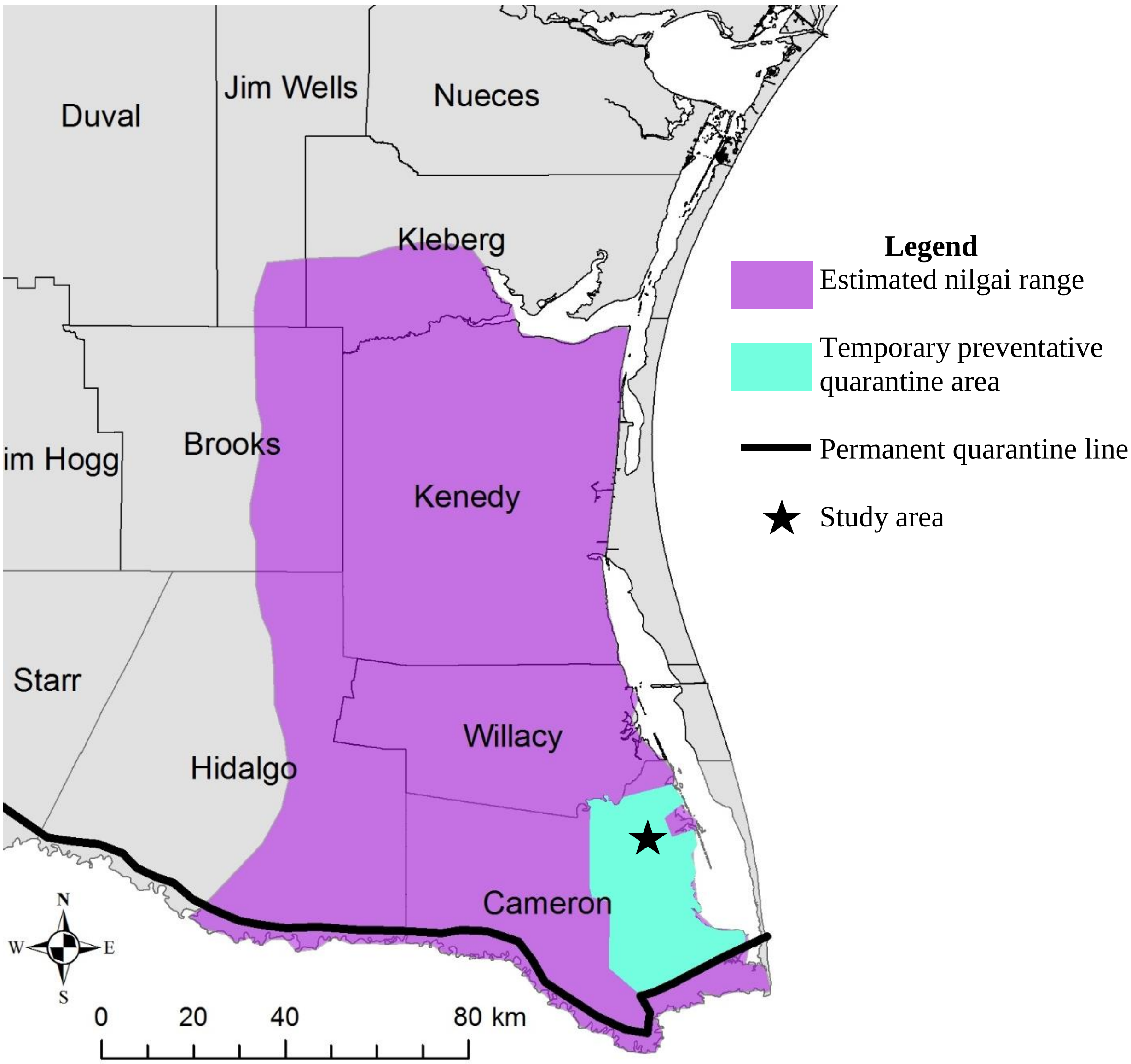


**Figure 2.1.** Location of the study area within the temporary preventative quarantine zone and estimated nilgai range in Cameron County, TX, USA. The permanent quarantine line manages for cattle fever ticks to prevent re-infestations of ticks in the U.S. The temporary preventative quarantine area was created in 2014 after wildlife were implicated in cattle fever tick outbreaks.

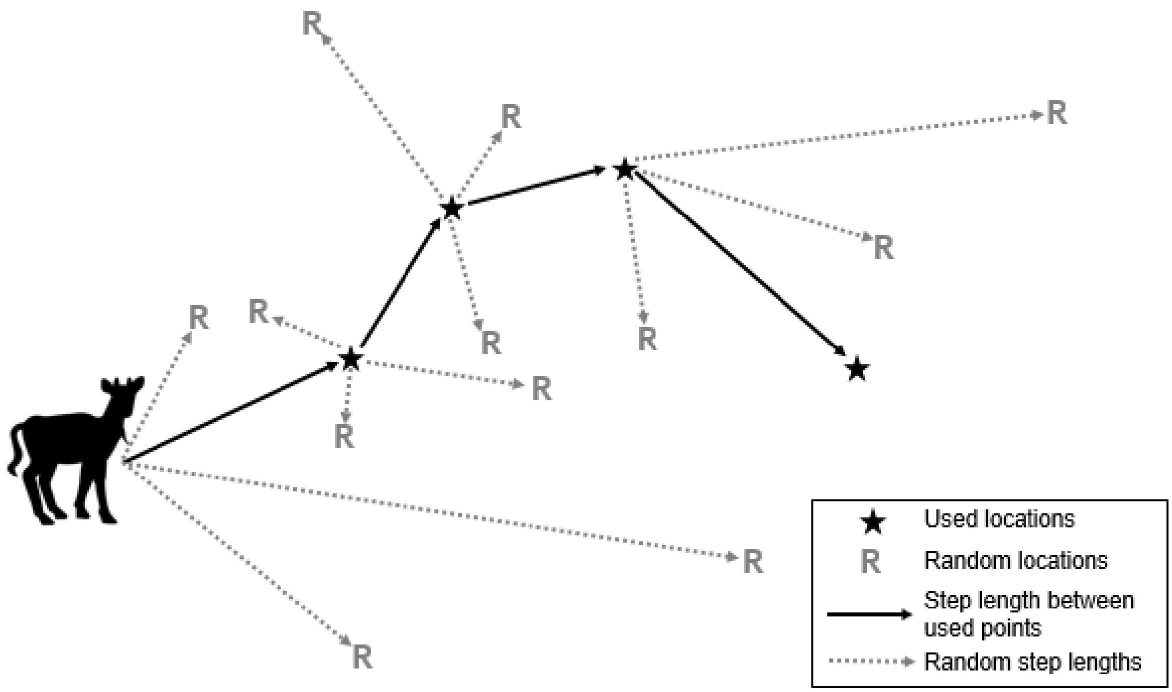


**Figure 2.2.** Example of a movement path for a nilgai antelope within a step-selection framework. Three random step lengths were created for each used location. The end points of the random steps were compared to used locations to determine habitat selection of GPS-collared nilgai (1-hr fix rate) in Cameron County, TX, USA, from April 2019–March 2020.

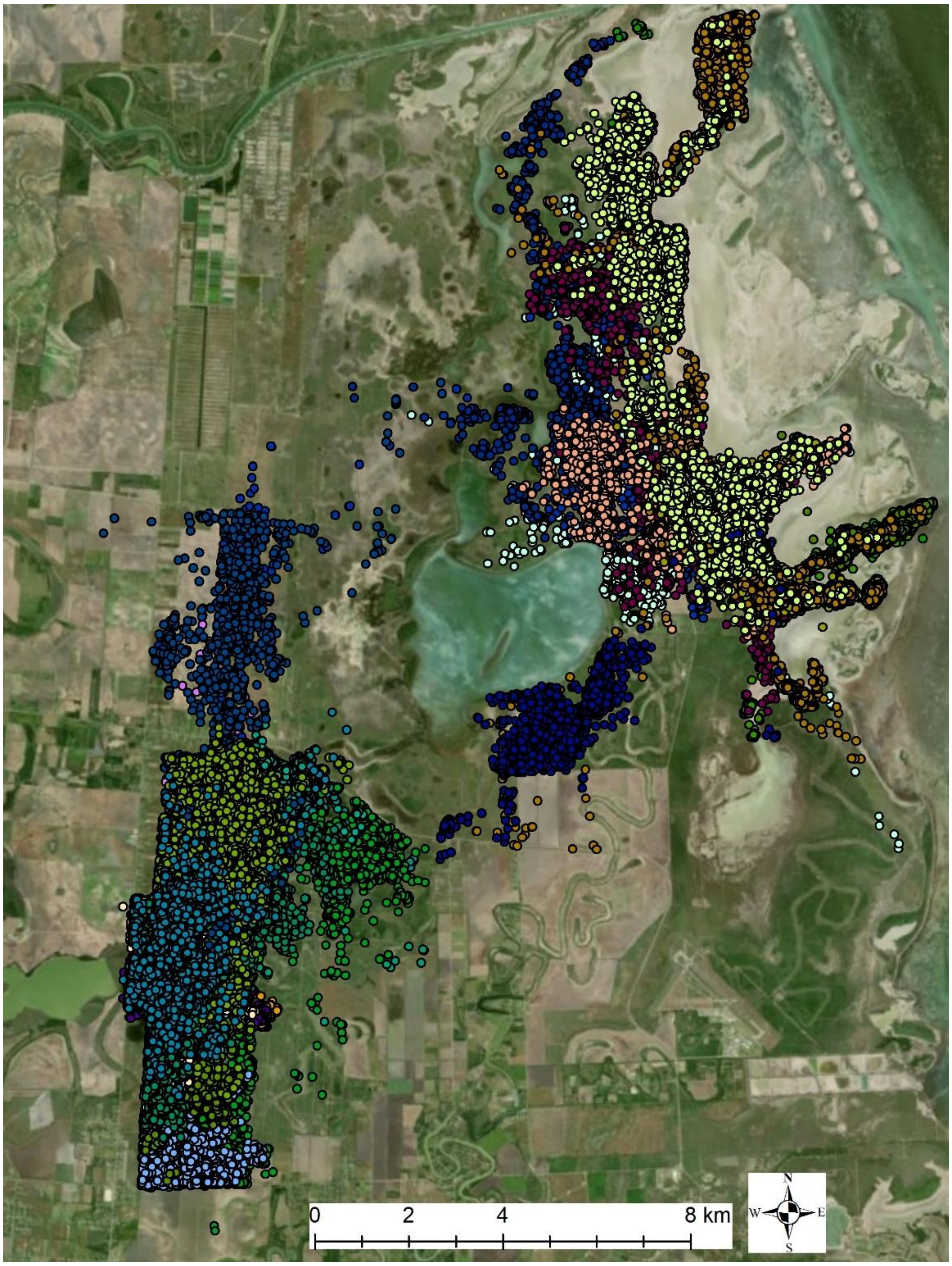


**Figure 2.3.** Used locations of 28 GPS-collared nilgai antelope (1-hr fix rate) in Cameron County, TX, USA, from April 2019–March 2020.

