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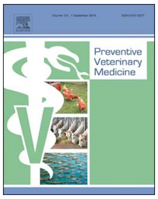

Movement patterns of nilgai antelope in South Texas: Implications for cattle fever tick management

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ABSTRACT

Wildlife, both native and introduced, can harbor and spread diseases of importance to the livestock industry. Describing movement patterns of such wildlife is essential to formulate effective disease management strategies. Nilgai antelope (*Boselaphus tragocamelus*) are a free-ranging, introduced ungulate in southern Texas known to carry cattle fever ticks (CFT, *Rhipicephalus* (*Boophilus*) *microplus*, *R.* (*B.*) *annulatus*). CFT are the vector for the etiological agent of bovine babesiosis, a lethal disease causing high mortality in susceptible *Bos taurus* populations and severely affecting the beef cattle industry. Efforts to eradicate CFT from the United States have been successful. However, a permanent quarantine area is maintained between Texas and Mexico to check its entry from infested areas of neighboring Mexico states on wildlife and stray cattle. In recent years, there has been an increase in CFT infestations outside of the permanent quarantine area in Texas. Nilgai are of interest in understanding how CFT may be spread through the landscape. Thirty nilgai of both sexes were captured and fitted with satellite radio collars in South Texas to gain information about movement patterns, response to disturbances, and movement barriers. Median annual home range sizes were highly variable in males (4665 ha, range = 571–20,809) and females (1606 ha, range = 848–29,909). Female movement patterns appeared to be seasonal with peaks during June-August; these peaks appeared to be a function of break-ups in female social groups rather than environmental conditions. Nilgai, which reportedly are sensitive to disturbance, were more likely to relocate into new areas immediately after being captured versus four other types of helicopter activities. Nilgai did not cross 1.25 m high cattle fences parallel to paved highways but did cross other fence types. Results indicate that females have a higher chance of spreading CFT through the landscape than males, but spread of CFT may be mitigated via maintenance of cattle fences running parallel with paved highways. Our results highlight the importance of documenting species-specific behavior in wildlife-livestock interfaces that can be used to develop effective disease management strategies in the United States and worldwide.

1. Introduction

Management of diseases in a wildlife-livestock interface can be difficult, especially in an environment where susceptible or host animals can move freely (Fèvre et al., 2006). The movement of livestock can be controlled with man-made barriers, but wildlife present a greater challenge in the wildlife-livestock interface. Quantifying movement patterns of wildlife improves understanding of potential spatiotemporal interactions between livestock and wildlife species (Vercauteren et al., 2007; Wyckoff et al., 2009). Additionally, documenting periods of wide-ranging movements (e.g., dispersal), potential barriers to movements (e.g., fences), and sex -specific movement behavior (e.g., mate

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search) of species involved in pathogen maintenance and transmission increases knowledge of potential risk factors associated with transmission of disease in susceptible populations (Rosatte et al., 2010; Yockney et al., 2013). Gaining such knowledge from wildlife will increase efficacy of management strategies aimed towards disease eradication in a wildlife-livestock interface (Pérez de León et al., 2012).

Bovine babesiosis is a tick-borne disease caused by the protozoan parasites of the genus *Babesia* (*B. bovis* and *B. bigemina*) with clinical manifestations of hemoglobinuria, dark red or brown-colored urine, anemia, high fever, and death (Bock et al., 2004). *B. bovis* and *B. bigemina* are known to occur in cattle in Africa, Asia, Australia, and Central and South America (de Wall and Combrink, 2006; Uilenberg, 2006) and are one of the most problematic issues in the livestock industry (Madder et al., 2011). The disease caused by these organisms and their vector, cattle fever ticks (CFT, *Rhipicephalus* (*Boophilus*) *microplus*, *R.* (*B.*) *annulatus*), were eradicated from the U.S. by 1943 by state and federal agencies under the Cattle Fever Tick Eradication Program. Because of widespread prevalence of CFT in neighboring states of Mexico, reintroduction is a significant threat (Pérez de León et al., 2014); thus, there is a permanent quarantine zone (PQZ) between Texas and Mexico (Pérez de León et al., 2012; Giles et al., 2014). The PQZ remains due to movement of tick host species such as white-tailed deer (*Odocoileus virginianus*, Kistner and Hayes, 1970), nilgai antelope (*Boselaphus tragocamelus*, Cárdenas-Canales et al., 2011), stray cattle (*Bos* spp.) and interactions between CFT and exotic weeds along the transboundary region with Mexico (Racelis et al., 2012; Esteve-Gassent et al., 2014). In recent years, there has been more infestation cases outside of the PQZ than within (Giles et al., 2014).

The expansion of CFT outside of the PQZ has resulted in a need to better understand movement of free-ranging host wildlife species. Two host species of concern in South Texas are white-tailed deer and nilgai. In South Texas, Moczygemba et al. (2012) reported mean home range sizes of 8355 and 9356 ha for female and male nilgai, respectively; whereas, mean home range size of male white-tailed deer ranges from 182 to 922 ha (Webb et al., 2007; Hellickson et al., 2008). Thus, nilgai have great potential to introduce CFT into new areas (Moczygemba et al., 2012). Nilgai are non-migratory and occur in small sexually segregated groups except during the breeding season (Leslie and Sharma, 2009). Males are reportedly transient (Sheffield et al., 1983) but nilgai movement patterns are relatively undocumented because the species were brought to Texas only at the beginning of last century and released into fenced areas in the southern part of the state. Because nilgai are not entirely impeded by fences (Sheffield et al., 1983), some nilgai eventually escaped and by the early 1970s, free-ranging nilgai were distributed in 9 Texas counties and in northeastern Mexico (Presnall, 1958; Sheffield et al., 1983). In Texas, nilgai are defined as an exotic species, which allows year-round hunting with no bag limits. Despite this, nilgai populations have become established and have expanded their range in Texas (Moczygemba et al., 2012).

