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Research article

Wildlife roadkill in the Tsavo Ecosystem, Kenya: identifying hotspots, potential drivers, and affected species

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A R T I C L E I N F O

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A B S T R A C T

Roadkill is one of the highest causes of wildlife mortality and is of global conservation concern. Most roadkill studies have focused on wildlife in developed countries such as the United States of America and temperate biomes, but there are limited data for the impacts of roads on wildlife in the African tropics, where road infrastructure development is projected to grow rapidly in natural environments and conservation areas. The Tsavo Conservation Area is an important biodiversity hotspot in eastern Kenya and is bisected by a major highway and railways that connect the port of Mombasa to the interior. Along this infrastructure corridor, roadkill was recorded for 164 days over an 11-year period (2007–2018). In total, 1,436 roadkill were recorded from 13,008 km driven of a 164.42 km Nairobi-Mombasa road representing 0.11 collisions per kilometer. The majority of roadkill were small to medium sized mammals (<15kg) (53%; n = 756), whereas birds comprised 32% (n = 460), reptiles 10% (n = 143), with the remaining 5% (n = 77) being large mammals (>15kg). Of the 460 birds recorded, 264 were identifiable represented by 62 species. All large mammals comprising 10 species were identified, including the African elephant, *Loxodonta africana* and the endangered African wild dog, *Lycaon pictus*. Thirteen species of small mammal were also identified dominated by Kirk's dik-dik (*Madoqua kirkii*). Reptiles were represented by 11 species which were identified to the species level. Roadkill hotspots were identified using a kernel density method. The spatial distribution of roadkill was associated with adjacent shrub vegetation and proximity to permanent and seasonal rivers, and differences in seasonality and habitats were observed. Roadkill was lowest on road sections that traversed settled areas as opposed to roads adjacent to the protected areas. The results demonstrate that roadkill for two of the taxonomic groups - mammals and birds - appear high with numerous species detected in the Tsavo Conservation Area. These results can be used to focus efforts to reduce wildlife mortality by guiding future mitigation efforts.

1. Introduction

Currently in East Africa there are several major infrastructure development corridors that are planned or in progress. These projects will crisscross the continent passing through remote regions and key ecosystems that sustain high levels of biodiversity. There are limited studies on the ecological impacts of roads in the African tropics (But see: Caro et al., 2014; Kioko et al., 2015; Nyirenda et al., 2017; Collinson et al., 2019), where road infrastructure development is projected to grow rapidly into pristine environments and protected areas (Laurance et al., 2015; Alamgir et al., 2017). Most road ecology studies have focused on understanding impacts of roads on wildlife in developed countries and temperate biomes (Dean et al., 2019).

Where it has been studied, road infrastructure is demonstrated to have negative impacts on wildlife conservation by increasing wildlife mortality, isolating populations, and reducing habitats and connectivity for wildlife populations (Vos and Chardon 1998; Seiler and Helldin 2006; Fahrig and Rytwinski 2009; Jackson and Fahrig 2011; Loss et al., 2014; Dean et al., 2019). These impacts can reduce genetic diversity and increase genetic isolation, leading to reduced evolutionary potential of the

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species affected (Lesbarrères et al., 2006; Clark et al., 2010; Holderegger and Di Giulio 2010; Jackson and Fahrig 2011). Roads also alter animal activity and distribution patterns, increase habitat disturbance, and enhance invasion by exotic species (Fahrig and Rytwinski 2009).

Roadkill is a threat to wildlife globally. The global and regional impacts of roadkill are significant, e.g. about 89–340 million birds die annually from vehicle collisions on U.S. roads alone (Loss et al., 2014). Animal-vehicle collisions also have a direct impact on humans via