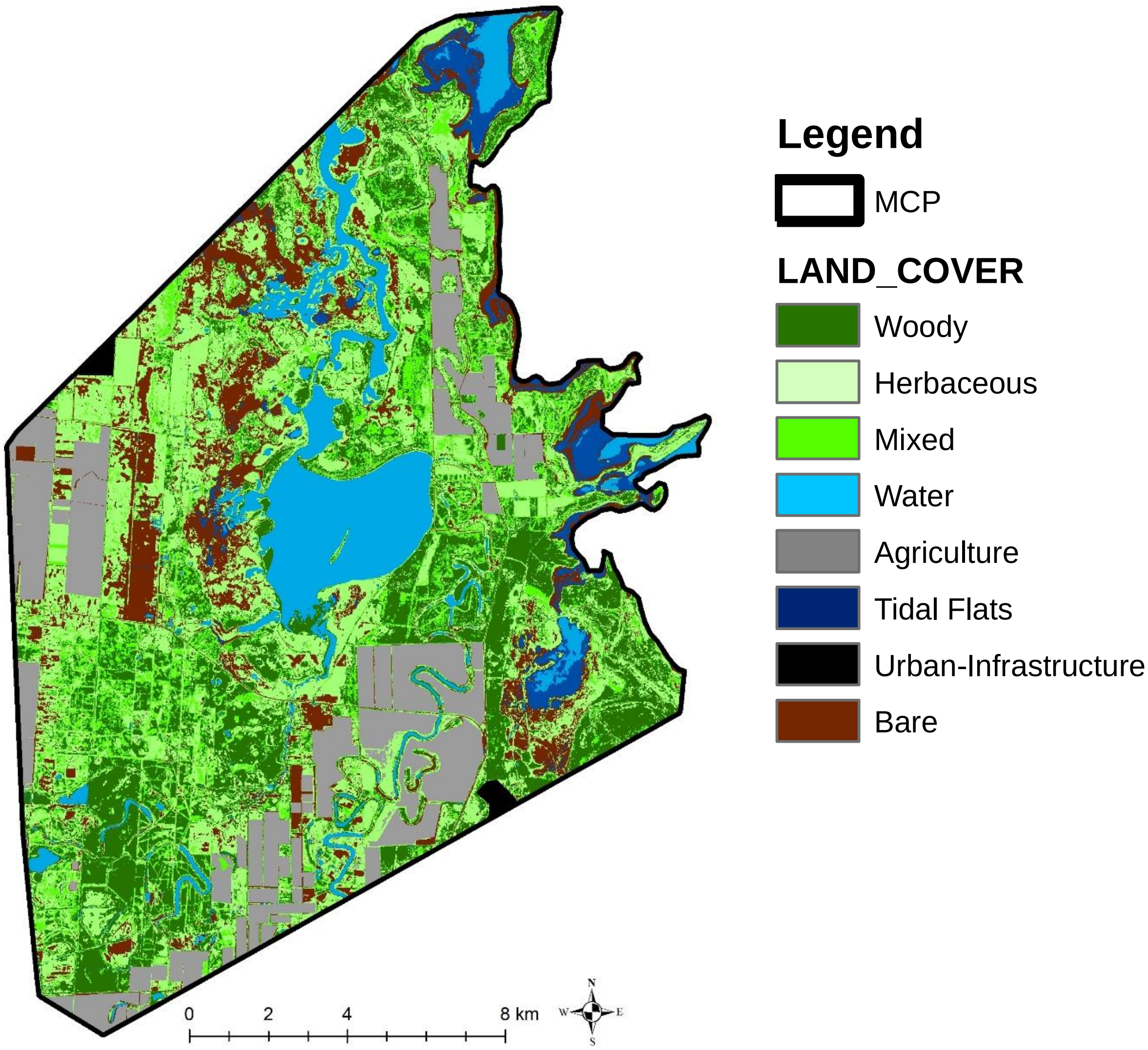


**Figure 2.4.** Land cover composition of the study area in Cameron County, TX, USA. A 100% minimum convex polygon (MCP) was created around all of the used points derived from GPS-locations from collared nilgai antelope (April 2019–March 2020) to determine what proportion of land cover classes were available in the study area.

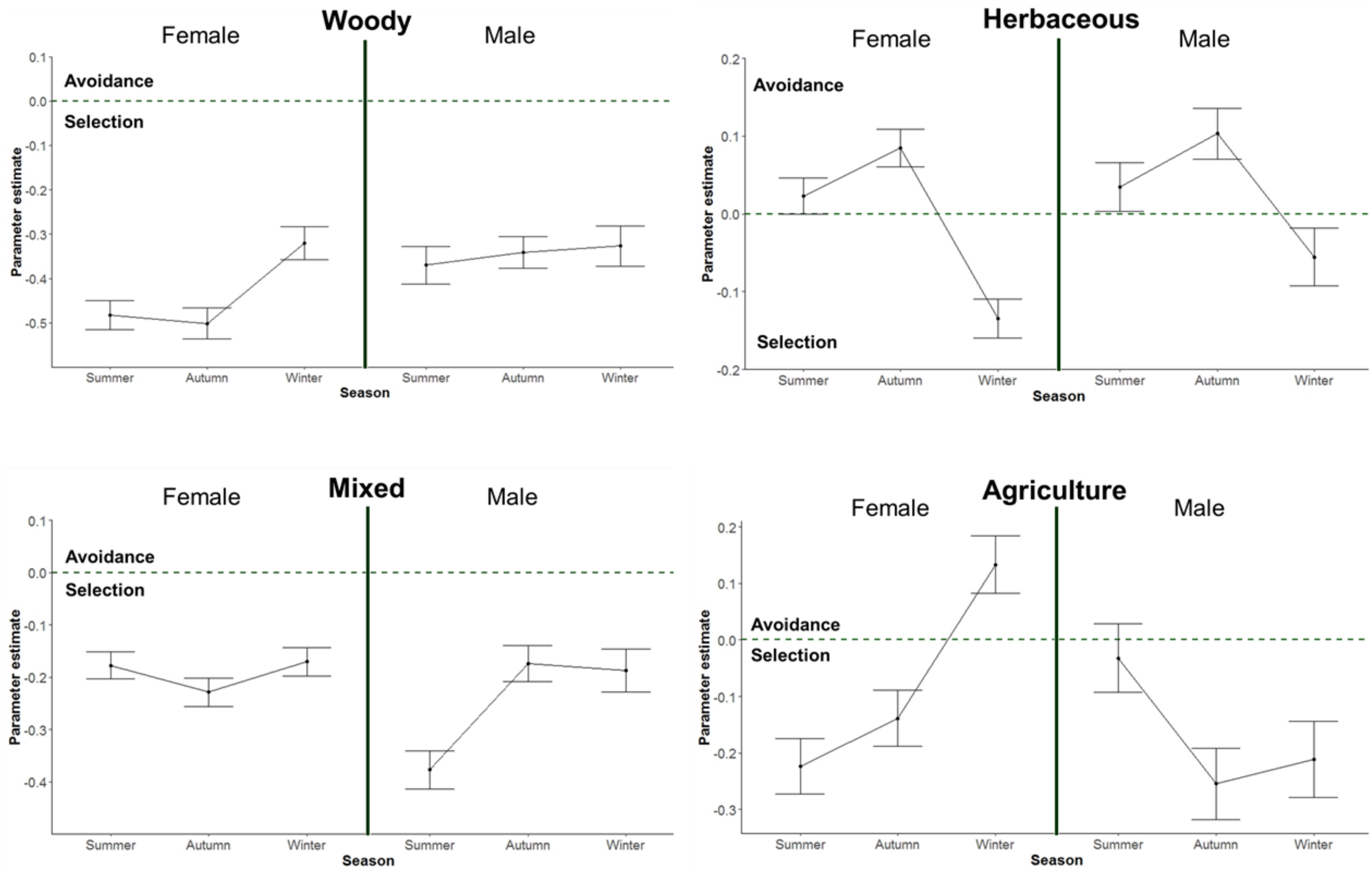


**Figure 2.5.** Model output beta coefficients for each land cover class (woody, mixed, agriculture, and herbaceous) estimated by step-selection functions for GPS-collared nilgai antelope by sex in Cameron County, TX, USA, from April 2019–March 2020.

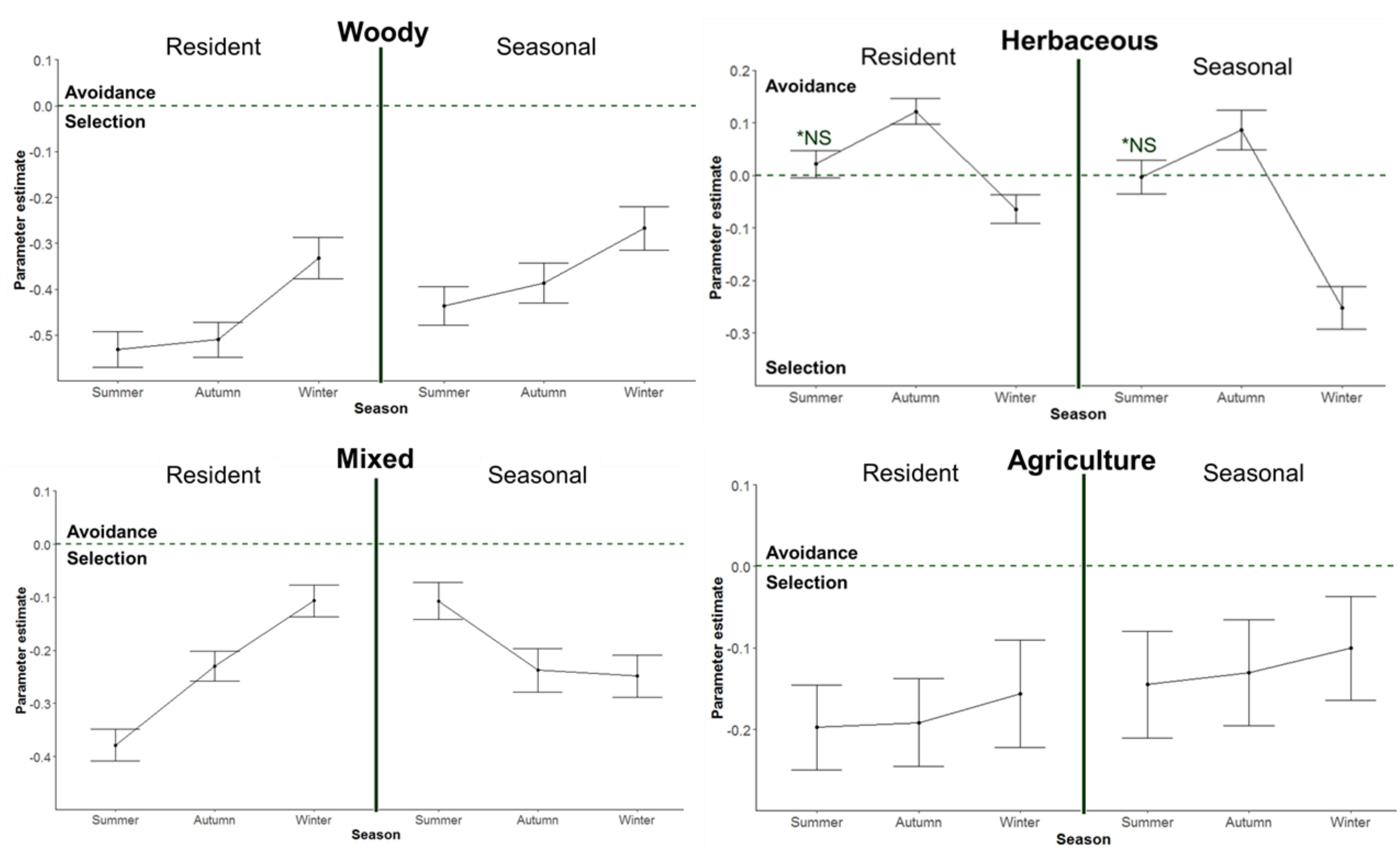


**Figure 2.6.** Model output beta coefficients for each land cover class (woody, mixed, agriculture, and herbaceous) estimated by step-selection functions in summer and winter for resident GPS-collared nilgai (n=17) and individuals that had separate seasonal ranges (n=7) in Cameron County, TX, USA, from April 2019–March 2020. During summer, distance to herbaceous cover was not a driver of selection.