There is a need to better understand nilgai movement patterns because long range movement of nilgai is now implicated in the spread of CFT not only in the PQZ along the Rio Grande, but also in the Temporary CFT Preventive Quarantine Areas (TPQZ) located north of the PQZ in Cameron, Willacy, and Kleberg Counties (Texas Animal and Health Commission, 2014). Recently, CFT has been found in several properties north of the TPQZ and south of state highway 186 in Willacy County (Fig. 1) prompting the expansion of CFT surveillance efforts. Understanding movement of nilgai and their home range is essential to establish effective quarantine boundaries to eradicate CFT. Failure to stop the spread of CFT could influence the cattle industry across much of the southern United States. To better understand how CFT may spread through the landscape via nilgai and to establish effective quarantine boundaries, this study had 3 objectives, to: 1) quantify home range size and evaluate whether seasonal movement patterns were driven by environmental conditions or physiological behavior, 2) evaluate nilgai response to 5 types of helicopter activities, and 3) measure permeability of three types of fences.

Although Moczygemba et al. (2012) found that home range sizes were similar between males and females, we hypothesized that male nilgai would have larger home range sizes and higher movement rates than females because sexual dimorphism suggests males have a greater nutritional demand (McNab, 1963) and males are reportedly transient (Sheffield et al., 1983). We also hypothesized seasonal changes in monthly movement patterns were a result of physiological changes (e.g., breeding, parturition, etc.). Alternatively, seasonal movement patterns may be a function of environmental conditions in semi-arid areas such as rainfall and temperature. Because nilgai may be sensitive to human disturbance (Sheffield et al., 1983), we predicted that nilgai would have higher movement rates during day(s) of helicopter activities in the study site, but most nilgai would remain on the study site because escape cover (i.e., canopy cover) is abundant (Goldstein et al., 2005). We hypothesized that fences running parallel with paved roads were the least permeable barrier relative to property boundary fences and intra-property fences.

2. Materials and methods

2.1. Study area

Nilgai were captured on a 10,984 ha property of the East Foundation bordering Port Mansfield, Texas (26°55′N, −97°42′E) immediately north of where current CFT infestations occur. Helicopter-based distance sampling in February 2015 indicated ~600 nilgai were present on the study site (Annala, 2015). The east boundary was the Gulf of Mexico, the north and west boundaries were adjacent to continuous landholdings, and the south boundary was state highway 186. The study site was surrounded by 1.25 m or 2.50 m high woven-wire fence to prevent exchange of cattle with adjacent properties. Fences were used to control cattle movements because unlike nilgai, cattle do not have the ability or propensity to go underneath fences. The study site overlapped 3 ecoregions; Coastal Sand Plains, Lower Rio Grande Valley, and Laguna Madre Coastal Marshes (Bailey et al., 1994). The Coastal Sand Plains and Lower Rio Grande Valley ecoregions were comprised of Tamaulipan thornscrub, oak forest and savannah, and grasslands. The Laguna Madre Coastal Marshes contained mosaics of coastal wetlands, ponds, and grasslands bordering the Laguna Madre. From April 2015 to May 2016, the sub-humid region received an average monthly rainfall of 6.66 cm (range = 0.03–20.90) and temperatures averaged 23.0° C (range = 13.6–28.3, Crop Weather Program, 2016).

2.2. Nilgai capture

In April 2015, we randomly captured thirty nilgai (5% of estimated population size) via helicopter net-gunning (Barrett 1982) and each nilgai was fitted with a satellite radio-collar. Captures were approved by Texas A & M University − Kingsville IACUC (no. 2015-03-30). We affixed two types of Lotek (Lotek Wireless Inc., Ontario, Canada) collars to nilgai; Globalstar (1-h fix interval, $n = 10$) and LifeCycle (13-h fix interval, $n = 20$). To extend lifespan of Globalstar batteries, fix intervals switched to 2-h after 1 year (April 2016). We did not collar calves (< 1 year old) because of their association with their dams. Mortalities ($n = 1$) and collar break-offs ($n = 4$) occurred during the study and these collars were re-deployed on new nilgai of the same sex via net-gunning (Table S1). Preliminary analyses indicated collared individuals did not interact with each other for extended periods of time; thus, we concluded we did not monitor individuals belonging to the same social group.

2.3. Home ranges

Prior to conducting movement analyses, the first 3 days post-collar

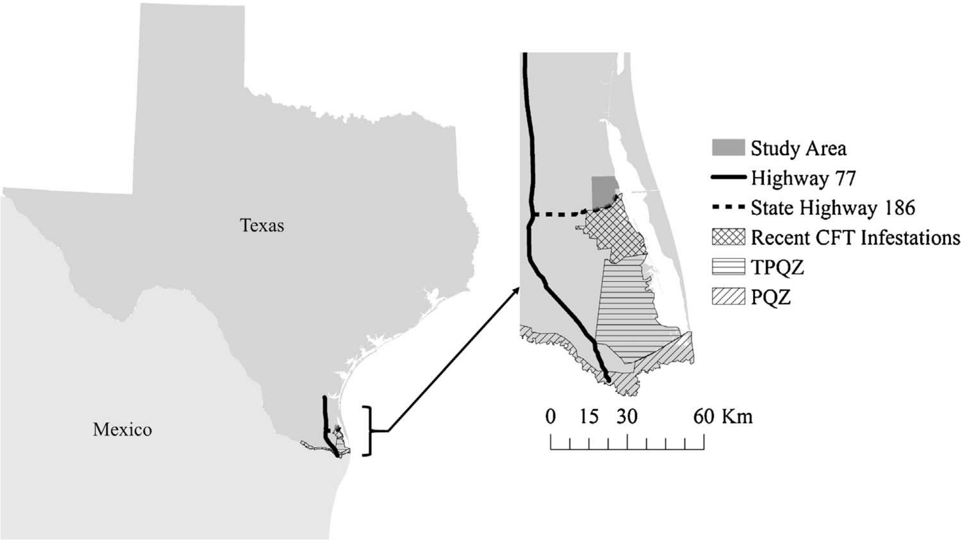

Fig. 1. Map of study area in South Texas. Nilgai were captured immediately north of where recent cattle fever tick (CFT) infestations occurred. TPQZ is temporary preventative quarantine zone and PQZ is permanent quarantine zone.

deployment observations were removed to ensure movements were not a response to nilgai capture activities (Morellet et al., 2009). We computed 95% minimum convex polygons (MCP, Mohr, 1947) to compare home range sizes between each sex during breeding/winter (Dec-Mar), gestation/summer (Apr-Jul), birth/lactation/autumn (Aug-Nov), and year-round (Apr 2015-May 2016). Biological seasons were defined based on descriptions in Sheffield et al. (1983). To match fix interval of 13-h collars, we extracted 13-h and 12-h time intervals from collars with 1-h and 2-h fix intervals, respectively.