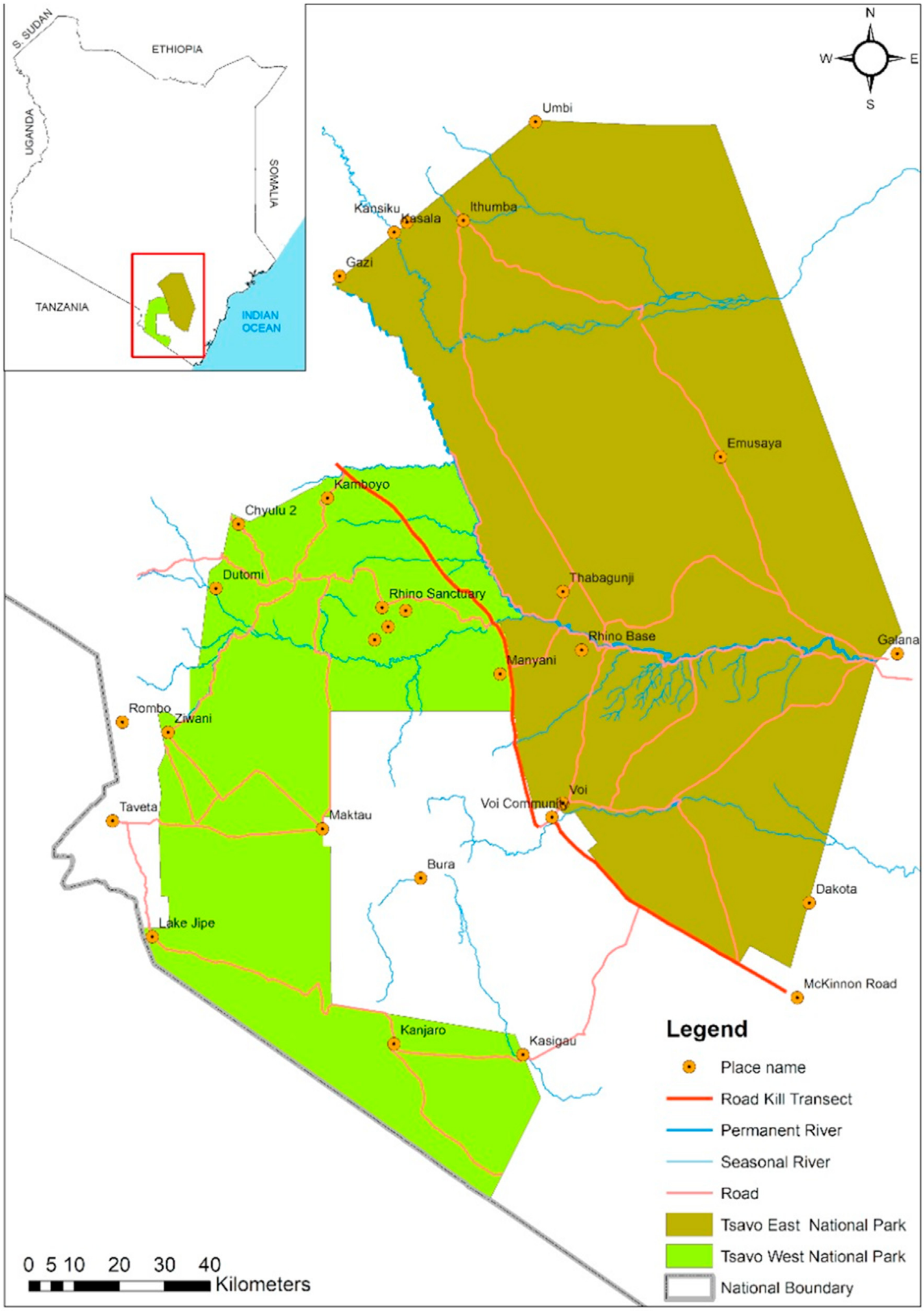

Figure 1. Tsavo Conservation Area (TCA) in southeastern Kenya (inset). The Red line indicates the Mombasa-Nairobi highway infrastructure corridor (MNHIC) adjacent to Tsavo National Parks along which roadkill data were recorded (2007–2018).

accidents and insurance claims for wildlife–vehicle collisions (Seiler 2005) and can also indirectly decrease tourism due to frequent roadkill encounters (Magnus et al., 2004). In some areas, roadkill has surpassed hunting as the leading cause of anthropogenic wildlife mortality (Taylor-Brown et al., 2019). Roadkill is, however, heterogeneous in spatial and temporal distribution. Roadkill is more likely to occur along road sections that are surrounded by thick vegetative cover versus open areas (Caro et al., 2000; Van Niekerk and Eloff 2005; Ansara 2008; Van Der Hoeven et al., 2010). Roadkill frequency increases with higher traffic speeds (Drews 1995; Smith-Patten and Patten 2008; Collinson 2013), and high traffic volume (Helldin and Seiler 2003). Despite reduced traffic volume at night (Van Langevelde and Jaarsma 2005), nocturnal and crepuscular species are more impacted by roads than diurnal species, possibly due to reduced driver visibility at night (Braunstein 1998) or behavioral freezing of most of these species when bright lights are directed at their eyes. Given observed heterogeneity in roadkill patterns, there is a need to empirically map roadkill patterns to establish baselines for monitoring and to identify roadkill hotspots and vulnerable species to enhance targeted mitigation efforts.

To ensure the effective management of all areas of biodiversity concern in Kenya, conservation areas have been created to assist in management. The Tsavo Conservation Area (TCA; Figure 1) is one of the management areas that is an important biodiversity hotspot. The ecosystem is crossed by the Mombasa-Nairobi highway infrastructure corridor (hereafter MNHIC) that traverses TCA, a major route serving an expansive area from the port of Mombasa through Kenya and into neighboring Uganda; Rwanda; Burundi; northern Tanzania; southern Ethiopia; Eastern Democratic Republic of Congo; and South Sudan (Gekara and Chhetri 2013). MNHIC includes a single highway, but the Government of Kenya intends to construct a 473-kilometer expressway next to the current road. The construction of this expressway is expected to further divide the TCA and affect wildlife connectivity between important habitats. Additional infrastructure that passes through the park includes an old meter-gauge railway constructed in 1900 that is mainly used for cargo and a new standard gauge railway (SGR) used for passengers and cargo. Both railways connect Kenya's main port city of Mombasa to the interior, running through the national capital of Nairobi. The old railway continues to Uganda and plans are underway to extend the SGR to Uganda. Along this corridor, there are also two high voltage power lines, two oil pipelines, and a water pipeline.

This study collects foundational, baseline data on roadkill to identify vulnerable species in order to evaluate the effects of temporal and landscape characteristics associated with vertebrate roadkill in the TCA. Specifically, we investigated the influence of season, adjacent vegetation cover, proximity to river drainages, and contiguous natural habitat on patterns of roadkill in the major highway and infrastructure development corridor in Kenya traversing the TCA.

2. Methods

2.1. Study area

Our study location is TCA in southeastern Kenya within the arid and semi-arid region at latitude 1°59′S-4°8′S and longitude 37°45′E-39°16′E (Figure 1). The TCA is an important biodiversity hotspot in Kenya; it consists of Tsavo West, Tsavo East, and Chyulu National Parks in Kenya, Mkomazi National Park in Tanzania, and adjacent ranches and community conservancies. It is one of the largest protected areas in Kenya and a stronghold of Kenya's elephant (*Loxodonta africana*) population. The most observed wildlife species in Tsavo National Parks are elephants, giraffe (*Giraffa camelopardalis*), African buffalo (*Syncerus caffer*), hippopotamus (*Hippopotamus amphibius*), Burchell's zebra (*Equus burchellii*), eland (*Taurotragus oryx*), waterbuck (*Kobus ellipsiprymnus*), Coke's hartebeest (*Alcelaphus buselaphus*), Grant's gazelle (*Gazella granti*), impala (*Aepyceros melampus*), lesser kudu (*Tragelaphus imberbis*), gerenuk (*Litocranius walleri*), warthog (*Phacochoerus africanus*) and fringe-eared oryx (*Oryx beisa callotis*). The TCA also hosts a significant number of endangered species like the black rhino (*Diceros bicornis*) and African wild dog (*Lycaon pictus*), which occur within their natural range, as well as small populations of species that have been translocated outside their natural geographic range in recovery efforts, e.g. Grevy's zebra (*Equus grevyi*) and hirola (*Beatragus hunteri*). This diverse herbivore community supports a guild of large carnivores that include lion (*Panthera leo)*, cheetah (*Acinonyx jubatus*), leopard (*Panthera pardus*), spotted hyena (*Crocuta crocuta*), striped hyena (*Hyaena hyaena*) and African wild dog. A checklist of the mammalian and avian fauna of the TCA is provided elsewhere (Lack et al., 1980; Lepage 2004; Tóth et al., 2014).