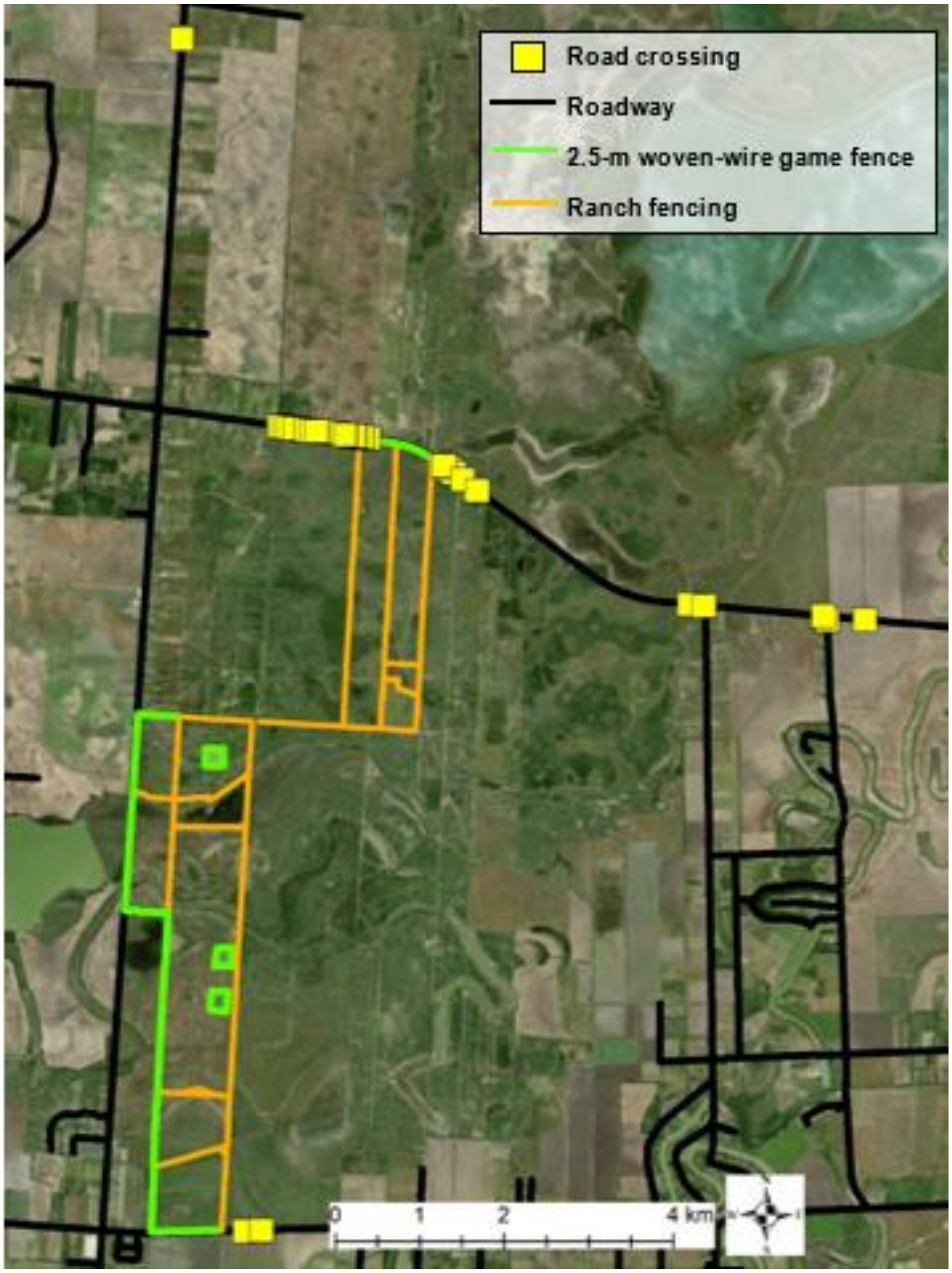


**Figure 2.7.** Locations of paved road-crossings of GPS-collared nilgai (1-hr fix rate) in Cameron County, TX, USA, from April 2019–March 2020. Game fence restricted nilgai access to paved roads on the ranches.

# CHAPTER III. FENCE-CROSSING BEHAVIOR OF NILGAI ANTELOPE IN SOUTH TEXAS: IMPLICATIONS FOR CONTROL OF CATTLE FEVER TICKS

**ABSTRACT** Cattle fever ticks (CFT), *Rhipicephalus (=Boophilus) microplus* (Cannestrini) and *R. (B.) annulatus* (Say), are a vector of the protozoan parasites responsible for bovine babesiosis, an economically devastating disease for the cattle industry. The ticks were introduced to the Americas during European colonization of the New World and were identified as the vector of bovine babesiosis in 1893. Cattle fever ticks were eradicated from the United States by 1943 in a massive, multi-decade effort. The U.S. government maintains a permanent quarantine zone along the southern border to prevent re-infestation from Mexico, where the tick and disease remain endemic. Wildlife, including introduced nilgai antelope (*Boselaphus tragocamelus*) are suitable alternate hosts and can disperse CFT from infested areas. Nilgai are an exotic ungulate species that have established free-ranging populations in South Texas. The presence of nilgai has become increasingly important due to their ability to make long-distance movements, potentially carrying CFT beyond the permanent quarantine zone. Nilgai prefer to cross under livestock fences rather than jump, and it is important to quantify their movements to understand the potential to spread ticks to neighboring properties. In addition, fence-crossing sites may be useful locations to deploy treatment methods. The USDA-Agricultural Research Service recently developed a motion-activated sprayer system designed to spray a tick-killing nematode solution onto an animal. As part of a field-test of the sprayer technique, I monitored nilgai movements across livestock fences using re-sightings of 41 tagged and 30 GPS-collared animals during 2019–2020 in Cameron County, Texas, USA. Nilgai were marked in a 3,472-ha area with 108–144 sprayers deployed at fence crossing sites. Collared nilgai had a fence crossing rate of 3–504 times during the year based on GPS location data. Movement data showed that during the year

17/30 nilgai crossed a fence >1 time per month, 9/30 nilgai had ≥1 month with 0 fence crossings, and 4/30 nilgai left the study area. Using trail camera photos to identify crossing locations, collared nilgai were captured crossing a fence 63 times, consisting of 17/30 individuals. Based on movement data, I anticipated a higher number of crossing events at monitored sites. The lack of crossing events at monitored sites indicates nilgai had alternative places to cross a fence line. Therefore, the efficacy of the sprayer technique may be insufficient when poorly maintained fences are present. Nilgai have recently been implicated in CFT outbreaks in this area. The limited amount of knowledge on the behavior and movement of nilgai in South Texas limits CFT eradication efforts in South Texas. The results of this study will help refine treatment strategies for targeted nilgai-CFT treatment programs.

**KEYWORDS** Nilgai antelope, *Boselaphus tragocamelus*, cattle fever ticks, fence crossing, wildlife disease management

Disease management in wildlife is necessary when the disease is zoonotic, domestic livestock are at risk, or there is a detrimental effect on the wildlife species (Wobeser 2006). An estimated 80% of animal pathogens at risk of infecting livestock or humans can have a wildlife component (Gortazar et al. 2015). Wildlife can spread infectious agents or serve as a host for tick-borne diseases (Miller et al. 2013, Currie et al. 2020). Wildlife species respond differently to disease management efforts, and therefore it is important to closely monitor at-risk populations to create the most effective solution.

Bovine babesiosis is one of the most economically detrimental diseases to the U.S. livestock industry (Bock et al. 2004, Cardenas-Canales et al. 2011), with a mortality rate up to 90% in naïve cattle (Giles et al. 2014). Bovine babesiosis is caused by parasites of the genus

*Babesia*, which are transmitted by the one-host cattle fever ticks (CFT), *Rhipicephalus (=Boophilus) microplus* (Cannestrini) and *R. (B.) annulatus* (Say; Bock et al. 2004, Gohil et al. 2013). Cattle fever ticks (CFT) are among the first known ectoparasites brought to the New World by early colonists throughout the 1500s (Bram et al. 2002). By the 1800s, bovine babesiosis and CFT were widely distributed throughout Mexico, the southern U.S., and California (Pérez de León et al. 2012). In 1868, the term "Texas fever" was coined when naïve northern cattle began dying after exposure to cattle from Texas (Assadian and Stanek 2002). Clinical signs of bovine babesiosis include a loss of appetite, weight loss, anemia, fever, and decreased milk production (USDA-APHIS 2010). Infected animals may display neurological symptoms, such as aggression, incoordination, seizures, blindness, and muscle tremors (USDA-APHIS 2017). Once transmission of this disease was traced to the one-host CFT in the 1890s, researchers quickly realized the vector needed to be eliminated to protect U.S. cattle herds from Texas fever (Assadian and Stanek 2002).

In 1906, the Cattle Fever Tick Eradication Program was created and began eradication efforts for bovine babesiosis in the U.S. (Pérez de León et al. 2012, Giles et al. 2014). By 1943, CFT were only found in a permanent quarantine zone along the Texas and Mexico border, extending about 800 km from Del Rio, TX to Brownsville, TX (Fig. 3.1; Pérez de León et al. 2012, Giles et al. 2014). After persistent infestations outside of the permanent quarantine zone, a temporary preventative quarantine area was created in 2014 in Cameron County, Texas, as another control measure (Olafson et al. 2018).

Although cattle are the preferred host for CFT, the presence of alternative wildlife hosts threaten tick control and eradication efforts. Eradication efforts proved successful, but complications occurred as other species were found to be competent hosts (Busch et al. 2014).

By the 1970s, Texas began to encounter failures with cattle-specific eradication methods due to increasing numbers of white-tailed deer (*Odocoileus virginianus*) and other wild ungulate hosts (Pound et al. 2010). White-tailed deer can carry CFT and are not confined by livestock fencing, risking the spread of disease (Cardenas-Canales et al. 2011). Deer are abundant in the Texas-Mexico border region and can freely travel to Mexico, where CFT are prevalent (Cooksey et al. 1989, Giles et al. 2014). Recreational endeavors, including sport hunting of white-tailed deer, have become increasingly popular with today's cattle ranchers in Texas, causing deer populations to flourish (Holman et al. 2011).

In 1924, another alternative host species for cattle fever ticks was introduced to South Texas rangelands. Since their introduction, nilgai antelope (*Boselaphus tragocamelus*) have naturally dispersed throughout the region, ranging from Baffin Bay to Brownsville, TX, and in northern Mexico as far west as Durango (Sheffield et al. 1971, Olafson et al. 2018). Current population estimates report over 36,000 nilgai in southern Texas (Olafson et al. 2018). On average, nilgai have 2–3x larger home ranges than deer, causing nilgai to be of greater concern in the spread of CFT (Foley et al. 2017). As a member of the family Bovidae, nilgai are a suitable replacement host for CFT, as they are more closely related to cattle than deer are (Goolsby et al. 2017, Singh et al. 2017). In the late 1970s, 3 nilgai were found infested with CFT in Webb County, Texas (Olafson et al. 2018). The presence of *B. bovis* and *B. bigemina* in free-ranging nilgai in Mexico has been documented (Cardenas-Canales et al. 2011).

As a large bovid species, nilgai make an excellent alternative host for CFT, complicating eradication efforts (Foley et al. 2017, Goolsby et al. 2019). There are no current methods to treat nilgai for CFT aside from culling (Goolsby et al. 2017). Nilgai do not respond to bait and typically do not eat from feeders (USDA-APHIS 2017). Researchers have tested different methods to attract nilgai to treatment locations, including odor lures, but no viable option has been discovered (Goolsby et al. 2017).

Laboratory experiments have proven successful at controlling CFT using entomopathogenic nematodes, a non-toxic biocontrol method (Samish and Glazer 1992, Alekseev et al. 2006, Singh et al. 2018a). Goolsby et al. (2018) reported moderate success in the application of a spray solution of infective juvenile nematodes directly to a host to treat for CFT. Many species of nematodes are available commercially, resulting in an alternative option to use on cattle or to treat wildlife for CFT (Singh et al. 2018a). The entomopathogenic nematodes *Steinernema riobrave* and *Heterorhabditis floridensis* may offer a biological control agent against ticks (Goolsby et al. 2018). The USDA-ARS developed a motion-activated sprayer system designed to spray the nematode solution onto an animal (Goolsby et al. 2019). Native to South Texas, *S. riobrave*, has proven results against CFT and would be a noninvasive, environmentally safe option (Singh et al. 2018b). The sprayer system is a novel method that needs to be field-tested, but has the potential to reduce tick loads on nilgai and other wildlife host species. For this method to be successful, these sprayer systems must be placed in an area frequented by nilgai to maximize opportunities for nilgai to be treated. Nilgai exploit weak points in a fence to create crossing areas, which allow them to move through different pastures and ranches (Sheffield et al. 1983, Moczygemba et al. 2012). Even with proper fences and barriers in place, deer and nilgai will go over and under these obstacles, posing a greater challenge for eradication methods (Foley et al. 2017). These fence-crossing sites could prove to be a valuable place to target nilgai with CFT treatment via the motion-activated sprayer system.