2.4. Movement distances

We analyzed fine-scale movements monthly by calculating the total movement distance for each nilgai for each calendar month during April 2015-May 2016. Because performance of satellite collars were not consistent, we only used nilgai-months with ≥20 locations. Total monthly movement distances do not differentiate between large (moving away from origin) versus small space-use (moving in circles) so we also calculated the maximum distance between two locations for each nilgai-month. Assessment of risk, in terms of increased nilgai mobility resulting in higher probability of spreading CFT, was done by plotting total distance moved per month against maximum distance between 2 points for each month-sex combination. To match fix interval of 13-h collars, we extracted 13-h and 12-h time intervals from collars with 1-h and 2-h fix intervals, respectively.

Because wildlife may increase space-use during stressful periods (e.g., drought), we assessed the relationship between nilgai movement and environmental conditions. We quantified the relationship between monthly average temperature and monthly total rainfall with each of the 2 monthly movement metrics (maximum distance and total distance). Environmental conditions should impact all nilgai regardless of sex, thus we pooled monthly movement metrics of all nilgai and used linear regressions to assess the relationship with monthly environmental conditions during April 2015–May 2016. Preliminary analyses revealed log-transformation of maximum distance produced better model fits whereas total distance did not need transformation. Because of the repeated measurements of individuals, we used animal ID as a random effect. We used AIC scores to compare 3 models (temperature alone, rainfall alone, and both temperature and rainfall) for both maximum distances and total distances. Then we derived marginal R^2 and conditional R^2 from the best models (Nakagawa and Schielzeth, 2013).

2.5. Helicopter activities

We assessed whether nilgai dispersed into new areas, which would increase the risk of CFT spread, after helicopter-based activities. Helicopter-based activities included 1) nilgai captures, 2) white-tailed deer captures (Barrett et al., 1982), 3) cattle gatherings, 4) large mammal surveys (DeYoung, 1985), and 5) nilgai population control. Deer captures occurred during 30–31 October, 2015 and two helicopters, one as a deer spotter and another as the primary net-gunner, were used to capture deer as encountered. Field crews used all-terrain vehicles to transport deer from the capture location to a processing site. Large mammal surveys were conducted on 22 February 2016. Fixed width transects were flown in a North-South direction at ~56 km/hr while maintaining 15 m elevation. Cattle gatherings occurred during 1–2 and 8–9 March, 2016 when a helicopter flew at low elevation to direct cattle towards holding pens. As part of CFT control efforts, there were 3 nilgai harvests conducted on 11 May, 26 May and 9 June 2016. Nilgai were harvested with a 0.223 caliber rifle from a helicopter and harvests totaled 50, 45, and 18 adult females and juveniles from the above dates, respectively. Harvested nilgai were inspected for CFT, none were found, further validating that the study site was not infected with CFT.

With the exception of nilgai captures, we calculated average movement rate (m/hr) for the day prior to, day(s) during the helicopter activity, and the day after. Movement rate was based on the average of consecutive hourly locations during daylight hours (sunrise to sunset). Only nilgai with 1-h and 2-h fix rates that were present within the study area on the day of the helicopter activity were included in this analysis. We also determined how many nilgai left the study area during the days of the helicopter activities, including nilgai captures, and the number of days until nilgai returned to the study site. We measured the distance between these nilgai that left the study site and the nearest study site boundary; all collars regardless of fix rate were used for this particular analysis. For the nilgai capture dataset, we extended our analysis to include 3 days post-capture because of potential lagged behavioral responses (Morellet et al., 2009).

2.6. Fence crossing index

Because delineation of CFT management zones depends on understanding potential barriers to nilgai movements, there is value in determining associations between nilgai breaches with fence types. We used a modified version of a highway permeability index developed by Dodd et al. (2007). The fence crossing index represents the number of crossings per fence approach for each of the three fence types (fence parallel to paved highways, property boundary fences, and intra-property fences). An approach was defined as a location within 150 m of the fence; a 150 m threshold was used because the mean distance between 2 consecutive points for all nilgai was 146 m. If a nilgai location was on the other side of the fence following a location within the 150 m buffer area, we considered the nilgai to have crossed the fence following an approach. The configuration of fence lines (i.e., corners of multiple fence types) created difficulty in determining which fence type was crossed when there were no locations within the 150 m buffer; these fence crossings were excluded from analyses. We considered successive locations within the 150 m buffer to be a single approach (Dodd et al., 2007) because the animal may bed down or forage near fences for extended periods. Only nilgai with 1-h or 2-h fix rates active during April 2015–June 2016 were considered for this analysis. Fence types and fence locations on the study site and adjacent properties were acquired by East Foundation personnel and digitized into ArcMap (ESRI, Redlands, CA).

We conducted all statistical analyses in R programming (R Core Team, 2015); because of small sample sizes and high variability in movement patterns among individuals, we used nonparametric approaches to test for differences. Analyzing data at the sex level reduced statistical power but is justified because trends can be used to establish hypotheses on this under-studied species. We used 2-group Mann-Whitney U test to compare home range size between the sexes and Kruskal-Wallis pair-wise contrast tests to compare monthly movement metrics between sexes and responses to helicopter activities; statistical significance was set at $P \leq 0.05$. R packages adehabitatHR (Calenge, 2006), PMCMR (Pohlert, 2016), lme4 (Bates et al., 2015), and MuMIn (Nakagawa and Schielzeth, 2013) were used for home range sizes, Kruskal-Wallis tests, mixed effects models, and R^2 calculations, respectively. We conducted additional mapping operations (buffering and digitizing) in ArcMap.