The rainfall regime in the TCA is influenced by the movement of the Inter-Tropical Convergence Zone - ITCZ (Van Wijngaarden 1985), producing a bimodal rainfall pattern. The ‘short’ rains occur during the months of November to December and the ‘long’ rains occur during months of March, April and May (Leuthold and Leuthold 1975), with average annual rainfall ranging between 200 and 700 mm per annum (Van Wijngaarden 1985). January, February and early March constitute the ‘hot dry’ season, while a ‘cool dry’ season prevails from June through October. Although the seasons described above are usually well defined, rainfall can vary considerably in its spatial and temporal distribution. The average normal daily temperatures range between 20 °C and 30 °C. The topography of the TCA consists of an undulating landscape dotted with hilly areas like the Yatta Plateau and Taita hills. The vegetation is dominated by Acacia–Commiphora bush and thickets with the density of trees and shrubs being low in grasslands and highest in bushlands and riparian forests.

2.2. Roadkill monitoring and attributes

The length of MNHIC monitored was 164.42 km, of which 65.49 km forms a boundary between Tsavo East and Tsavo West National Parks. The remaining section, about 96.93 km, consists of road abutting Tsavo East to the north and private ranches or wildlife sanctuaries to the south (Figure 1). Data were collected by driving along the MNHIC using 4WD vehicles at a speed of 40–50 km/h, once or twice a month throughout the year for 11 years from February-2007 up to February-2018. Overall, in a single day of roadkill monitoring, we drove either the 65.49 road section separating the parks or the 96.93 section abutting the park and private ranches with 2 observers and a driver starting around 7 am and ending around 10 am. In total, 13,008.24 km were driven, of which 6,978.96 (72 days in 50 months) involved the road section crossing between Tsavo East and Tsavo West National parks and 4,715.28 km (92 days in 71 months) on the road section between Tsavo East and the private ranches.

Roadkill locations were recorded using a GPS (Garmin GPS72H). Once recorded, roadkill was removed to avoid recounts. Roadkill were grouped into four major classes: reptiles, birds and small to medium sized mammals (species with adults weighing <15kg), large mammals (species with adults weighing >15kg). To the extent possible, each roadkill was further identified to order, family, genus and species (Branch 1998; Hockey et al., 2005; Skinner and Chimimba 2005; Carruthers and Du Preez 2011). Any roadkill that could not be classified or identified was recorded as unknown. We assume these estimates are minimum counts because of removal of carcasses by scavengers may have taken place.

Elevation for each roadkill location was derived from a digital elevation model (DEM) for the Tsavo National Parks at a spatial resolution of 10 m obtained from Kenya Wildlife Service GIS database. The DEM was exported in ArcGIS version 10.4 (ESRI 2015) and geo-referenced point data for wildlife roadkill were overlaid. The elevation values in each wildlife roadkill point data were extracted (Mitchell and Minami 1999; ESRI 2015). Straight-line distances between roadkill locations and the nearest permanent and seasonal rivers were also measured in ArcGIS. Land cover data for each roadkill point was obtained from the United Nation's Food and Agriculture Organization land cover data (Ahlqvist 2008).

In order to determine whether roadkill occurred at random with respect to elevation, location of permanent and seasonal rivers, and land cover, we extracted the same attributes at randomly selected points along road in our study area. A hundred random points were generated along the road using Arc Toolbox in the ArcGIS Software version 10.2.2 (ESRI 2015). This allowed for a comparison of broad landscape features between roadkill locations and random road points along the same transportation corridor. Such a comparison is useful to assess patterns of roadkill, i.e., hotspots or spatial clustering.

Information on the activity patterns for the top species represented in roadkill was collated from literature on diel behavior of the various species. We used primary literature as well as secondary literature sources. We cite the dominant activity pattern in our analyses of behavioral patterns that influence roadkill patterns observed for small mammals (Waser 1980; Kaunda 2000; Admasu et al., 2004; Estes 2012), large mammals (Fuller and Kat 1990; Ryan and Jordaan 2005; Kolowski et al., 2007; Estes 2012), and reptiles (Phillips 1995; McMaster and Downs 2013; Drabik-Hamshare 2016; Myers et al., 2020).

2.3. Statistical data analysis

To identify hotspots for roadkill in Tsavo National Parks, we used a kernel density method (Bíl et al., 2013; Thakali et al., 2015; Kazemi et al., 2016). Kernel density measures the dispersion pattern of locations of interest within a given area and uses this to estimate areas of high and low intensity. ArcGIS Spatial Analyst Tool (ESRI 2015) and the Home Range Tools for ArcGIS 10.X version 2.0.2 (Rodgers et al., 2007) was used to generate kernel densities with raster colors indicating areas of high and low intensities of roadkill, i.e. hotspots.

To calculate the rate of roadkill per taxon per kilometer, we divided the numbers of roadkill for each taxon by the total distance driven in kilometers during the study period. To assess the influence of seasons on temporal patterns of roadkill, we categorized our roadkill data by month of occurrences into four seasons experienced in the TCA: the short dry season, the cool dry season, the short rains, and the long rains. We then used chi-square analyses to test whether roadkill occurred during some seasons more than expected based on the duration of seasons in months.

In order to test whether roadkill was distributed at random with respect to vegetation cover, we compared the frequency distribution of random points across vegetation types with the distribution of roadkill across vegetation cover types using chi-square analyses. The influence of elevation, seasonal and permanent rivers, on roadkill, was compared to the elevation of each roadkill point and mean distance of each roadkill point to rivers with that from randomly generated points using student t-tests. All statistical analyses were conducted using the R software (Ver 3.6.0) for statistical computing (Developer Core Team 2019).

3. Results

In total, 1,436 observations of roadkill were documented after driving 13,008 km of 162.42-km paved Nairobi-Mombasa highway between February 2007 and February 2018. This represents a rate of 0.107 roadkill per km. Small to medium-sized mammals constituted the majority (53%) at a rate of 0.058 individuals per km, followed by birds (32%), then reptiles (10%), and large mammals (5%) and a rate of 0.058, 0.035, 0.011, and 0.006 individuals per kilometer respectively. Nearly all (751) small to medium-sized mammal samples were identified to species and constituted 19 species; five samples could not be identified. From 460 bird samples, 264 were identified representing 62 species. For the reptiles 13 species were identified for 116 observations, while 27 observations could not be identified. All large mammal samples were identified to the species level; 10 species were identified, including the threatened elephant, and the endangered African wild dog.