The limited amount of knowledge on the behavior and movement of nilgai limits CFT eradication efforts in South Texas. The intent of this study was to attempt to treat nilgai via the motion-activated sprayer system if possible, with the expectation that there would need to be some field adjustments. Therefore, the assessment of nilgai movements and use of fence crossings will inform the overall logistical feasibility and efficacy of this technique. The specific objectives of this study were to: 1) assess nilgai movements relative to fences using GPS-collar data, and 2) evaluate the use of marked nilgai at monitored fence crossing locations using trail camera data. As part of a field-scale test of the efficacy of the sprayer system approach, the information collected will determine if fence modifications are a viable option for treating nilgai for CFT.

**STUDY AREA**

This study took place on privately owned properties in Cameron County, Texas, all located within the temporary preventative quarantine area. Wildlife and cattle are exposed to *R.* (*B.*) *microplus* in this area, and cattle are regularly treated. Ranches 1 and 2 are located southeast of the community of Rio Hondo and surround an 840-ha tract managed by the U.S. Fish and Wildlife Service. These ranches are managed more for hunting, although each ranch has cattle. Ranch 1 is a 777-ha property with clay, silty clay loam, and fine sandy loam soils (WSS 2019). Ranch 2 is a 632-ha property with a soil composition of fine sandy loam and clay soils (WSS 2019). During April 2019–March 2020, this area experienced an annual rainfall of 62 cm, with a mean temperature ranging from 19.3 to 29.5 C (Prism 2020). These properties are all located in the Lower Rio Grande Valley, Lower Rio Grande Alluvial Floodplain, and Gulf Coast Prairies and Marshes ecoregions (TPWD 2019). Characteristics of these ecoregions include arid grasslands and woody patches along the Gulf Coast (Bailey et al. 1994). This is consistent with the common vegetation found on these properties, including honey mesquite thornscrub

(*Prosopis glandulosa*), live oak (*Quercus virginiana* [Mill.]), Guinea-grass (*Megathrysus maximus*), and prickly pear cactus (*Opuntia engelmannii*).

The Ranch 3 is a 2,063-ha property surrounded by the Laguna Atascosa National Wildlife Refuge, and located along the Gulf Coast. The ranch has livestock and agricultural crops. Soil types include silty clay, silty clay loam, sandy clay loam, and clay (WSS 2019). During April 2019–March 2020, Ranch 3 experienced an annual rainfall of 61 cm, with average temperatures ranging from 20.1 to 28.2 C (Prism 2020). This property is in the Laguna Madre Coastal Marshes and Southern Gulf Prairies ecoregions. These ecoregions feature tidal mud flats, grassy meadows, and a hypersaline lagoon system (Bailey et al. 1994). Common plants found in these regions include honey mesquite, live oak, gulf cordgrass (*Spartina spartinae* [Trin.]), and seacoast bluestem (*Schizachyrium scoparium* var. littorale).

These ranches are within restricted quarantine areas, requiring specific protocols when handling and shipping cattle. Before transport, cattle must be 'scratched' (physically searched for ticks), determined tick-free, and then dipped or sprayed using coumaphos, an organophosphate acaricide (Graham and Hourrigan 1977, Pelzel 2005). The most common CFT-treatment option is "systemic dipping," where all cattle that remain on the property are dipped every 7–14 days for 6–9 months or until tick-free (Pound et al. 2010, Pérez de León et al. 2012). Dipping cattle involves individually moving them through a vat or spray box until they are completely submerged in solution and then moved to a drip pad to dry (Karns et al. 1995). In 2016, Bm86 immunomodulator, a cattle vaccine for CFT, was added to eradication practices within the quarantine zone (TAHC 2016). All cattle within the permanent quarantine zone are now required to receive the vaccine at least once a year, and cattle may need the vaccine twice a year in the temporary preventative quarantine area if there is an elevated risk in the area (TAHC 2016). A once popular and more economic option was a "pasture vacation," where infested cattle are dipped in an acaricide and then vacated from the area for up to 9 months. However, with the emergence of wildlife host species, this method is no longer likely to be effective. The current treatment method for deer is ivermectin-medicated corn placed in feeding stations in counties of concern (Pelzel 2005, Pound et al. 2010, Goolsby et al. 2017, USDA-APHIS 2017).

## METHODS

### Nilgai Capture and Marking

In February 2019, 30 nilgai (19 F; 11 M) were captured as encountered using a net gun fired from a helicopter. This has proven to be a successful method to capture large mammals (Webb et al. 2008) and previous studies have used this method to capture nilgai (Moczygemba et al. 2012, Foley et al. 2017). Once a nilgai was netted, a ground crew blindfolded the individual, tied the legs, and removed the net. I met the ground crew at the capture location to collect data from the nilgai. I ear-tagged each individual with Global Maxi cattle tags (Allflex USA, Inc, Dallas, TX) labeled with unique numbers on either ear. The ear-tags were numbered and color-coded to assist with individual identification. In March 2019, 38 new nilgai (23 F; 15 M) were captured and tagged. I deployed VERTEX Lite-3D IRIDIUM global positioning system (GPS)-collars (VECTRONIC Aerospace, Germany) on 30 individuals (10 M; 20 F). I deployed 14 collars on Ranch 1, 5 on Ranch 2, and 11 on Ranch 3. The 30 deployed collars were programmed to collect locations at a 1-hr fix rate. These collars upload locations daily via satellite for close monitoring of movement and survival status. In September 2019, collared nilgai were recaptured to get a second tick count. I also removed 2 collars from nilgai on Ranch 2 and 1 on Ranch 1 and redeployed collars on 3 (2 M; 1F) new nilgai on Ranch 3. I kept data collection <15 minutes and nilgai were released immediately after handling. Procedures and capture activities were consistent with recommendations by the American Society of Mammologists (Sikes et al. 2016) and approved by the Texas A&M–Kingsville Institutional Animal Care and Use Committee, approval 2018-09-19.

**Fence-Crossing Locations**

I mapped out property boundaries and internal fences on Ranch 1, Ranch 2, and Ranch 3 (Fig. 3.2). I encountered 3 types of fencing materials on my study site: 5-strand barbed wire, 1.25-m net-wire livestock fence, and 2.5-m net-wire game fence. I marked established and potential fence-crossing sites with a hand-held GPS unit. I defined crossings as an area in the fence that had been altered by an animal or where a hole or gap under the fence was large enough for a nilgai to pass through. I classified crossings based on how an animal would cross the fence. An under-crossing had the bottom portion of fence pushed up or missing, providing enough space for a nilgai to pass underneath. The height of the under-crossings was measured from the ground to the start of the intact fence. An over-crossing had the top portion of fence pushed down or sagging low enough to allow nilgai to easily jump or step over the fence (Fig. 3.3). The height of the over-crossings was measured from the ground to the top of the bent or sagging area. If a barbed-wire fence was missing middle strands it was considered a through-crossing if nilgai could pass directly through the fence. If a fence was poorly maintained and a nilgai could go under or over the fence, it was classified as both.

**Motion-activated Sprayer System**

The motion-activated sprayer system (Fig. 3.4) was developed by researchers at the USDA-ARS, Edinburg and College Station, TX and modified by USDA-APHIS, Aircraft and Equipment Operations, Edinburg, TX, to target nilgai for CFT treatment (Goolsby et al. 2019). The sprayer systems were assembled using parts readily available from distributers, including Automation

Direct (Automation Direct, Cumming, GA) and Wylie Sprayers (Wylie Manufacturing, Edinburg, TX, USA; Goolsby et al. 2019). These sprayer systems were deployed at specific fence-crossing locations. Locations that received sprayer systems displayed animal tracks or lined up with game trails. The motion-activated sprayer system was created to spray nilgai with a solution containing entomopathogenic nematodes *S. riobrave* (Cabanillas, Poinar, and Raulston; Nemasys-R, BASF, Inc, Florham Park, NJ, USA) that can control CFT (Goolsby et al. 2019). The infective juvenile nematode invades a suitable tick host, releases symbiotic bacteria into the hemolymph, the bacteria multiply, and kill the tick host within 2 days (Samish and Glazer 1992, Alekseev et al. 2006). The sprayer tank holds a solution of 26 L of water mixed with Nemasys R, a gelatin cake of nematodes. Inside the tank is an aerator that is set to run for 2 min every 12 min. This ratio provides ample aeration to oxygenate the water for the nematodes. The control box holds a processor, which operates the aerator, pump, and sensor. The sprayer system is powered by a deep-cycle, 12-volt battery. Each unit has 3 sprayer nozzles on the ground, which are connected by tubing to the tank. On both sides of the crossing, motion-detection sensors are placed about 1 m off the ground and within 2 m from the fence to detect movement from nilgai and other species. Once the sensor is triggered, it activates the pump for 10 sec to move the aqueous solution through the nozzles, and it will be sprayed onto the passing animal. Field personnel deployed and maintained between 108 and 144 sprayer systems across the 3 ranches. The number of deployed sprayers varied monthly depending on the ability to service the systems promptly, occasional limited access to areas due to flooding, and temporary maintenance on the system. Sprayer systems at fence-crossing sites were present between April and September 2019 (hereafter the ‘active period’). Sprayer systems were removed from the field in early October 2019 for the remainder of the study (October 2019–March 2020, hereafter the ‘inactive period’).

Sprayer sites were monitored using motion-triggered trail cameras, a non-invasive and effective way to document animal movements, activity patterns, and social interactions (Singh et al. 2017, Jakes et al. 2018). Field personnel installed a trail camera to monitor the animal activity at each fence crossing site. I used HF2X HyperFire 2 Covert IR Cameras (Reconyx, Holmen, WI) set at medium-high sensitivity and 3 photo-bursts with 1 sec between photos. Field personnel maintained trail cameras at each site by checking placement, memory cards, and batteries every 1-2 weeks; photos were managed and classified using the Colorado Parks and Wildlife Photo Warehouse software (Ivan and Newkirk 2016; Colorado Parks and Wildlife-Mammal Research Station, Fort Collins, CO). Field personnel maintained trail cameras at all sprayer locations for 1 year (April 2019–March 2020), even after the sprayer systems were removed from the field.

**Data Analysis**

I removed locations collected during the first 3 days of post-collar deployment to give the nilgai time to adjust after captures (Foley et. al 2017). Data analysis for this study began 01 April 2019 and ended 31 March 2020. I screened the collar data for unrealistic locations using methods outlined by Bjørneraas et al. (2010), removing 0.27% (<1% per individual) of locations. All final locations used also had a dilution of precision (DOP) value <10 (see 'Chapter 1: Data Processing' for more details).

I examined hourly GPS locations from the 30 collared nilgai over the course of a year and assessed individual interactions with fence lines. I used movement data to determine a fence-crossing rate, defined as having at least 2 locations on either side of the fence (Lewis et al. 2011). I used ArcMap 10.8 (ESRI; Redlands, CA) to connect locations chronologically to create a straight-line movement path for each nilgai. I used the "intersect" function to determine where a nilgai's movement path crossed a fence (Prokopenko et al. 2017). Although nilgai do not travel in the straight lines I created between points, this information is a good indication of which area they most likely crossed at, and provided me a crossing rate for each individual. Due to the potential of GPS-error, I removed crossing events that only had 1 location on the opposite side of the fence (Lewis et al. 2011). There were also many instances where the line intersected fence corners, which I also removed from the analysis (Fig 3.5). I separated fence crossings by external boundaries and internal fence lines. This distinction was made to quantify how often nilgai traveled between properties compared to remaining on the same ranch. Nilgai that travel between ranches have a greater chance of spreading ticks and can be harder to treat if CFT-eradication efforts are not consistent across different properties. I identified the location of crossing events by marked (tagged or collared) nilgai using the classified trail camera data (Fig. 3.6). I compared crossing events from the movement data with the photo data to help assess the effectiveness of the sprayer technique within the parameters of this study. I did not know the survival status or movement patterns of uncollared, tagged nilgai post-capture, so I assumed all marked individuals had an equal chance of being treated at a sprayer site.