3. Results

3.1. Home ranges

We acquired year-round locations from 23 nilgai and the median 95% MCP year-round home ranges (ha) did not differ (Mann-Whitney U test $P = 0.88$) between females (1606, IQR = 11,515) and males (4665, IQR = 4964). Home range sizes did not differ between sexes during breeding season (Mann-Whitney U test $P = 0.16$), gestation/summer season (Mann-Whitney U test $P = 0.06$), and lactation/autumn (Mann-Whitney U test $P = 0.82$, Fig. 2).

3.2. Movement distances

Total monthly movement and maximum distances were not statistically different between males and females for any month (Kruskal-Wallis test $P = 0.60$–1.00, Figs. S1 and S2). Risk of spreading CFT, in terms of nilgai space-use, appeared to be highest during late gestation (Jun-Aug) for females, pre-breeding season (Nov-Dec) for males, and breeding season (March) for both sexes (Fig. 3). Maximum monthly distance between 2 points for each nilgai was positively correlated with total monthly distance moved ($r^2 = 0.59$). After removing an extremely wet month that acted as an outlier, the effect of both rainfall and temperature on total monthly distance was the favored model. However, the fixed effects alone essentially had no contribution (marginal $R^2 < 0.01$) whereas the fixed effects in addition to random effects (individual ID) explained more of the variance in the model (conditional $R^2 = 0.39$). The model with temperature as the only covariate was the favored model for maximum monthly distances but fixed effects explained very little variance ($R^2 < 0.01$) whereas fixed effects in addition to random effects explained most of the variance (conditional $R^2 = 0.43$).

3.3. Helicopter activities

Nilgai captures elicited the strongest response in terms of number of individuals that left the study site (40%), mean distance from the study site (7.7 km), and mean days to return to the study site (70 days, Table 1). Two nilgai, including a collar break-off, did not return to the study site and we excluded these 2 nilgai from the days-to-return analysis. Of the 4 types of helicopter activities other than nilgai captures, nilgai on-site during nilgai harvests, large mammal surveys, and deer captures did not change movement rates as a response to helicopter activities (Kruskal-Wallis test $P = 0.31$–1.00, Fig. 4). Other than capture, nilgai had the greatest response to cattle gatherings in terms of change in movement rates (Fig. 4). The increase in movement rate from the day prior to the days during cattle gatherings were not statistically significant although the decrease in movement rates after both gatherings were statistically significant (Kruskal-Wallis test $P = 0.02$ between 2 and 3 Mar 2016 and $P < 0.01$ between 8 and 10 March, 2016). Further, cattle gatherings resulted in more collared nilgai leaving the study site relative to any other type of helicopter activity (other than nilgai capture; Table 1). However, straight line distances from the boundary of the study area to the furthest location of nilgai that left the study area during the cattle gatherings were relatively short (range = 0.41–3.08 km, Table 1). Most nilgai that left the study site had locations overlapping the boundaries of the study site during days prior to helicopter activities.

3.4. Fence crossing index

We detected 1680 fence approaches; most were towards boundary fences ($n = 1051$) and interior fences ($n = 606$). Few approaches occurred at fences running parallel to roads ($n = 23$). Most fence crossings occurred at interior fences (0.44 crosses per approach) in comparison to boundary fences (0.15) and fences running parallel with paved roads (0).

4. Discussion

Analysis of fine-scale nilgai movements indicate that females may pose greater risk of spreading CFT though the landscape in South Texas even though year-long home range sizes were statistically similar between sexes (Moczygemba et al., 2012, this study). Relative to males, females had elevated space-use during summer (Jun–Aug, Figs. 3, Fig. S1 and Fig. S2). Although males had elevated movement rates during December, the CFT impact is likely minor because the heightened space-use of female nilgai during July-August occurs after the spring rainfall in this region (typically May-Jun, Ruthven et al., 2003). In semi-arid environments, tick populations generally increase during wet seasons (Pérez de León et al., 2012); thus, female nilgai that expand their ranges after the spring rainfall may be more likely to be carrying ticks into new areas. Further, the width of the PQZ along the Rio Grande ranges from 0.1 to 16.1 km (Texas Animal and Health Commission, 2014). During Jun-Aug, when tick populations are likely high, the largest maximum monthly distance was 24.4-37.0 km and 9.0-15.3 km for females and males, respectively. The differential in terms of space use suggest that females have the ability to spread ticks across an area wider than the PQZ in a short period of time (Fig. 5).

We found that seasonal movement patterns were more likely to be a function of physiological changes instead of environmental fluctuations. Prior to peak parturition during September-October, females separate from their social group (Fall, 1972; Sheffield et al., 1983); thus, increased movement of females may be a response to the break-up of social groups. The reduction in movement metrics during late autumn to winter may indicate females re-establishing social groups as the breeding season approaches (Sheffield et al., 1983). Elevated movement rates in March by both sexes were likely attributed to breeding activities based on the 243–247 day gestation period relative to the peak in