The most common small to medium-sized mammal in the roadkill was the Kirk's dik-dik (*Madoqua kirkii*) and the most common bird roadkill species was the migratory Eurasian roller (*Coracias garrulus*). Among birds recorded was a single specimen of the critically endangered Taita thrush (*Turdus helleri*; Table S1). The Kenyan sand boa (*Coracias garrulus*) was the most recorded roadkill reptile (Table 1). The spotted hyena was the most common of the large mammals represented in roadkill (Table 1).

Roadkill appeared to be more evenly distributed during the combined wet seasons and more clustered during the combined dry season along the MNHIC for all the species (Figure 2).

The occurrence of roadkill was associated with seasons more than expected based on the annual duration (months) of the combined wet and dry seasons (Figure 3).

Table 1. Five most abundant roadkill species in each vertebrate category recorded along the Mombasa-Nairobi highway infrastructure corridor (MNHIC) in Tsavo Conservation Area, Kenya between 2007-2018.

Category	Species	Scientific Name	IUCN Status	Activity pattern	Count	Roadkill per km
Large mammals (>15kg)	Spotted hyena	*Crocuta crocuta*	Least Concern	Nocturnal	46	0.0035
	Buffalo	*Syncerus caffer*	Near Threatened	Diurnal/nocturnal	9	0.0007
	Plains zebra	*Equus quagga*	Near Threatened	Diurnal	9	0.0007
	Savanah elephant	*Loxodonta africana*	Vulnerable	Diurnal/nocturnal	5	0.0004
	African wild dog	*Lycaon pictus*	Endangered	Diurnal	3	0.0002
Small to medium- sized mammals (<15kg)	Kirk's dik-dik	*Madoqua kirkii*	Least Concern	Nocturnal/diurnal	109	0.0084
	Cape hare	*Lepus capensis*	Least Concern	Nocturnal	73	0.0056
	Common genet	*Genetta genetta*	Least Concern	Nocturnal	59	0.0045
	White-tailed mongoose	*Ichneumia albicauda*	Least Concern	Nocturnal	47	0.0036
	Black-backed jackal	*Canis mesomelas*	Least Concern	Nocturnal/diurnal	25	0.0019
Birds	Eurasian roller	*Coracias garrulus*	Least Concern	Diurnal	39	0.0030
	Common bulbul	*Pycnonotus barbatus*	Least Concern	Diurnal	31	0.0024
	Laughing dove	*Spilopelia senegalensis*	Least Concern	Diurnal	18	0.0014
	Ring-necked dove	*Streptopelia capicola*	Least Concern	Diurnal	18	0.0014
	Red-billed quelea	*Quelea quelea*	Least Concern	Diurnal	11	0.0008
Reptiles	Kenyan sand boa	*Gonglyophis colubrinus*	Least Concern	Nocturnal	27	0.0021
	Puff adder	*Bitis arietans*	Least Concern	Nocturnal	17	0.0013
	Black throated savannah monitor lizard	*Varanus albigularis*	Least Concern	diurnal	17	0.0013
	Red spitting cobra	*Naja pallida*	Least Concern	Nocturnal/diurnal	7	0.0005
	Leopard tortoise	*Stigmochelys pardalis*	Least Concern	Diurnal	7	0.0005

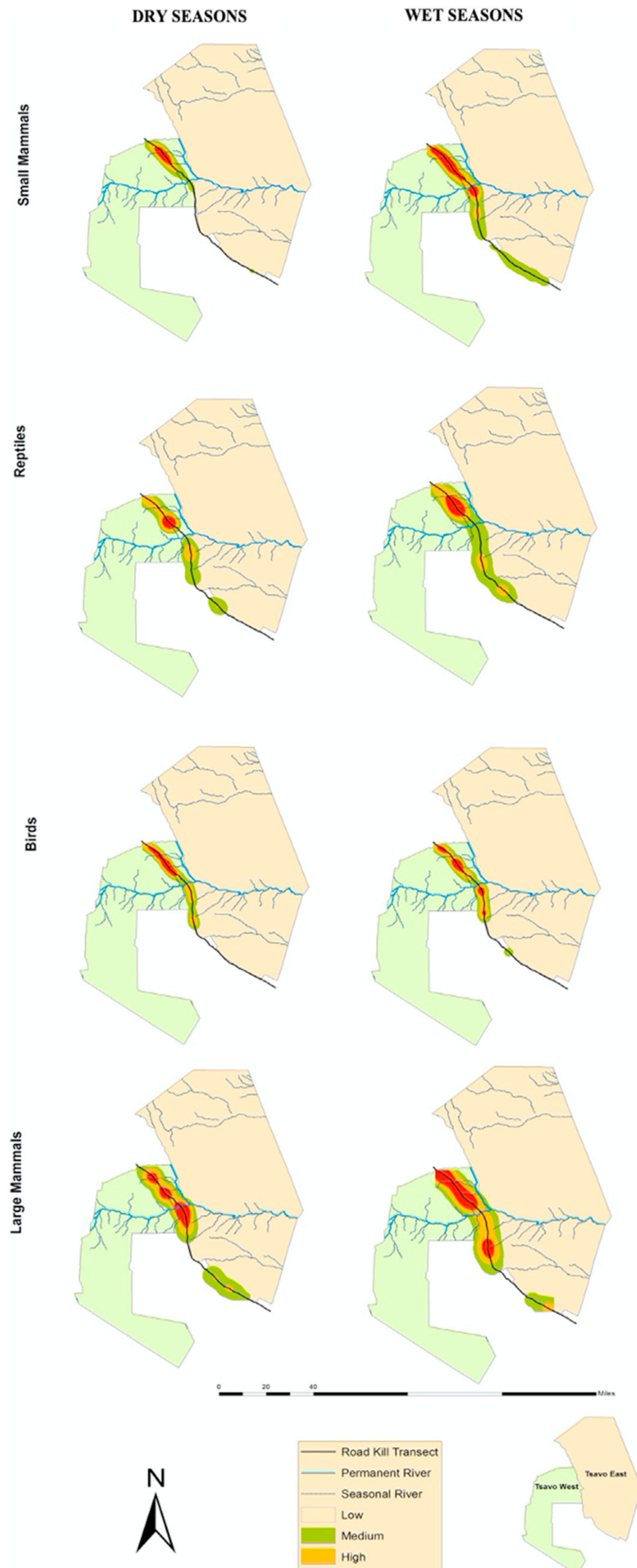

Figure 2. Roadkill hotspots (2007–2018) for small to medium-sized mammals (<15kg), reptiles, birds and large mammals (>15kg) along the Mombasa-Nairobi, Kenya highway infrastructure corridor (MNHIC) for dry and wet seasons.