## RESULTS

### Fence Crossing Locations

There were 438 potential fence-crossing sites documented in the study area that could have been used by nilgai. Ranch 1 had 154 potential fence-crossing sites. Crossing types included over (65.6%), under (23.4%), through (7.1%), and unknown (3.2%). The average over-crossing on Ranch 1 had a height of 80.6 cm (range: 28–138) and width of 109.8 cm (range: 41–530). The average under-crossing on Ranch 1 had a height of 79.8 cm (range: 30–124) and width of 102.7 cm (range: 36–177). Ranch 2 had 45 potential fence-crossing sites. Crossing types included over

(54.3%), under (28.9%), through (13.3%), both (2.2%), and unknown (1.3%). The average over-crossing on Ranch 2 had a height of 87.4 cm (range: 8–120) and width of 107 cm (range: 33–540). The average under-crossing on Ranch 2 had a height of 86 cm (range: 13–120) and width of 104.8 cm (range: 42–300). Ranch 3 had 239 potential fence-crossing sites. Crossing types included over (2.1%), under (83.2%), through (10.9%), and both (3.8%). The average over-crossing on Ranch 3 had a height of 60.4 cm (range: 20–89) and width of 71.4 cm (range: 78–500). The average under-crossing on Ranch 3 had a height of 61.1 cm (range: 37–100) and width of 67.5 cm (range: 25–350). Overall, 26% of potential fence-crossing sites had a nilgai latrine nearby. The potential fence crossing sites showed clear signs of animal activity via tracks or established trails. During the active period, sprayers were setup at 60–73 potential crossing sites on Ranch 1, 16–24 on Ranch 2, and 24–42 on Ranch 3.

**Fence Crossings—Movement**

Ranch 1 had 6.9 km of internal fencing, 6.9 km of boundary fencing, and 10.4 km of game fence. Ranch 2 had 7.8 km of internal fencing, 5.1 km of boundary fencing, and 0.9 km of game fence. Ranch 3 had 15.9 km of internal fencing, 13.2 km of external fencing, and 1.1 km of game fence (Table 3.1). Ranch 1 had 2 openings in the boundary fence that could have acted as an alternative crossing location by nilgai to leave the ranch. There was no boundary fencing on the western side of the ranch and half of the northernmost boundary was game fence and the other half had a dike and no fence. The boundaries of Ranch 2 with no fencing allowed nilgai to move off of the property without restrictions. Ranch 3 did not have boundary fencing bordering the Laguna Madre, which could have allowed nilgai to travel around the eastern portion of the northernmost and southernmost fence lines.

Intersections between an animal's movement path and fence lines produced 8,379 fence crossings by 30 individuals in a year. The collar data showed nilgai crossed boundary fences 30% and internal fences 70% of the yearly total. There was no fence crossing data that suggested nilgai crossed game fence.

Movement data showed fence-crossing rates varied substantially for each individual throughout the year (Fig. 3.7). Collared nilgai had 3–504 fence-crossing events on Ranch 1 (n=12), 42–482 on Ranch 2 (n=5), and 5–434 on Ranch 3 (n=13). Fence-crossing rates were higher in the active period (range: 703–1,143 per month) than in the inactive period (range: 423–589 per month). The highest fence-crossing rate for collared nilgai was in August, with 1,143 events. Collared females (n=19) had a total fence crossing rate of 3–488 and collared males (n=11) had 42–504. Four individuals left the study area for most of the year, which prevented them from using a sprayer site. Seventeen nilgai crossed a fence ≥ 1 every month their collar was active, and therefore had the potential to be treated every month. There were 9 individuals that remained within the study area and had ≥1 month where they did not cross a fence. Four nilgai crossed boundary fences more than internal fence lines. Two nilgai remained on Ranch 3 without ever crossing a boundary line. The remaining 28 nilgai left the study area ≥1 time during the year. Total boundary crosses per individual ranged from 0–393 and total internal crosses ranged from 0–411.

**Fence Crossings—Photos**

The trail cameras captured 4,798,580 photos from April 2019–March 2020. Of those photos, 14.3% were of animals (Table 3.2). Out of the 14.3%, white-tailed deer were seen the most out of any wildlife species, with 34.8% of photos, followed by cattle at 22.4%, and nilgai at 19.4%. Other wildlife species photographed at sprayer sites included armadillo (*Dasypus novemcinctus*), songbirds, bobcat (*Lynx rufus*), coyote (*Canis latrans*), feral hog (*Sus scrofa*), collared peccary (*Tayassu tajacu*), opossum (*Didelphis virginiana*), lagomorphs, raccoon (*Procyon lotor*), rodents, striped skunk (*Mephitis mephitis*), tortoises, and turkey (*Meleagris gallopavo*). Unmarked nilgai were documented crossing a fence in 16,918 photos. Out of the 19.4% of nilgai photos, 4,004 were of marked nilgai and 2,565 of those photos were of nilgai crossing a fence. The 2,565 nilgai fence-crossing photos represented 163 crossing events.

Overall, crossing events based on photo data were highest on the Ranch 1 Ranch site, with 122 crosses. Ranch 2 had 7 crossing events and Ranch 3 had 34. Fence-crossings consisted of 63 events of collared nilgai, with 17/30 individuals captured at a sprayer site (Table 3.3). Collared individuals were identified crossing at a monitored site at a rate of 0.2–3.7% of their fence-crossing rate per year. The remaining 100 crossing events were of tagged, uncollared nilgai. From the 163 crossing events identified at monitored sites, crossing rates were higher in the inactive period (67.5%) than the active period (32.5%). There were 91 crossing events at a barbed wire fence and 72 at a net-wire fence. Nilgai traveled over a fence 58 times and under 105 times. Nilgai crossed over barbed wire fences 6.6% of the time and traveled underneath 93.4%. Nilgai crossed over net-wire fences 72.2% of the time and traveled underneath 27.8%. Out of 108–144 sprayers during the active period, 40 sites captured a marked individual. Out of those sites, 13 sites only had 1 crossing event for the year. The top 3 monitored crossing sites for marked nilgai were on Ranch 1. Site CONW03 (under-crossing) had the most marked nilgai crossings at 24 events, CONE05 (over-crossing) had 19 events, and CONW01 (under-crossing) had 17 crossing events.

Males were seen crossing at a monitored site 115 times, females were captured 43 times, and there were 5 events where the sex was undetermined. Out of the female observed crossings, 65.1% were at a barbed wire fence, 34.9% were at a net-wire fence, 76.7% were under-crossings, and 23.3% were over-crossings. Out of the male crossing events at monitored sites, 53% were at a barbed wire fence, 47% were at a net-wire fence, 60% were under-crossings, and 40% were over-crossings. A collared male on Ranch 1 experienced collar malfunctions beginning in mid-October. There was no collar data for this individual for most of the inactive period, however during this time the nilgai was captured 14 times by cameras. This individual had the highest photo capture rate, although a fence crossing number based on movement data was unknown.

## DISCUSSION

The eradication of CFT and bovine babesiosis in the presence of wildlife hosts is difficult task. As an international concern, federal agencies, lawmakers, and law enforcement need to work in unison in managing for this costly disease (Graham and Hourrigan 1977). Eradication efforts for CFT are further complicated due to agricultural practices, recreational activities, and environmental conditions of the quarantine areas (Pérez de León et al. 2010). Over time, CFT exposed to acaricides can build up immunity, making current practices obsolete (Pelzel 2005). The presence of nilgai and other wildlife hosts continue to complicate CFT-eradication efforts in South Texas.

My study analyzed movements of 30 randomly sampled nilgai within the study area to determine how nilgai were interacting with fences. The movements of these nilgai are relevant to the Cattle Fever Tick Eradication Program because the nilgai are located within the temporary preventative quarantine area, which is known to have CFT. Based on movement patterns extracted from collar data, nilgai did cross fences. However, not all nilgai used fences equally. Four nilgai left the study area, which limited their potential to get treated. Those that remained in the study area did not always interact with fences.

The study sites are in the temporary preventative quarantine zone and representative of ranches in the area. The properties used in this study contained poorly maintained fence lines, providing alternative places for the nilgai to cross. There were 438 potential fence-crossing locations with signs of animal activity that were documented across all 3 ranches and a maximum of 144 sprayers deployed at a time. Ranches often consist of multiple pastures, which can result in open gates, creating yet another alternative for nilgai to travel unabated about the ranch. Approximately 25% of potential crossing sites were monitored during this study, so I expected to capture closer to 25% of crossing events on camera. However, due to the poor condition of fences, nilgai in this study had an abundance of alternative areas to cross the fence.

Within the parameters of the study, I observed that the sprayer technique is not a viable treatment option on its own to target nilgai when fences are poorly maintained (Table 3.3). The following points should be considered for this method to be successful on the average ranch in South Texas. Movement data indicated that nilgai often crossed boundary fences. Treated cattle are currently the most often used method to remove ticks from the landscape, as cattle are regularly treated within the quarantine zone. However, when wildlife hosts traverse areas without cattle, they have the potential to create tick reservoirs. As host species travel to and from a ranch, there is the potential to carry ticks with them. Nilgai sampled in this study demonstrated high individual variation in movements and space use, which resulted in not all nilgai having the potential to be treated. Only 57% of collared nilgai had the potential to be treated every month during the year. The remainder had the potential to sustain CFT. To fully understand the potential of the sprayer systems to treat nilgai, future field-tests should be performed on ranches with well-maintained fence lines that can restrict movement to fixed crossing locations. Fence crossings could also be blocked to reduce the number of crossings and increase traffic at crossings where sprayers are deployed.

Field-testing new methods often involve trial and error. There were more photo-based crossing events during the inactive period. However, I did not collect enough evidence to determine conclusively if nilgai were deterred by the sprayer systems. During the active period, technicians were on the ranches multiple times per week servicing the sprayers and cameras. The increase in human activity could have deterred nilgai from the sprayer sites, resulting in the increased crossing activity of marked nilgai in the inactive period.

There were almost twice as many collared females than males in this study. However, more collared males were observed crossing at monitored sites. Both sexes traveled underneath the fence more often than jumping over the fence. Nilgai are large, muscular ungulates that despite their size, are capable of jumping over fences. In this study, 35.6% of observed fence crossings were of nilgai traveling over the fence. The site with the $2^{nd}$ highest observed fence crossing events was an over-crossing. The poor condition of fence lines within the study area could have made crossing over a fence easier for nilgai. An adult bull weighs on average 241 kg and the average female weight is 169 kg (Sheffield et al. 1983, Sankar et al. 2004, Leslie 2008). Adult nilgai typically stand 120–140 cm at shoulder height (Sheffield et al. 1983, Sankar et al. 2004, Leslie 2008). As a large animal, jumping over fences increases the risk of fence damage and mortality for the individual (Scott 1992, Poor et al. 2014), and decreases an animal's chance of receiving treatment. Traveling under a fence is a slower process, especially for nilgai, that have to get on their knees to crawl under sometimes very narrow openings. Crawling under the fence also provides an opportunity for the nilgai to be treated passively via nematode treated soil (Goolsby and Shaprio-Ilan 2020). Zoromski (2019) reported nilgai using a fence crossing that was 44 cm in height. The extra time it takes a nilgai to travel underneath a fence at a sprayer site improves the chance they have at getting immersed in solution or treated by nematode wetted soil and foliage (Goolsby and Shaprio-Ilan 2020).

Nilgai were able to cross barbed wire and net-wire fences, but were not observed crossing game fencing. Ranch 1 is surrounded by game fence on 3 sides, and locations of nilgai with GPS collars showed they never crossed that barrier. Nilgai often spent time near the game fence, presumably for foraging or walking along the ranch roads that paralleled the fence. The lack of crossings through 2.5-m tall game fence is consistent with the findings of previous studies (Moczygemba et al. 2012, Foley et al. 2017).