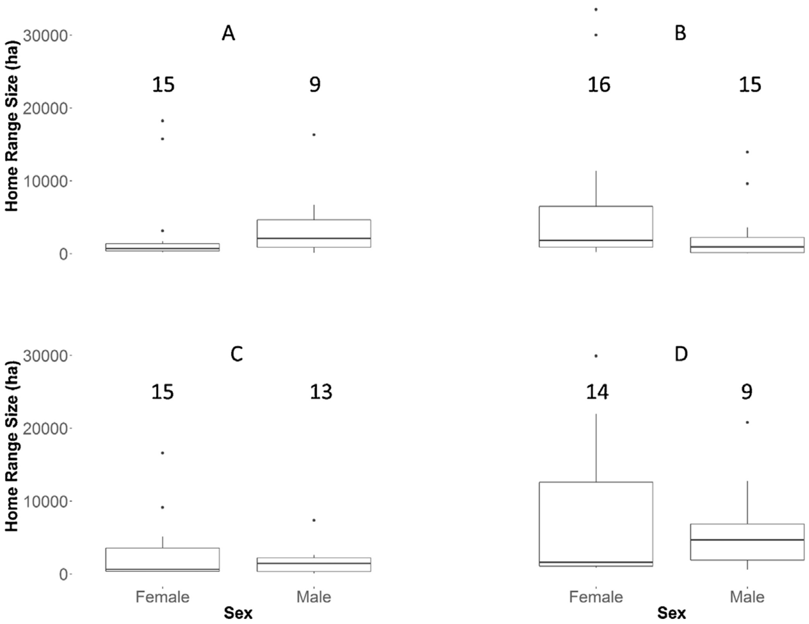

Fig. 2. Box plots of home range sizes of female and male nilgai during breeding (A, Dec–Mar), summer/gestation (B, Apr-Jul), birth/lactation (C, Aug–Nov), and year-round (D) in South Texas, 2015–2016. Numbers indicate number of nilgai analyzed.

parturition (Sheffield et al., 1983). Because large distance movement of nilgai is of interest for CFT management and were highly variable among individual nilgai, it is clear that more research is needed to make more inferences on sex-specific spatiotemporal space-use patterns. For instance, we did not find support for our hypothesis that home range size would be larger in male nilgai. Nilgai home range size may be a product of social group behavior or habitat quality (Lindstedt et al., 1986). Female nilgai in Sariska Tiger Reserve, Rajasthan, India had a seasonal home range of 3.6 km^2 with an annual home range of 7.3 km^2 (Sankar, 1994) which is ~90% smaller than home ranges in South Texas (Moczygemba et al., 2012, this study). Variation in home ranges is probably a function of habitat as nilgai avoid dense forest typical of India and prefer savanna hills or undulating plains of grass and patches of shrubs which are abundant in South Texas (Sheffield et al., 1983).

Nilgai did not appear to respond adversely to helicopter activities other than nilgai captures. While there was an increase in movement rate during the cattle gatherings, the rate was relatively low (188–411 m/h) considering the large size of nilgai home ranges. Also,

Table 1
Number of collared nilgai present on study site and number that left the study site during 5 helicopter activities in South Texas during 2015–2016. Mean distance (km) is the straight-line distance between the nilgai location after moving off the study site and the nearest study site boundary.

Helicopter Activity	*N* on-site	*N* off-site	Mean distance (SD)	Mean days to return (SD)
Nilgai capture[a]	35	14	7.7 (8.6)	84 (100)[b]
Deer capture	15	0	NA	NA
Mammal survey	13	2	2.0 (1.1)	8 (1.4)
Nilgai harvest	15	2	2.1 (1.9)	NA[c]
Cattle gathering	12	4	1.4 (1.2)	21 (12.8)

[a] Analyses were for 3 days post-capture, including collar re-deployments.

[b] Two nilgai did not return to study site including a collar break-off and were excluded from days-to-return analysis.

[c] Both nilgai did not return to study site and were excluded from days-to-return analysis.

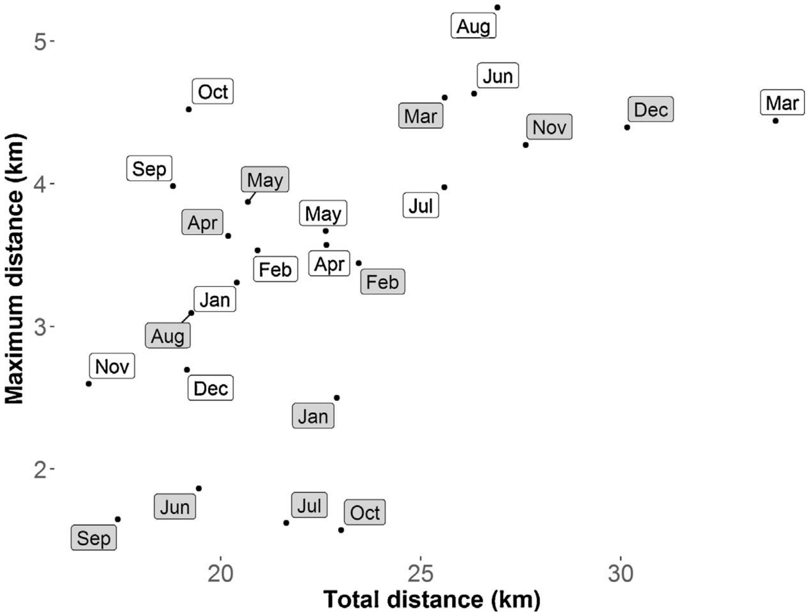

Fig. 3. Plot of median total distance moved per month (km) and median maximum distance (km) between 2 points per month for males (grey) and females (white) during 2015–2016 in South Texas. Month-sex combinations at the top right of graph indicate high mobility whereas month-sex at the bottom left indicate relatively sedentary periods.