For small mammals, more roadkill than expected was observed during hot dry months and during the short rains but fewer than expected during the long rains (χ^2 (3, N = 756) = 40.921, p < 0.0001). Among large mammals, more roadkill than expected occurred during the short rains but less than expected during the long rains (χ^2 (3, N = 77) = 11.494, p = 0.009). Roadkill for birds occurred more than expected in the cool dry months and less than expected in the hot dry months ($\chi^2_{(3, N=460)}$ = 168.85, p < 0.0001). In the case of reptiles, more road deaths occurred in the cool dry months and short rains whereas fewer deaths occurred in the hot dry months and long rains ($\chi^2_{(3, N=143)}$ = 7.8, p = 0.05033) compared to a random expectation. For all comparisons, roadkill occurred at a higher (~45–75 m) elevation compared to randomly distributed points along the same section of the highway (p < 0.0001 for all comparisons; Figure 4).

In terms of land cover, more roadkill occurrences for all taxa occurred in the areas covered by shrubs more than expected based on availability but occurred less or as expected for herbaceous cover, and for tree and shrub cover (p < 0.0001 for all comparisons; Figure 5).

Roadkill was closest to permanent rivers for small to medium-sized mammals by 19% (mean distance = 14,289 m, t_{110} = 2.5662, p = 0.0116), large mammals by 21 % (mean distance = 14,079 m, t_{171} = -2.2416, p = 0.0263), birds by 30% (mean distance = 12,487, t_{107} = -3.9424, p = 0.0001) and reptiles by 28% (mean distance = 12,737 m, t_{126} = 3.5846, p = 0.0005) compared to an expectation based on a random occurrence (17,723 m) (Figure 6). Similarly, roadkill occurred closer to seasonal rivers by 39% for large mammals (t_{175} = -3.8132, p = 0.0002, mean distance = 5,340 m), 42% for small to medium- sized mammals (t_{113} = 5.2461, p < 0.0001, mean distance = 5,107 m), 60% for birds (t_{105} = -7.6267, p < 0.0001, mean distance = 3,530 m) and 47% for reptiles (t_{143} = 5.5448, p < 0.0001, mean distance = 4,630 m) more than expected from a random distribution of roadkill along the entire road length (8,800 m).

Most of the roadkill appears constrained in an area with more seasonal and permanent rivers, which is the area of the MNHIC that is contiguous between the parks. The lower area between the park and the ranches exhibited fewer roadkill hotspots, especially during the dry season. While the 67-km section shared by *both* the Tsavo East and Tsavo West National Park boundaries is only 29% of the road section monitored in this study, 77% of all roadkill incidents occurred in this section. The section of the road separating Tsavo West and Tsavo East was mostly comprised of 98% shrubs (40–65% cover) and the rest (2%) was by herbaceous cover. This contrasted with the rest of the road abutting Tsavo East on one side and the private ranches and community conservancies on the other side, where herbaceous cover constituted 25% of the land cover, shrubs (40–65% cover) comprised 39% of land cover and 36% covered by tree and shrub cover. The mean ± SD elevation in meters Above Sea Level (ASL) was 505.38 ± 78.30 and the mean distance in meters from permanent rivers was 24,648 ± 13,943 and mean ± SD distance to seasonal rivers was 13,274 ± 6,560. In contrast the length of road separating Tsavo East and Tsavo West had a higher elevation (559.98 ± 61.99, t_{97} = 3.8859, p = 0.0002) and shorter