Fences have become so integrated into society that they are often overlooked when it comes to wildlife conservation (Poor et al. 2014, Jakes et al. 2018). In an ecological setting, fences have been used to keep domestic animals in a regulated area and to restrict movements of wildife that may cause damage (VerCauteren et al. 2006). During a questionnaire survey in Nepal, respondents listed physical barriers, such as fences and trenches, as top methods used to keep nilgai out of cropland; some even used electric fences (Khanal et al. 2017). Similarly, other ungulate species, including pronghorn antelope (*Antilocapra americana*), mule deer *(Odocoileus hemionus*), and elk (*Cervus canadensis*), often migrate between seasonal areas and may have large home ranges which can be restricted by fencing (Poor et al. 2014). Studies of animal movements can provide insight into how a species interacts with fences (Mysterud and Rolandsen 2018).

The U.S. livestock industry saves billions of dollars annually by being free of cattle fever ticks (Bock et al. 2004, Miller et al. 2013). Therefore, it is imperative to create a treatment plan to target wildlife hosts. The top 3 species documented near the sprayer sites were deer, cattle, and nilgai. This indicates all 3 host species frequent the same areas and have the potential to co-mingle and share ticks (Olafson et al. 2018). Deer were the top species identified at monitored sites. Although, it is unknown how many individuals crossed at these sites, this method has the potential to treat deer for CFT as well. The sprayer systems could be an option to target deer when treated feed is not an option. Cattle dipping is done every 2 weeks, killing all ticks on contact, but does not prevent cattle from re-infestations (USDA-APHIS 2010). It is currently unknown how often nilgai would need to be treated with the nematode solution to be effective. Based on movement behaviors, it has been suggested that nilgai would respond best to a treatment that only needed to be administered once (Moczygemba et al. 2012). My sample of collared nilgai documented 2 young animals traveling a straight-line distance of 40 km from their capture locations. These long-distance movements can overlap multiple ranches with the potential of spreading CFT. Every time a nilgai crosses a boundary fence, they risk spreading CFT to a new area. After observing the diverse interactions individuals had with fences, a combination of treatment options may be needed to reach the 13/30 nilgai that did not consistently interact with fences.

## MANAGEMENT IMPLICATIONS

There are no methods currently in practice to treat nilgai for cattle fever ticks. Nilgai do not respond to bait, have large home range sizes, can make long-distance movements, and can be hunted yearlong. Motion-activated sprayer systems were designed to target nilgai for CFT-treatment. Determining where to deploy these sprayer systems is key to maximizing the number of nilgai treated. There is still a great need to better understand the way nilgai interact with livestock, other wildlife, and manmade barriers such as fences. Within the parameters of this study, 57% of collared nilgai had the potential to be treated via the sprayer system at least monthly. The sprayer systems might be more effective if movements were constrained to fixed crossing locations. In addition to nilgai, white-tailed deer had the potential to get treated, which could help reduce tick numbers on the landscape. Game fence proved successful in restricting nilgai, and could be implemented more to limit and focus host movement. The results from this study indicate that >1 tick-treatment option is needed to eliminate CFT from the ranchland where wildlife reservoirs occur. Information extracted from this study will aid in the continued development of methods to target nilgai for CFT.

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**Table 3.1.** Meters of fence lines, potential fence-crossing locations, and densities of fence-crossing locations for each ranch in Cameron County, TX, USA, from April 2019–March 2020. Fence lines were separated into external boundary fences and internal fences. Potential fence-crossing locations were defined as an area a nilgai could pass under or over a fence. Densities were calculated to determine how many potential fence crossings each ranch had per m of property fencing.

| | Fence lines (m) | | | Fence-crossing locations | | | Density[1] | | |
|---|---|---|---|---|---|---|---|---|---|
| Ranch | Boundary fence | Internal fence | Total | Boundary fence | Internal fence | Total | Boundary fence | Internal fence | Total |
| Ranch 1 | 6,900 | 6,900 | 13,800 | 126 | 28 | 154 | 1/55 | 1/246 | 1/90 |
| Ranch 2 | 5,100 | 7,800 | 12,900 | 26 | 18 | 45 | 1/196 | 1/433 | 1/287 |
| Ranch 3 | 13,200 | 15,900 | 29,000 | 105 | 134 | 239 | 1/125 | 1/119 | 1/122 |

[1]=Density = 1 fence crossing location/m of fence line

**Table 3.2.** Animal species documented at fence-crossing sites in Cameron County, TX, USA, from April 2019–March 2020. There were 4,798,580 photos collected during the year of which 14.3% contained animal photos.

| **Species** | **Number of photos** | **Percent (%)** |
|---|---|---|
| White-tailed deer | 239,005 | 34.81% |
| Domestic cattle | 153,722 | 22.39% |
| Nilgai antelope | 133,055 | 19.38% |
| Birds | 77,855 | 11.34% |
| Feral hog | 30,988 | 4.51% |
| Small mammal | 19,954 | 2.91% |
| Coyote | 5,949 | 0.87% |
| Lagomorph | 5,914 | 0.86% |
| Collared peccary | 5,157 | 0.75% |
| Raccoon | 5,036 | 0.73% |
| Turkey | 3,189 | 0.46% |
| Bobcat | 2,555 | 0.37% |
| Opossum | 1,586 | 0.23% |
| Armadillo | 1,522 | 0.22% |
| Domestic pets | 728 | 0.11% |
| Tortoise/Turtle | 200 | 0.03% |
| Other | 200 | 0.02% |
| Striped skunk | 40 | 0.01% |
| Horse | 21 | <0.01% |
| **Total** | **686,676** | **100%** |

**Table 3.3.** Observations of GPS-collared nilgai antelope documented at a fence-crossing site in Cameron County, TX, USA, from April 2019–March 2020. Crossing events were defined as the intersection of an animal's movement path with a fence line. Crossing events were separated by occurrence in the active or inactive period. Active period was when the motion-activated sprayer systems were deployed from April–September 2019. The inactive period was when sprayer systems were absent from the field between October 2019 and March 2020. Fence-crossing rates were camera-documented occurrences of collared nilgai crossing a fence. (FC-Movement = fence-crossing events derived from collar data, FC-Photo = fence-crossing events at monitored locations via trail cameras)

| Collar ID | Days monitored | FC-Movement | FC-Photo | % of identified crossings[1] | Active period | Inactive period |
|---|---|---|---|---|---|---|
| 35107 | 366 | 427 | 7 | 1.6% | 0 | 7 |
| 35108 | 366 | 488 | 1 | 0.2% | 1 | 0 |
| 35109 | 366 | 301 | 3 | 1% | 3 | 0 |
| 35111 | 366 | 202 | 1 | 0.5% | 1 | 0 |
| 35112 | 366 | 402 | 7 | 1.7% | 2 | 5 |
| 35113 | 366 | 482 | 1 | 0.2% | 0 | 1 |
| 35115 | 266 | 382 | 4 | 1% | 3 | 1 |
| 35118 | 177 | 260 | 1 | 0.4% | 1 | 0 |
| 35118B | 183 | 398 | 3 | 0.8% | 0 | 3 |
| 35120[2] | 204 | 440 | 3 | 0.7% | 2 | 1 |
| 35121 | 366 | 277 | 3 | 1.1% | 0 | 3 |
| 35122 | 218 | 163 | 6 | 3.7% | 6 | 0 |
| 35125 | 366 | 487 | 3 | 0.6% | 0 | 3 |
| 35126 | 366 | 46 | 1 | 2.2% | 1 | 0 |
| 35127[3] | 269 | 448 | 14 | 3.1% | 0 | 14 |
| 35131 | 366 | 504 | 4 | 0.8% | 2 | 2 |
| 35135 | 177 | 300 | 1 | 0.3% | 1 | 0 |

[1]= (FC-Photo/FC-Movement)*100
[2]=This individual was documented at a sprayer site an additional 14 times, but due to collar malfunction there is no movement data available to estimate an expected crossing rate.
[3]=This individual's collar detached early due to wear-and-tear on the device, and was also documented at a sprayer site an additional 14 times with no collar.

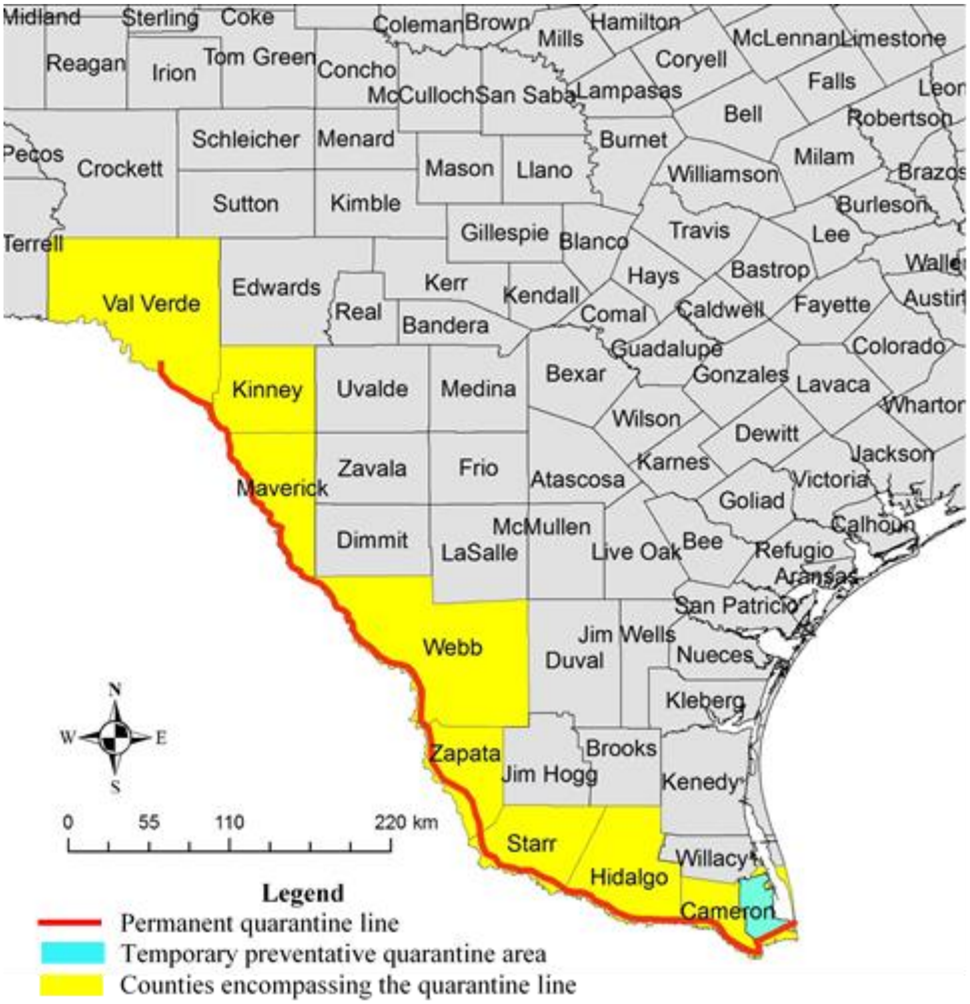


**Figure 3.1.** The location of the permanent quarantine zone and temporary preventative quarantine area in Texas, USA. The permanent quarantine zone acts as a buffer to prevent the re-infestation of cattle fever ticks in the U.S. The temporary preventative quarantine area was created in 2014 after wildlife were implicated in cattle fever tick outbreaks.