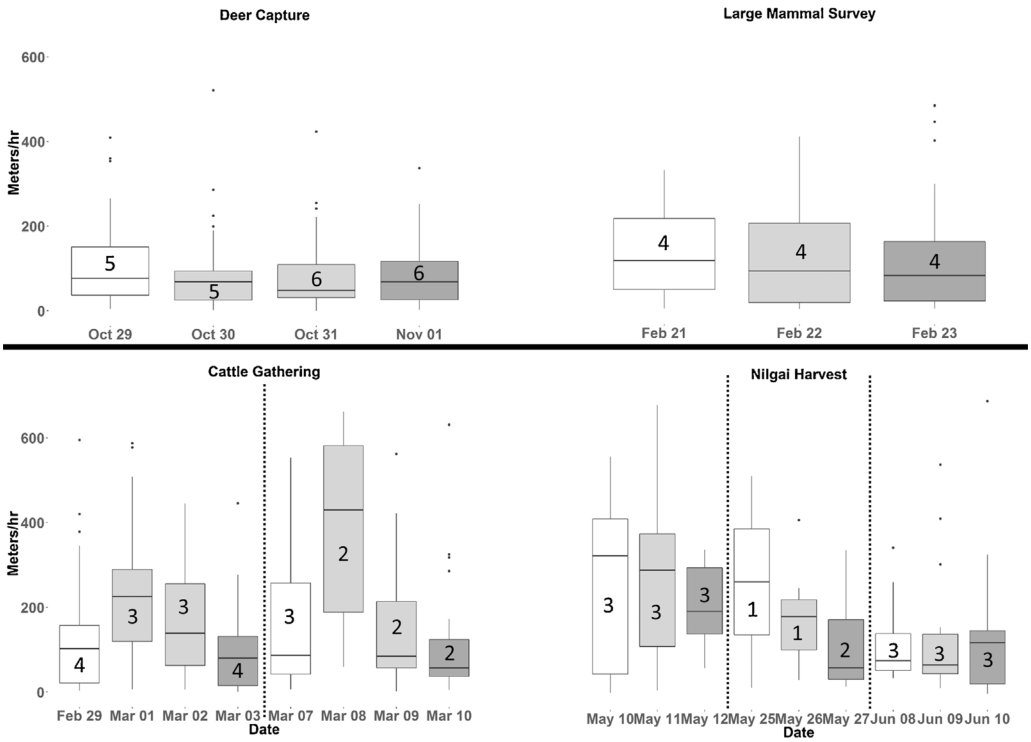

Fig. 4. Box plots of movement rate of nilgai the day prior to, during, and after 4 types of helicopter activities in South Texas, 2015–2016. Colors indicate pre (white), during (light grey), and after (dark grey) helicopter activities; vertical lines separate multiple occurrences of helicopter activities. Numbers indicate number of nilgai analyzed. Movement rate during nilgai harvests were converted from m per 2 h to m/hr for illustrative purposes.

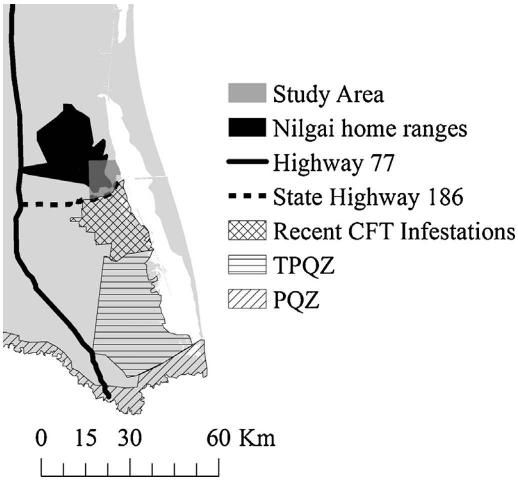

Fig. 5. Map of study area with nilgai home ranges (95% MCP). Collared nilgai had large space use relative to CFT management zones. TPQZ is temporary preventative quarantine zone and PQZ is permanent quarantine zone.

most nilgai that left the study site as a result of helicopter activities were found near the property boundary prior to the helicopter activity; thus, these nilgai did not need to travel long distances to leave the study site. Nilgai likely relocated to a "safe" location relative to the position of the helicopter. Because none of the collared nilgai appeared to relocate to new areas as a response to helicopter activities other than nilgai capture, CFT stakeholders should recognize the negligible impact of a common ranch management tool on nilgai movements. Additionally, the lack of increased nilgai movements in response to nilgai population control supports the feasibility of using aerial gunning as a management tool to control exotic ungulate populations (Campbell et al., 2010; Messenger, 2014).

Our fence crossing analyses revealed similar results to Sheffield et al. (1983) and Moczygemba et al. (2012). As hypothesized, no collared nilgai crossed fences running parallel with paved highways, whether 4-lane or 2-lane. It appears that the presence of paved roads or high-speed vehicles in conjunction with fences act as a deterrent to nilgai. It is unknown if paved highways acts as a visual or audial barrier to nilgai but future research could assess feasibility of developing road barriers (D'Angelo et al., 2006; Valitzski et al., 2009) because nilgai apparently infrequently attempt to cross these paved highways based on the low number of road-kills on state highway 186 (J. Goolsby, pers. comm.). The apparent reluctance of nilgai to cross paved highways suggest highways running parallel with 1.5-m woven-wire cattle fences deter nilgai movement to the extent that these fences could function as boundaries of CFT management units (Fig. 5).

5. Conclusions

Cumulatively, our study improves understanding of space-use patterns of an under-studied, large-ranging, exotic ungulate. Our findings will be used to improve CFT management strategies in the transboundary region encompassing south Texas and northeast Mexico. Our results also have applications for other entities managing diseases in the wildlife-livestock interface. For instance, veterinary cordon fencing is used to control movement of wildlife and livestock in Africa where foot-and-mouth disease is a concern (Hargreaves et al., 2004). Disease outbreaks have occurred when cordon fences were breached by wildlife (Jori et al., 2011). Our finding that nilgai perceived fences running parallel to highways as a barrier indicates that effective cordon fencing may not only be material-specific but also location-specific. We were able to determine that nilgai were unlikely to leave the study area as a response to human disturbance or environmental changes. By explicitly testing hypotheses, managers can directly evaluate whether certain activities (prescribed burns, tourism, etc.) have unintended consequences in terms of elevating space-use patterns in species of concern. Another management strategy used to minimize risk of disease outbreaks is localized harvest. For example, culling of badgers (*Meles meles*) and foxes (*Vulpes vulpes*) reduced cases of tuberculosis and rabies, respectively (Smith and Harris, 1991; Griffin et al., 2005). Population control may be more effective when applied prior to individuals expanding space-use (Skuldt et al., 2008). Localized harvest of nilgai prior to social female group break-up during summer may reduce spread of ticks into adjacent properties. There is not a panacea for managing disease in wildlife-livestock interfaces; collecting and quantifying species-specific behavioral data is critical for establishing effective management strategies.