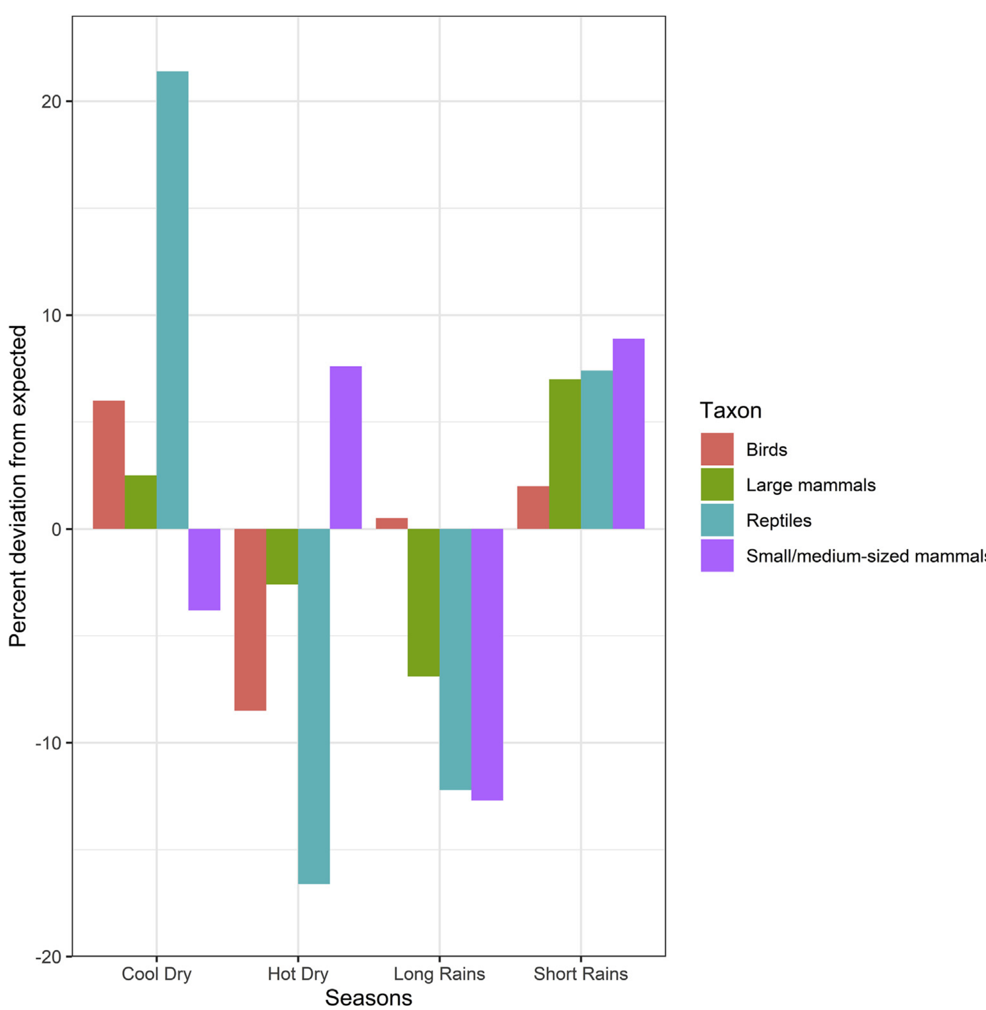

Figure 3. Deviations of observed roadkill (2007–2018) from expected by taxa across different seasons along the Mombasa-Nairobi highway infrastructure corridor (MNHIC) in Tsavo Conservation Area, Kenya.

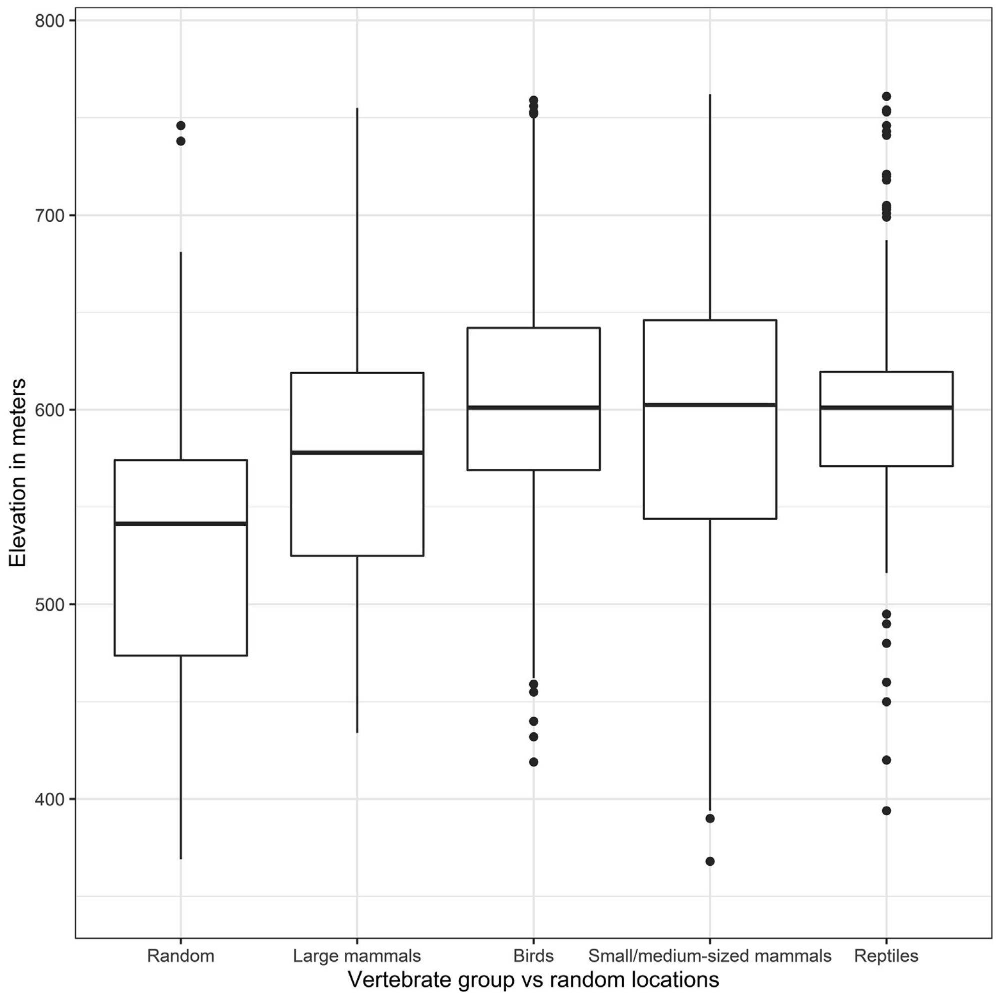

Figure 4. Variation of roadkill (2007–2018) in different taxa in relation to elevation along the Mombasa-Nairobi highway infrastructure corridor (MNHIC) in Tsavo Conservation Area, Kenya.

distances to permanent (9,914.10 ± 5,335.08, t_{68} = -7.1273, $p < 0.0001$) and seasonal rivers (3,754.67 ± 1,391.66, t_{57} = -10.306, $p < 0.0001$) respectively.

4. Discussion

Eleven years of monitoring revealed strong roadkill patterns regarding taxa, spatial heterogeneity, and seasonality occurring along the largest infrastructure corridor through protected areas in Kenya. The distribution of roadkill across species was varied. In terms of numbers, small to medium-sized mammals were the most abundant roadkill (53%), followed by birds (32%), reptiles (10%), and lastly large mammals (5%). These findings contrast those from Tarangire-Manyara ecosystem and Mapungubwe Transfrontier conservation area in South Africa, where birds were the most common roadkill at 50% and mammals (large and small to medium-sized combined) came second at 27–30% (Kioko et al., 2015; Collinson et al., 2019). The deviation in taxon composition represented in roadkill across studies may also be influenced by data collection protocols such as the timing of surveillance, and speed of the drive during monitoring. When observers drive relatively fast along the road, they will likely miss many birds and other smaller animals that would be recorded if observers drive slowly. Similarly, drives carried out later during the day tend to record more bird roadkill and less mammalian roadkill as documented in Australia (Englefield et al., 2020). The findings from TCA are similar to those in the Kafue National Park, Zambia (Nyirenda et al., 2017). Variation in the taxon composition of roadkill is also influenced by the abundance and distribution of taxa in the area (Canova and Balestrieri 2019). Lack of population or biomass estimates for each taxon precludes comparing roadkill frequencies to estimates of abundance in the TCA.