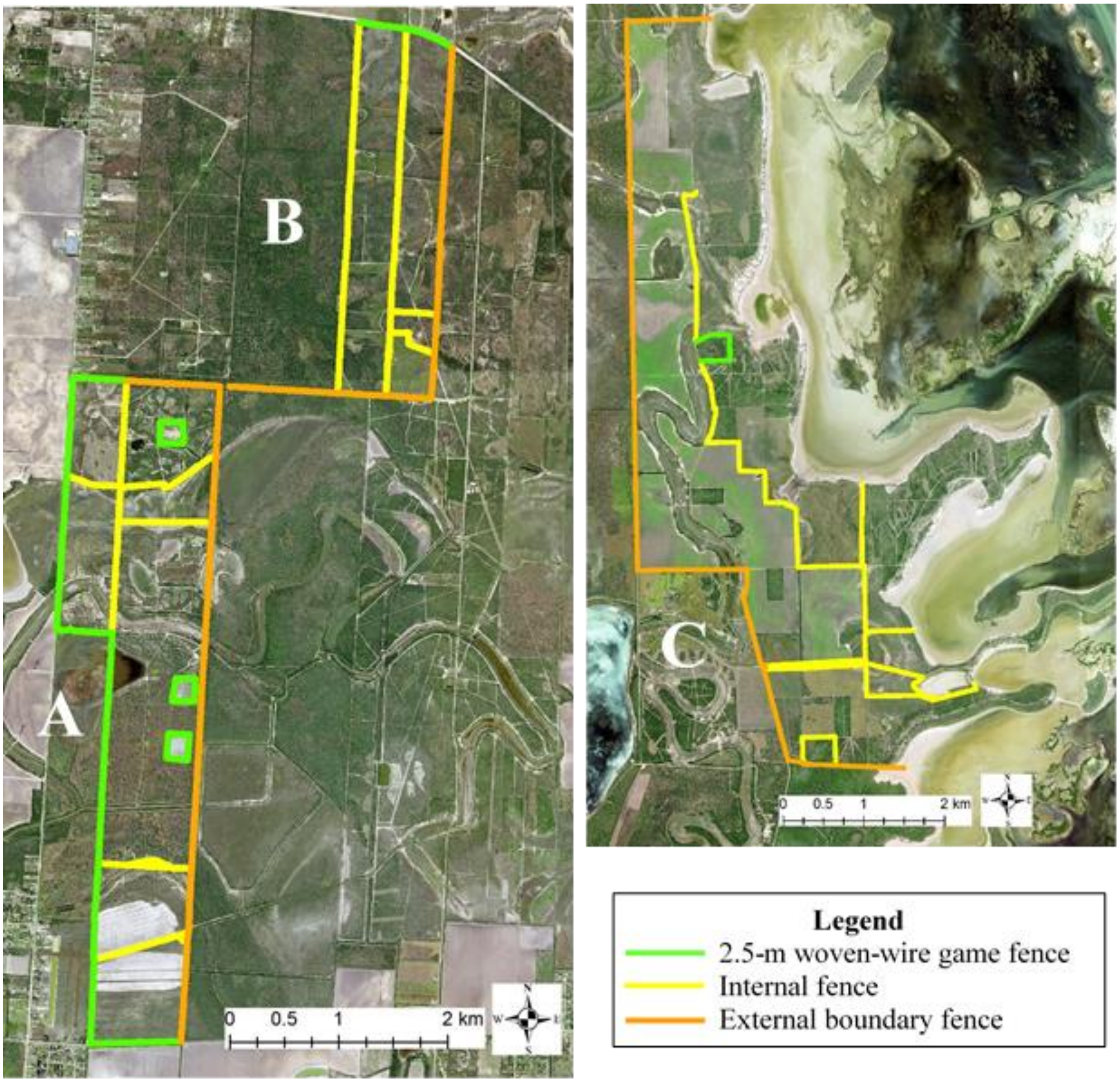


**Figure 3.2.** Study sites and fence types present in Cameron County, TX, USA: (A) Ranch 1, (B) Ranch 2, and (C) Ranch 3.

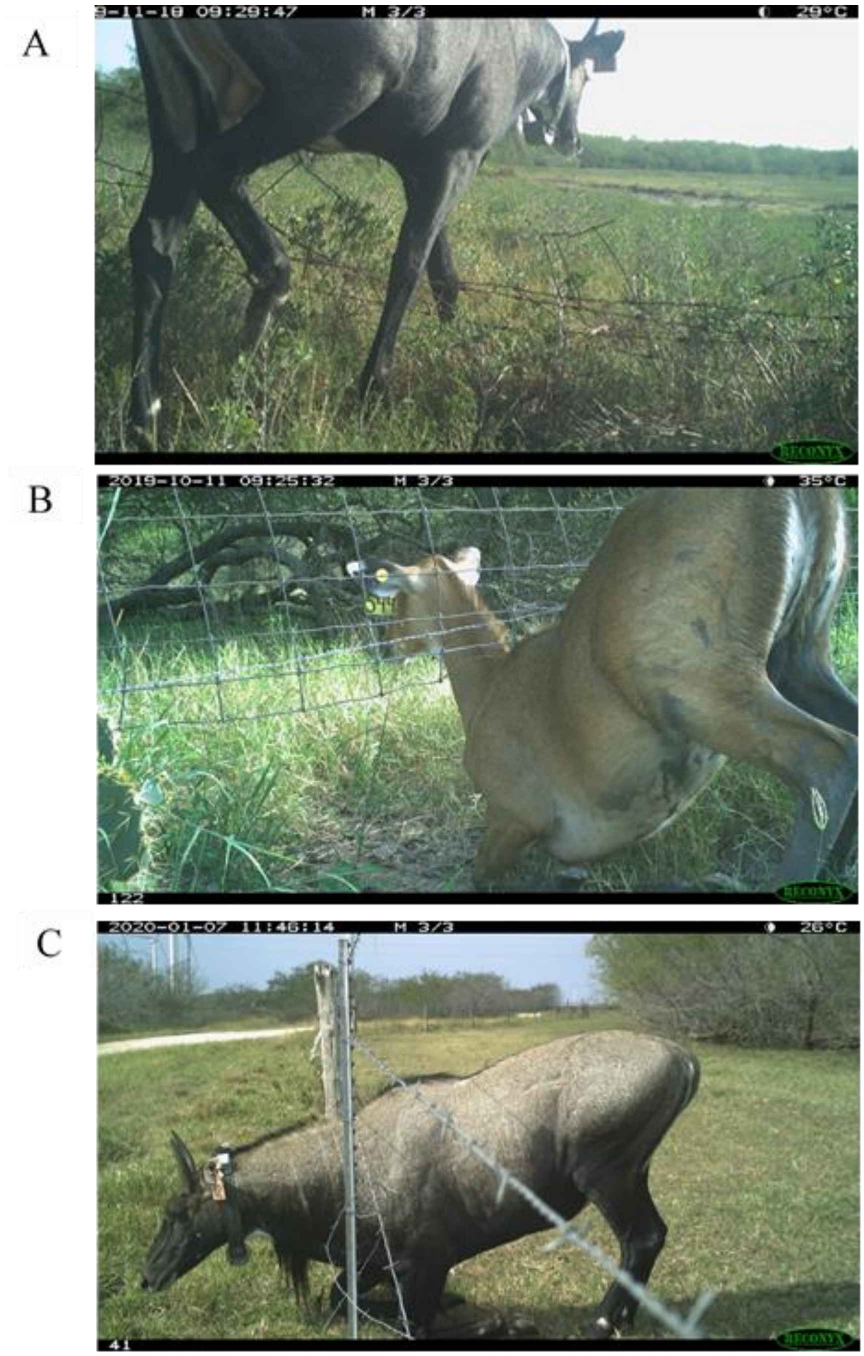


**Figure 3.3.** Marked (tagged or GPS-collared) nilgai antelope crossing fences in Cameron County, TX, USA, from April 2019–March 2020. (A) A collared male passes over a net-wire fence. (B) A tagged female crosses underneath a net-wire fence. (C) A collared male crosses underneath a barbed wire fence.

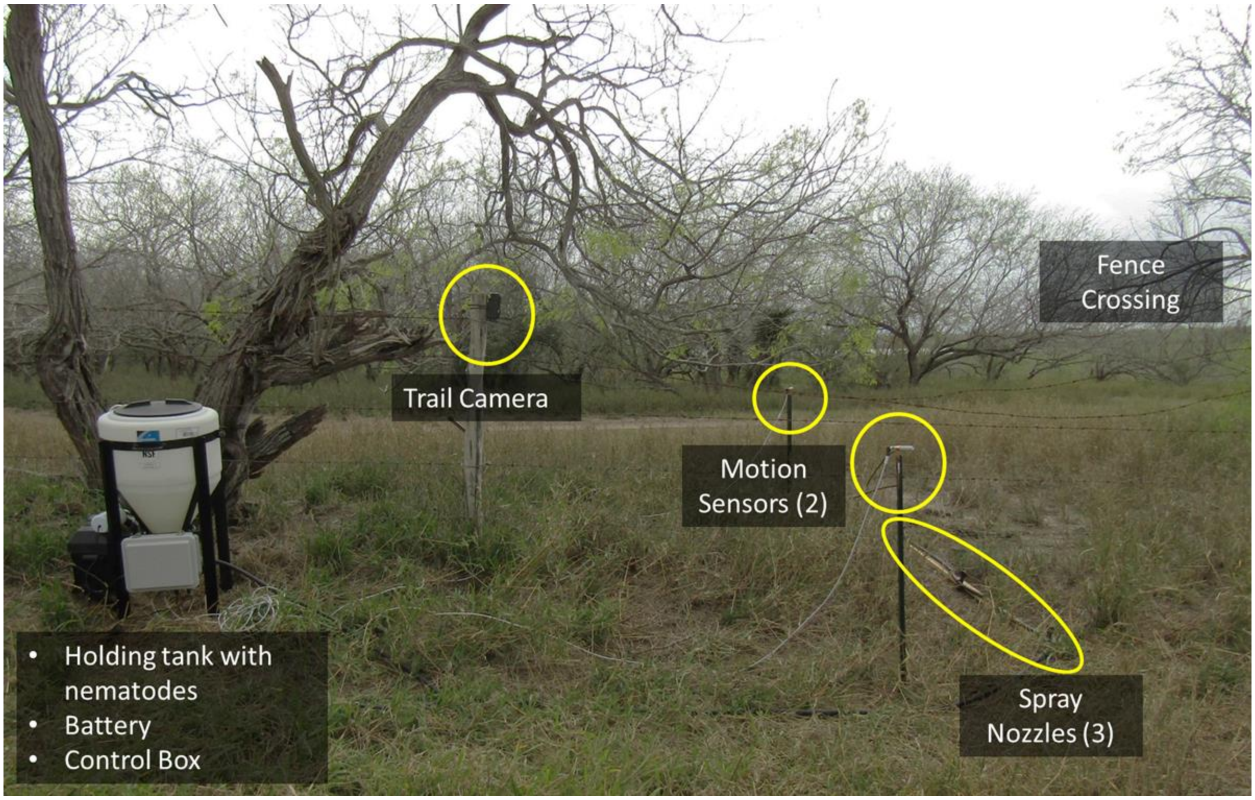


**Figure 3.4.** The motion-activated sprayer system set up at a fence-crossing location. These sprayer systems were deployed across 3 ranches in Cameron County, TX, USA from April 2019–September 2019. These sprayer systems were designed to treat nilgai antelope for cattle fever ticks as the nilgai crossed the fence line.