Conflicts of interest

The authors state no conflict of interest for preparing this article.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.prevetmed.2017.08.002.

References

Annala, M., 2015. Using Mark-recapture Distance Sampling in Aerial Surveys of Large Mammals in South Texas. Master's Thesis. Department of Range and Wildlife Science, Texas A & M University, Kingsville, Texas.

Bailey, R.G., Avers, P.E., King, T., McNab, W.H., 1994. Ecoregions and Subregions of the United States (map; Scale 1:7,5000,000). United States Department of Agriculture Forest Service, Washington, DC.

Barrett, M.W., Nolan, J.W., Roy, L.D., 1982. Evaluation of a hand-held net-gun to capture large mammals. Wildl. Soc. Bull. 10, 108–114.

Bates, D., Maechler, M., Bolker, B., Walker, S., 2015. Fitting linear mixed-effects models using lme4. J. Stat. Softw. 67, 1–48.

Bock, R., Jackson, L., de Vos, A., Jorgensen, W., 2004. Babesiosis of cattle. Parasitology 129, 247–269.

Cárdenas-Canales, E.M., Ortega-Santos, J.A., Campbell, T.A., García-Vázquez, Z., Cantú-Covarrubias, A., Figueroa-Millán, J.V., DeYoung, R.W., Hewitt, D.G., Bryant, F.C., 2011. Nilgai antelope in northern Mexico as a possible carrier for cattle fever ticks and *Babesia bovis* and *Babesia bigemina*. J. Wildl. Dis. 47, 777–779.

Calenge, C., 2006. The package adehabitat for the R software: a tool for the analysis of space and habitat use by animals. Ecol. Model. 197, 516–519.

Campbell, T.A., Long, D.B., Leland, B.R., 2010. Feral swine behavior relative to aerial gunning in southern Texas. J. Wildl. Manage. 74, 337–341.

Crop Weather Program, 2016. Texas A & M Agrilife Research and Extension Center, http://cwp.tamu.edu/.

D'Angelo, G.J., D'Angelo, J.G., Gallagher, G.R., Osborn, D.A., Miller, K.V., Warren, R.J., 2006. Evaluation of wildlife warning reflectors for altering white'tailed deer behavior along roadways. Wildl. Soc. Bull. 34, 1175–1183.

de Wall, D.T., Combrink, M.P., 2006. Live vaccines against bovine babesiosis. Vet. Parasitol. 138, 88–96.

DeYoung, C.A., 1985. Accuracy of helicopter surveys of deer in south Texas. Wildl. Soc. Bull. 13, 146–149.

Dodd, N.L., Gagnon, J.W., Boe, S., Schweinsburg, R.E., 2007. Assessment of elk highway permeability by using global positioning system telemetry. J. Wildl. Manage. 71, 1107–1117.

Esteve-Gassent, M.D., Pérez de León, A.A., Romero-Salas, D., Feria-Arroyo, T.P., Patino, R., Castro-Arellano, I., Gordillo-Pérez, G., Auclair, A., Goolsby, J., Rodriguez-Vivas, R.I., Estrada-Franco, J.G., 2014. Pathogenic landscape of transboundary zoonotic diseases in the Mexcio-US border along the Rio Grande. Front. Public Health 2, 1–23.

Fèvre, E.M., Bronsvoort, B.M.D.C., Hamilton, K.A., Cleaveland, S., 2006. Animal movements and the spread of infectious diseases. Trends Microbiol. 14, 125–131.

Fall, B.A., 1972. On Social Organization and Behavior of Nilgai Antelope, *Boselaphus Tragocamelus* (Pallas) in South Texas, Master's Thesis. Department of Wildlife and Fisheries Science, Texas A & M University, College Station, Texas.

Giles, J.R., Peterson, A.T., Busch, J.D., Olafson, P.U., Scoles, G.A., Davey, R.B., Pound, J.M., Kammlah, D.M., Lohmeyer, K.H., Wagner, D.M., 2014. Invasive potential of cattle fever ticks in the southern United States. Parasit. Vectors 7, 189.

Goldstein, M.I., Poe, A.J., Cooper, E., Youkey, D., Brown, B.A., McDonald, T.L., 2005. Mountain goat response to helicopter overflights in Alaska. Wildl. Soc. Bull. 33, 688–699.

Griffin, J.M., Williams, D.H., Kelly, G.E., Clegg, T.A., O'Boyle, I., Collins, J.D., More, S.J., 2005. Prev. Vet. Med. 67, 237–266.

Hargreaves, S.K., Foggin, C.M., Anderson, E.C., Bastos, A.D.S., Thomson, G.R., Ferris, N.P., Knowles, N.J., 2004. An investigation into the source and spread of foot-and-mouth disease virus from a wildlife conservancy in Zimbabwe. Rev. Sci. Tech. Off. Int. Epiz 23, 783–790.

Hellickson, M.W., Campbell, T.A., Miller, K.V., Marchinton, R.L., DeYoung, C.A., 2008. Seasonal ranges and site fidelity of adult male white-tailed deer *(Odocoileus virginianus)* in southern Texas. Southwest Nat. 53, 1–8.

Jori, F., Brahmbhatt, D., Fosgate, G.T., Thompson, P.N., Budke, C., Ward, M.P., Ferguson, K., Gummow, B., 2011. A questionnaire-based evaluation of the veterinary cordon fence separating wildlife and livestock along the boundary of the Kruger National Park, South Africa. Prev. Vet. Med. 100, 210–220.

Kistner, T.P., Hayes, F.A., 1970. White-tailed deer as hosts of cattle fever-ticks. J. Wildl. Dis. 6, 437–440.

Leslie, D.M., Sharma, K., 2009. Tetracerus quadricornis (Artiodactyla: bovidae). Mammalian Species Arch. 843, 1–11.

Lindstedt, S.L., Miller, B.J., Buskirk, S.W., 1986. Home range, time, and body size in mammals. Ecology 67, 413–418.