The dominance of mammals as a major roadkill taxon has also been recorded in several other studies (Lodé 2000; Lesbarrères et al., 2006; Canal et al., 2019). The difference in taxa dominating roadkill across studies may be related to local patterns in vertebrate diversity. Small to medium-sized mammals, which was mostly represented by dik-dik, suffered the greatest roadkill mortality. All small to medium sized mammals recorded as roadkill were nocturnal species that are easily blinded by strong vehicle headlight and this could have caused the high number recorded (Estes 1991; Kingdon 2004). For large mammal roadkill, hyenas were the most commonly killed, possibly because they scavenge other roadkill, they have a tendency to walk on roads and are also mostly nocturnal (Estes 1991; Kingdon 2004). Diminished visibility by motorist could also have contributed to the high mortality of nocturnal animals. Similar studies have also shown that nocturnal wildlife are most likely to be hit by vehicles than diurnal wildlife (Estes, 1991; Kingdon, 2004). Birds were the second most affected by roadkill after mammals; other studies (Kambourova-Ivanova et al., 2012) showed that birds and mammals are the most affected by roadkill. Despite being the second most abundant roadkill, bird roadkill disappeared faster on the roads (Svensson 1998), which likely reflects that they are consumed and taken by different scavengers and predators such as crows, kites, and buzzards and at night also by mammals such as

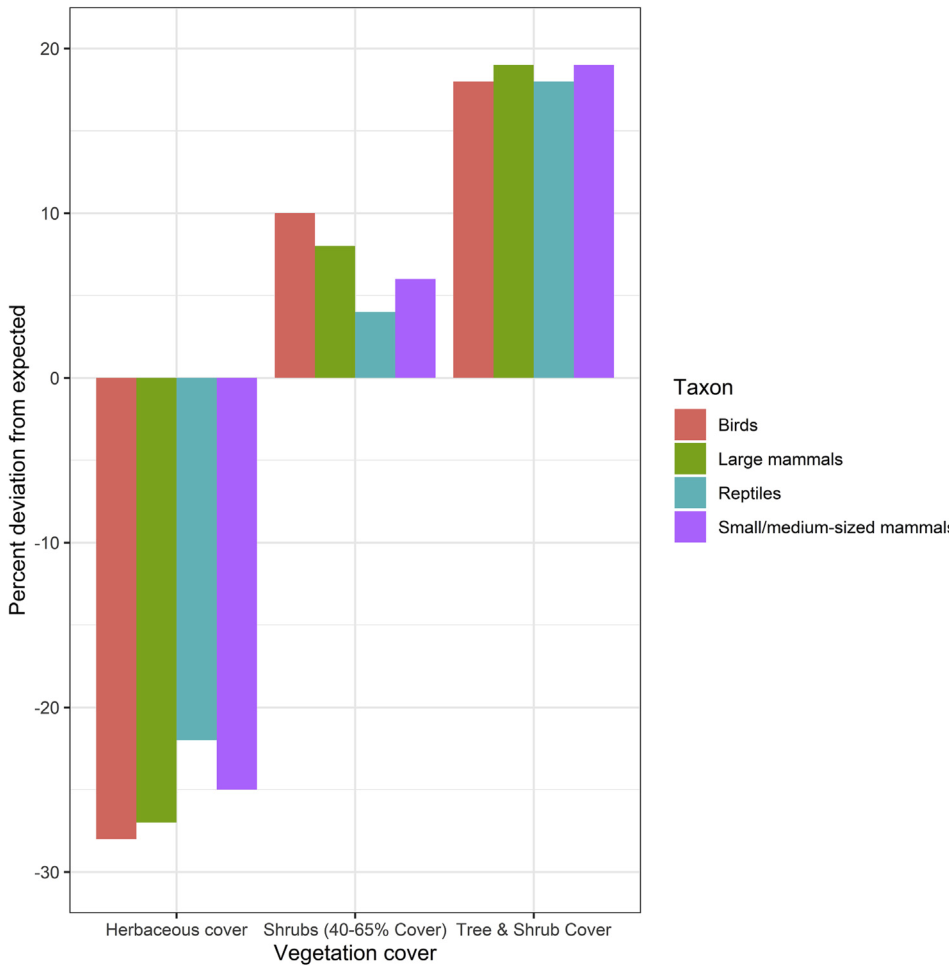

Figure 5. Deviations of observed roadkill (2007–2018) by taxa across different land cover types along the Mombasa-Nairobi, Kenya highway infrastructure corridor (MNHIC), Kenya.

hyenas and jackals. Because bird, small to medium-sized mammals and reptile's roadkill are readily consumed and easily moved by scavengers, the number of observations recorded as roadkill in our data is a minimum estimate.

Results from this study also revealed that roadkill patterns were seasonal, being more frequent in the dry season but more distributed along the highway in the wet season. The dispersed nature of roadkill recorded during the wet season could be attributed to availability of surface water and food. Most wildlife do not rely on the seasonal and permanent rivers during the wet season as there is usually surface water distributed in most parts of the park and the ranches, mammals therefore would tend to move more in new places as there is palatable vegetation and water that is evenly distributed. During the dry season animals tend to be confined in areas where there is vegetation and water supply (Da Rosa and Bager 2012). There was more roadkill near permanent and seasonal rivers than areas that do not have seasonal and permanent rivers. Numerous reports suggest that linear landscape elements such as riparian corridors, ditches, steep slopes and ridges, as well as fences and other transport infrastructure, may funnel animals alongside or across the roadway and thereby increase the risk of wildlife collisions (Malo et al., 2004).

The distribution of roadkill exhibited hotspots and was significantly clustered compared to random points along the infrastructure corridor. Most roadkill was recorded in a section of road passing through protected areas (Tsavo East and Tsavo West), as compared to the area that connects Tsavo East to the ranches and major settlements. These results are similar to those from the roads crossing the Kafue National Park, Zambia where there were more roadkill along sections of the road crossing the park more than corresponding section not crossing the park (Nyirenda et al., 2017) or more roadkill on road sections adjacent to the protected areas (77.3%) compared to sections of the road crossing non-protected areas (Kioko et al., 2015). In Spain, one study revealed that the highest number of roadkill occurred on roads in highly protected areas compared to roads in non-protected habitat (Garriga et al., 2012). These differences in roadkill by protection status are likely influenced by abundance of wildlife in protected areas compared to non-protected areas. Such a result indicates the opportunity to improve mitigation measures, e.g. signage, along road sections that traverse protected areas on either side; studies have shown that such mitigation measures can reduce roadkill by 40% (Rytwinski et al., 2015).