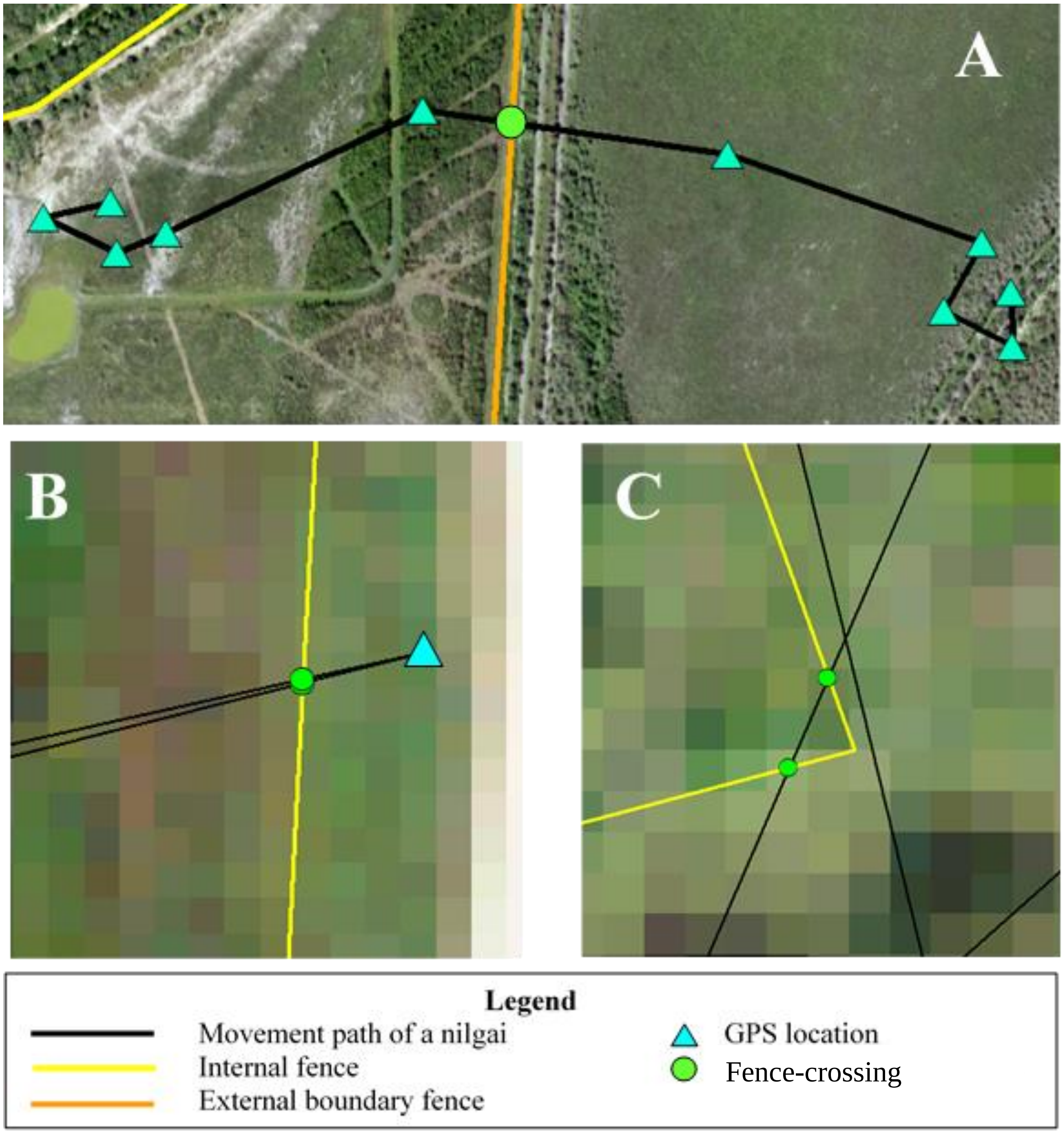


**Figure 3.5.** Fence crossings were quantified based on movement data from GPS-collared nilgai antelope (1-hr fix rate) in Cameron County, TX, USA, from April 2019–March 2020. (A) A fence-crossing event is when a nilgai's movement path intersects a fence line with at least 2 locations on either side of the fence. Potential crossing events that involved only 1 location on the other side of the fence (B) or an intersection with a fence corner were removed (C).

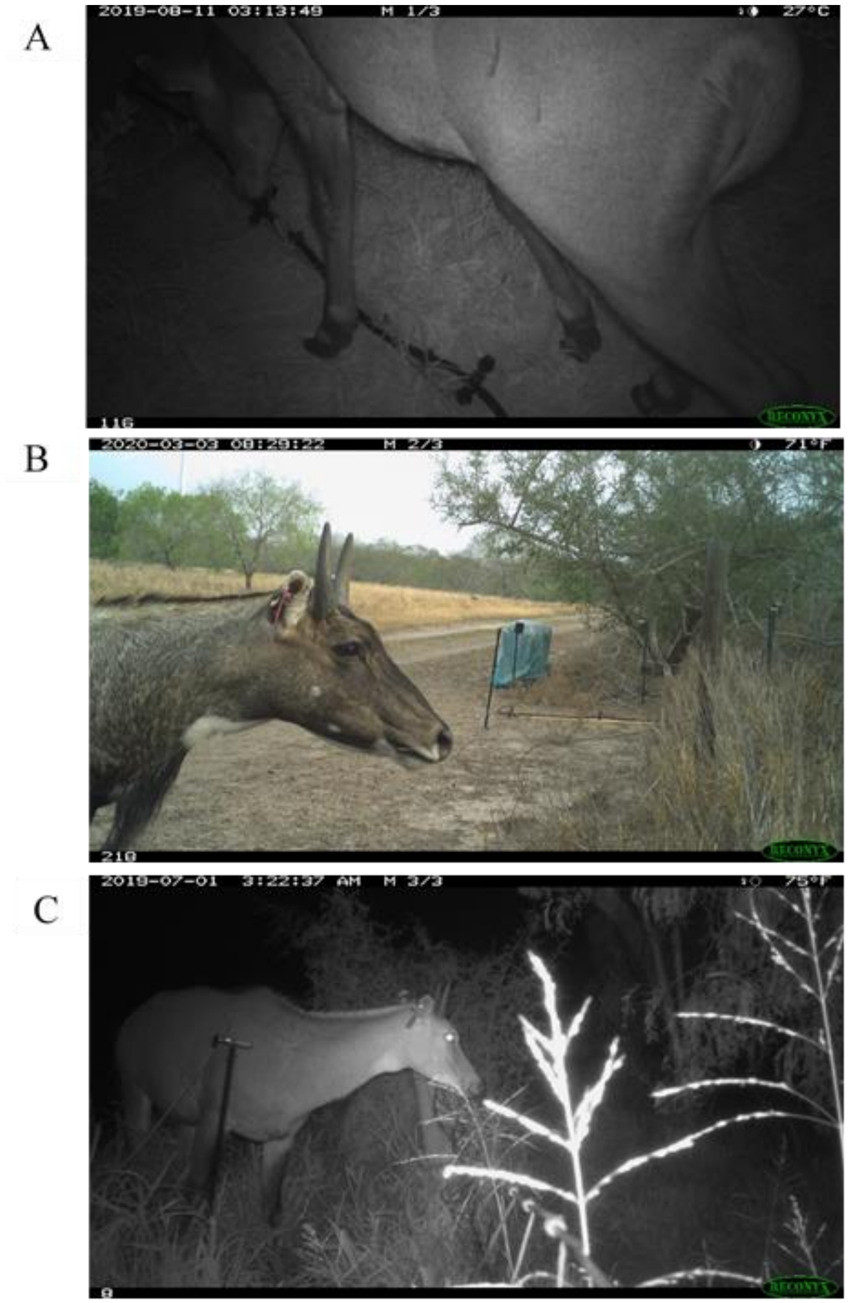


**Figure 3.6.** Nilgai antelope at fence crossings with motion-activated sprayer systems in Cameron County, TX, USA, from April 2019–March 2020. The sprayer systems were designed to target nilgai for cattle fever tick treatment. (A) A nilgai crossing over the sprayer system nozzles. (B) A tagged male near a sprayer system. (C) A tagged male standing by a motion sensor, about to cross the fence.

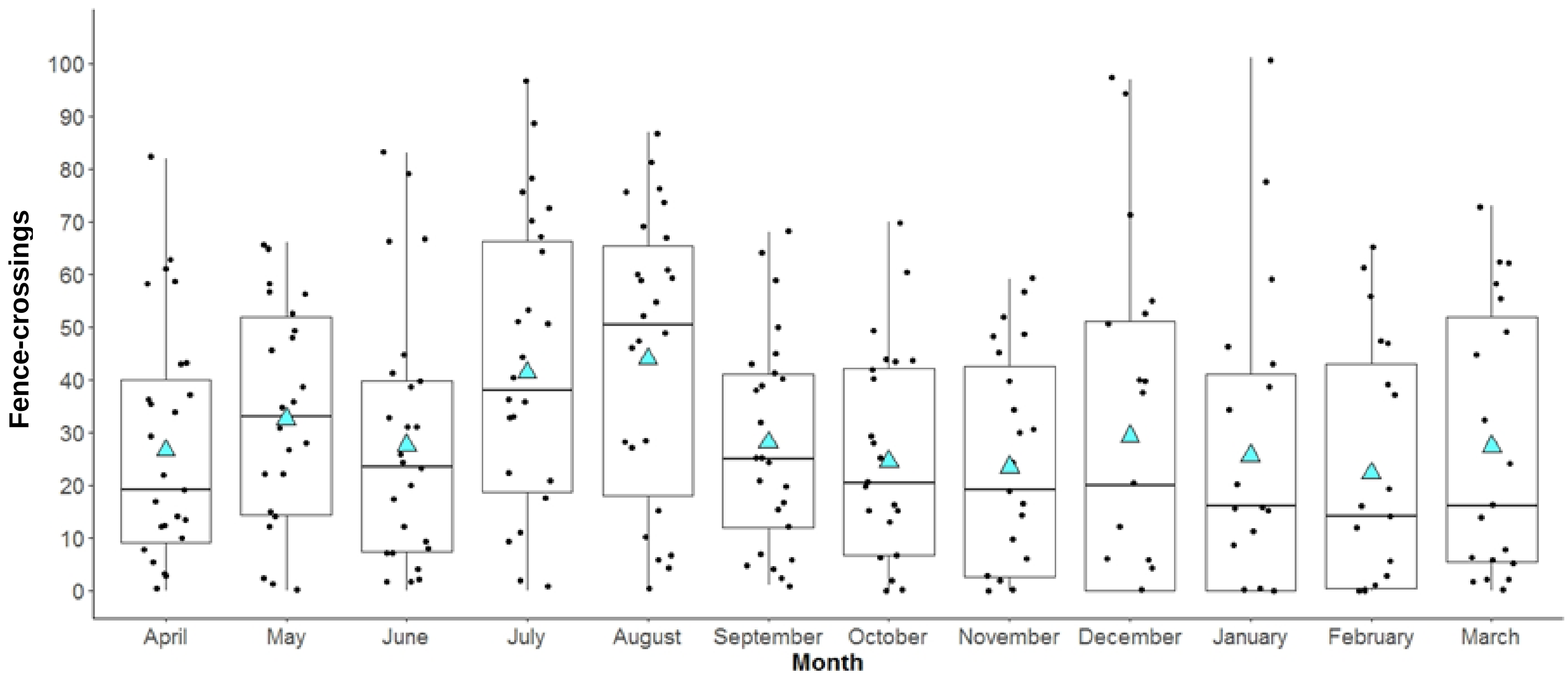


**Figure 3.7.** Fence-crossings per month derived from movement data for 30 GPS-collared nilgai antelope (1-hr fix rate) in Cameron County, TX, USA, from April 2019–March 2020. Fence-crossings were determined when the movement path of an individual intersected a fence line. Boxes represent median and interquartile ranges, and the triangle (△) represents the monthly average of crossing rates.

## VITA

KATHRYN M. SLIWA

## EDUCATION

**Texas A&M University-Kingsville, Kingsville, Texas**
Master of Science, August 2018–May 2021
Department of Rangeland and Wildlife Sciences
**Major**: Range and Wildlife Management

**Delaware Valley University, Doylestown, Pennsylvania**
Bachelor of Science, August 2011–May 2015
Department of Animal Biotechnology and Conservation
**Major**: Conservation and Wildlife Management
**Minors**: Animal Science and Environmental Science

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## PROFESSIONAL EXPERIENCE

**Wildlife/Habitat Technician** April–July 2018
*Oregon State University, Riley, OR*

**Carnivore/Deer Wildlife Technician** August 2017–March 2018
*Michigan Predator-Prey Project, Mississippi State University, Baraga, MI*

**Pheasant Research Technician II** January–July 2017
*University of Nebraska-Lincoln, NE Coop. Fish and Wildlife Research Unit, Culbertson, NE*

**Hunter Survey Technician I** October–December 2016
*University of Nebraska-Lincoln, NE Coop. Fish and Wildlife Research Unit, Culbertson, NE*

**Biological Science Technician (GS-04)** March–July 2016
*Padre Island National Seashore: Division of Sea Turtle Science and Recovery, Corpus Christi, TX*

**Conservation/Education Intern** August–December 2015
*Bald Head Island Conservancy (NGO), Bald Head Island, NC*

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## AWARDS AND SCHOLARSHIPS

Philip M. Plant Graduate Scholarship, $1200 (*2021*)
Houston Safari Club Foundation, Dan L. Duncan Scholarship, $3000 (*2020*)
South Texas Quail Coalition Scholarship, $3500 (*2019-2021*)
2$^{nd}$ Place, Don Pendleton Memorial Graduate Poster Competition, TSSRM (*2019*)
Cum Laude, DVU Class of 2015 (*2015*)