Madder, M., Thys, E., Achi, L., Toure, A., DeDeken, R., 2011. Rhipicephalus (Boophilus) microplus: a most successful invasive tick species in West-Africa. Exp. Appl. Acarol. 53, 139–145.

McNab, B.K., 1963. Bioenergetics and the determination of home range size. Am. Nat. 97, 133–140.

Messenger, M., 2014. Population Reduction of Nilgai in the Boca Chica Beach, Bahia Grande, and Brownsville Navigation District Areas, Cameron County, Texas. http://content.govdelivery.com/attachments/USDAAPHIS/2014/07/11/file_attachments/306647/Draft%2BNilgai%2BEA%2BComplete.pdf.

Moczygemba, J.D., Hewitt, D.G., Campbell, T.A., Ortega-S, J.A., Field, J., Hellickson, M.W., 2012. Home ranges of the nilgai antelope (Boselaphus tragocamelus) in Texas. Southwest Nat. 57, 26–30.

Mohr, C.O., 1947. Table of equivalent populations of North American small mammals. Am. Midl. Nat. 37, 223–249.

Morellet, N., Verheyden, H., Angibault, J.M., Cargnelutti, B., Lourtet, B., Hewison, M.A., 2009. The effect of capture on ranging behaviour and activity of the European roe deer Capreolus capreolus. Wildl. Biol. 15, 278–287.

Nakagawa, S., Schielzeth, H., 2013. A general and simple method for obtaining R2 from generalized linear mixed-effects models. Methods Ecol. Evol. 4, 133–142.

Pérez de León, A.A., Pete, T.D., Auclair, A.N., Messenger, M.T., Guerrero, F., Schuster, G., Miller, R.J., 2012. Integrated strategy for sustainable cattle fever tick eradication in U.S.A. is required to mitigate the impact of global change. Front. Physiol. 3, 1–17.

Pérez de León, A.A., Vannier, E., Almazán, C., Krause, P.J., 2014. Tick-borne protozoa. In: 2nd edition. In: Sonenhine, D.E., Roe, R.M. (Eds.), Biology of Ticks Vol. 2. Oxford University Press, New York, pp. 147–179.

Pohlert, T., 2016. The Pairwise Multiple Comparison of Mean Ranks Package (PMCMR). R Package. http://CRAN.R-project.org/package=PMCMR.

Presnall, C.C., 1958. The present status of exotic mammals in the United States. J. Wildl. Manage. 22, 45–50.

R Core Team, 2015. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria. http://www.R-project.org/.

Racelis, A.E., Davey, R.B., Goolsby, J.A., Perez de Leon, A.A., Varner, K., Duhaime, R., 2012. Facilitative ecological interactions between invasive species: *Arundo donax* (Poaceae) stands as favorable habitat for cattle ticks (Acari: ixodidae) along the US-Mexico border. J. Med. Entomol. 49, 410–417.

Rosatte, R., Ryckman, M., Ing, K., Proceviat, S., Allan, M., Bruce, L., Donovan, D., Davies, J.C., 2010. Density, movements, and survival of raccoons in Ontario, Canada: implications for disease spread and management. J. Mammal. 91, 122–135.

Ruthven III, D.C., Braden, A.W., Knutson, H.J., Gallagher, J.F., Synatzske, D.R., 2003. Woody vegetation response to various burning regimes in South Texas. J. Range Manage. 56, 159–166.

Sankar, K., 1994. The Ecology of Three Large Sympatric Herbivores (chital, Sambar, Nilgai) with Special Reference to Reserve Management in Sariska Tiger Reserve, Rajasthan. Ph.D. Thesis. Department of Zoology, University of Rajasthan, Jaipur, India.

Sheffield, W.J., Fall, B.A., Brown, B.A., 1983. The Nilgai Antelope in Texas. The Texas Agricultural Experiment Station, Texas A & M University System, College Station.

Skuldt, L.H., Mathews, N.E., Oyer, A.M., 2008. White-tailed deer movements in a chronic wasting disease area in south-central Wisconsin. J. Wild. Manage. 72, 1156–1160.

Smith, G.C., Harris, S., 1991. Rabies in urban foxes (Vulpes vulpes) in Britain: the use of a spatial stochastic simulation model to examine the pattern of spread and evaluate the efficacy of different control regimes. Philos. Trans. R Soc. Lond. B Biol. Sci. 334, 459–479.

Texas Animal and Health Commission, 2014. New Temporary Cattle Fever Tick Preventative Quarantine Area in Cameron County. http://www.tahc.state.tx.us/news/2014/2014-10-03_FeverTickBlanket.pdf.

Uilenberg, G., 2006. Babesia – a historical overview. Vet. Parasitol. 130, 3–10.

Valitzski, S.A., D'Angelo, G.J., Gallagher, G.R., Osborn, D.A., Miller, K.V., Warren, R.J., 2009. Deer responses to sounds from a vehicle-mounted sound-production system. J. Wildl. Manage. 73, 1072–1076.

Vercauteren, K.C., Lavelle, M.J., Seward, N.W., Fischer, J.W., Phillips, G.E., 2007. Fence-line contact between wild and farmed white-tailed deer in Michigan: potential for disease transmission. J. Wildl. Manage. 71, 1603–1606.

Webb, S.L., Hewitt, D.G., Hellickson, M.W., 2007. Scale of management for mature male white-tailed deer as influenced by home range and movements. J. Wildl. Manage. 71, 1507–1512.

Wyckoff, A.C., Henke, S.E., Campbell, T.A., Hewitt, D.G., VerCauteren, K.C., 2009. Feral swine contact with domestic swine: a serologic survey and assessment of potential for disease transmission. J. Wildl. Dis. 45, 422–429.

Yockney, I.J., Nugent, G., Latham, M.C., Perry, M., Cross, M.L., Byrom, A.E., 2013. Comparison of ranging behaviour in a multi-species complex of free-ranging hosts of bovine tuberculosis in relation to their use as disease sentinels. Epidemiol. Infect. 141, 1407–1416.