Roadside areas and habitats with shrub cover were associated with the highest roadkill occurrence compared to areas that had herbaceous cover. This result is similar to other studies (Smith--Patten and Patten 2008), in which vegetation next to roads appears to encourage crossings because animals use increased vegetative structure more readily. This could have been a cause of the roadkill difference between shrubs and herbaceous cover, as wildlife are able to use the shrubs as cover before crossing. The shrubs could also have hindered motorist visibility and their ability to notice the wildlife close to the road. Consequently, braking distance or the ability to slow down at a safe distance to avoid roadkill is likely compromised. Open areas enhance the ability of motorists to see

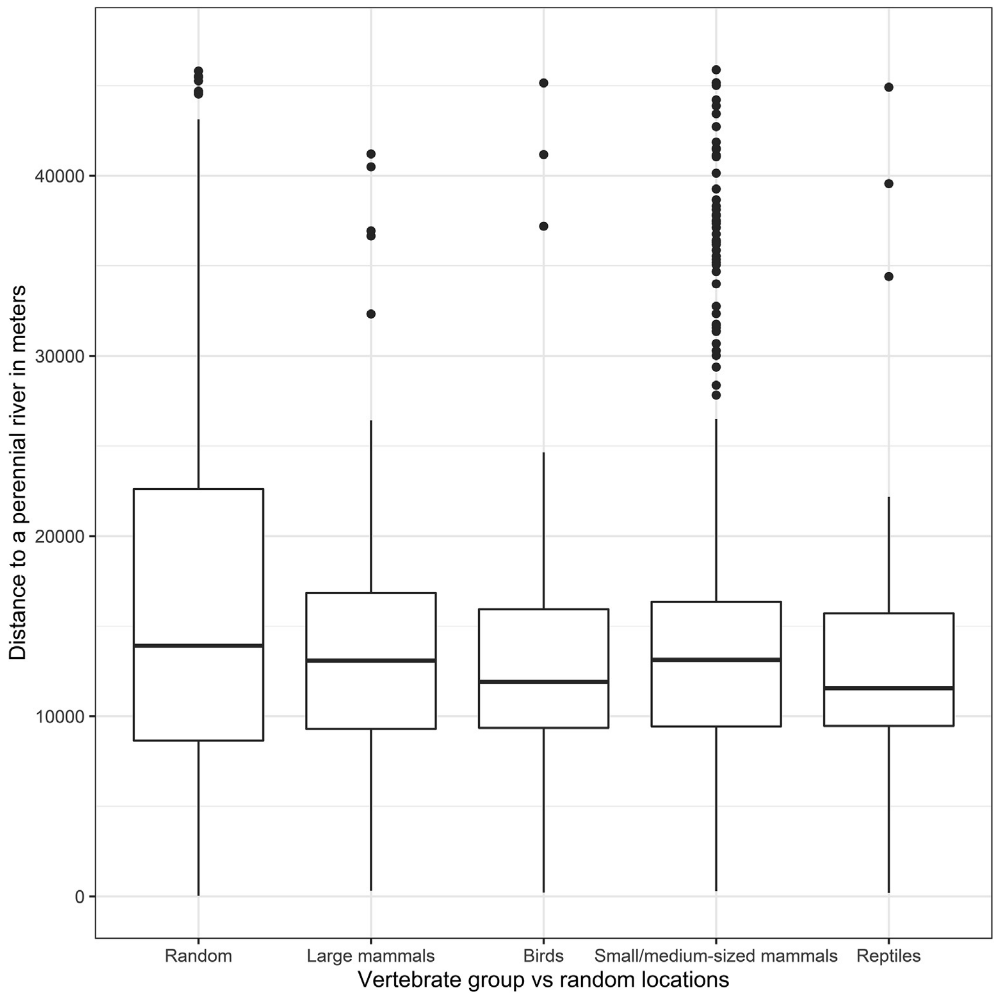

Figure 6. Variation in roadkill (2007–2018) in different taxa in relation to distance to the nearest perennial river along the Mombasa-Nairobi, Kenya highway infrastructure corridor (MNHIC) in Tsavo Conservation Area, Kenya.

animals from a distance and slow down before hitting wildlife, especially large mammals. This is likely the reason there were fewer large mammals hit on the section of the road crossing non protected habitat compared to protected habitat where the vegetation is comparatively open. Shrubs and herbaceous cover also provide suitable habitats for some species including Kirk's dik-dik (Boshe 1984) and common genet, among the top species represented as roadkill among small mammals.

5. Conclusion and recommendations

The results show that roadkill in the MNHIC is associated with contiguousness of protected habitat, proximity to seasonal, permanent rivers and shrub vegetation. Roadkill monitoring documented species of concern such the critically endangered Taita thrush, the endangered African wild dog and threatened elephants. These findings indicate a need and opportunity to limit further road mortality of these species. Roadkill associated with elephants and buffalo are usually associated with vehicle damage and a high risk of human mortality during road accidents. There is a need to mitigate the impact of infrastructure by modifying human behavior using road signs and speed limits or through vegetation management such as clearing roadside vegetation to allow motorist to see the wildlife when they approach the road. As infrastructure development continues along the MNHIC (i.e., the proposed expressway), this analysis has identified important roadkill hotspots and patterns to consider in mitigation efforts.

Declarations

Author contribution statement

Fredrick Lala: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Wrote the paper.

Patrick I. Chiyo, William J. Severud, Aaron W. Morris: Analyzed and interpreted the data; Wrote the paper.

Erustus Kanga, Patrick Omondi, Shadrack Ngene: Contributed reagents, materials, analysis tools or data; Wrote the paper.

Joseph Bump: Conceived and designed the experiments; Analyzed and interpreted the data; Wrote the paper.

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Data availability statement

Data included in article/supplementary material/referenced in article.

Declaration of interests statement

The authors declare no conflict of interest.

Additional information

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