

Article

Analysis of Water Deer Roadkills Using Point Process Modeling in Chungcheongnamdo, South Korea

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Abstract: The expansion of road networks and increased traffic loads have resulted in an increase in the problem of wildlife roadkill, which has a serious impact on both human safety and the wildlife population. However, roadkill data are collected primarily from the incidental sighting, thus they often lack the true-absence information. This study aims to identify the factors associated with Korean water deer (*Hydropotes inermis*) roadkill in Korea using the point processing modeling (PPM) approach. Water deer roadkill point data were fitted with explanatory variables derived from forest cover type, topography, and human demography maps and an animal distribution survey. Water deer roadkill showed positive associations with road density, human population density, road width, and water deer detection point density. Slope and elevation showed negative associations with roadkill. The traffic volume and adjacent water deer population may be the major driving factors in roadkill events. The results also imply that the PPM can be a flexible tool for developing roadkill mitigation strategy, providing analytical advantages of roadkill data, such as clarification of model specification and interpretation, while avoiding issues derived from a lack of true-absence information.

Keywords: wildlife management; spatial modeling; animal–vehicle collisions; mitigation measures; citizen science



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1. Introduction

Over time, the expansion of road networks and following traffic loads have exerted various impacts on wildlife habitat, behaviour, and population dynamics [1]. They include habitat loss and degradation, impeding habitat recolonization [2], reduction of landscape connectivity, subsequent disturbing behaviours (e.g., road avoidance, effects of car traffic on bird bleeding [3]), and direct mortality from collisions of vehicles (i.e., roadkill) while crossing the fragmented habitats [4]. Roadkill would be the leading human cause of terrestrial vertebrate mortality and, therefore, it can be a critical threat to endangered or vulnerable population if the roadkill rate exceeds reproduction and immigration rates [5].

Roadkill (also commonly referred to as wildlife–vehicle collision or animal–vehicle collision) not only plays a major role in the mortality of wildlife by humans [5], but also poses a critical issue regarding the safety of humans by animals [6]. Roadkills involving large mammals, such as ungulate species, are of particular concern; for example, it is believed that more than 1 million deer–vehicle collisions occur every year in the United States, resulting in substantial economic damage, human injuries and death [7]. Therefore, roadkill of wildlife became a major socio-economic issue, and considerable research efforts for mitigation of risks have been conducted in recent decades [8].

Korean water deer (*Hydropotes inermis argyropus*; hereafter, “water deer”) is a subspecies of water deer with exclusive distribution on the Korean Peninsula. Water deer occupy a wide range of habitats of forests, grasslands, and riparian areas [9]. Due to its distinctly limited distribution, excessive poaching, and habitat loss [10], the International Union for Conservation of Nature Redlist has identified water deer as vulnerable (VU [11]). Yet, Korea has a fairly large population of water deer, resulting in serious conflicts between local farmers and a significant roadkill risk [10]. Choi [12] estimated that over 60,000 water deer roadkills occur annually in Korea. Therefore, understanding roadkill events and their driving factors becomes the foundation for development of cost-effective strategies for mitigation and wildfire management [13].

However, designing a roadkill study as a randomized experiment is difficult. Thus, most of the studies rely on the survey (i.e., observational) or monitoring datasets [14]. Moreover, the surveys and monitoring are usually based on incidental sightings. Therefore, the roadkill survey data are likely collected as a form of “presence-only” data [15], which have no or less reliable information regarding “true-absence” [16]. As a handy and prevailed remedy, ecologists have often added randomly chosen “pseudo-absence data” (naïve logistic regression; sensu Hastie and Fithian [17]), but it still has the limitations in model specification, interpretation, and implementation [18]. A variety of techniques have been suggested for management of this issue, including boosted regression trees [19], random forest [20], maximum entropy (MaxEnt [21]), and point processing modeling (PPM [22]).

Among those alternatives, the analytical benefits of PPM have been demonstrated across disciplines, which frequently manage presence-only data [23]. PPM provides a powerful method with a specific form of intensity (point density), embracing other popular techniques, including logistic regression and MaxEnt [22]. The PPM fits each data point directly, thus several disadvantages derived from counting the number of detection observation points can be avoided (i.e., aggregation [24]). In addition, the PPM is relatively tolerant of imperfect detection in wildlife monitoring case studies [25]. Despite these benefits, studies analyzing the opportunistic data with this spatial modelling technique have rarely been reported [13]. Likewise, although the roadkill issue has emerged in Korea, quantitative research efforts (including PPM) regarding water deer roadkill for development of effective management strategies are still limited [12].

The objective of this study is to evaluate the factors associated with water deer roadkills using PPM. In this study, we compiled the long-term water deer roadkill monitoring data with spatial information from the Chungnam Wild Animal Rescue Center (CWARC), which has one of the most extensive vertebrate roadkill datasets in Korea. The geographic, demographic, and water deer distribution survey data were then tested for the effects on water deer roadkills.

2. Materials and Methods

2.1. Study Area

The study was conducted throughout the Province of Chungcheongnam (“Chungcheongnam-do” or “Chungnam”). The province is located in the mid-western part of South Korea (35°58′30″~37°03′44″ N, 125°31′21″~127°38′30″ E; Figure 1). The total land area of the province is 8226 km² and mainly consists of hilly or lowland areas; 65.7% of the total land area is less than 100 m asl and less than 5 degrees in slope. Forests and agricultural lands cover more than 70% of the total land [26]. The majority of forests (i.e., ~80% of 4080 km²) were reforested during the last four decades. Coniferous, deciduous, and mixed forests are evenly distributed, covering 37%, 30%, and 27% of the total forest lands, respectively. The average stocking volume of the forests is 139 m³/ha [27].

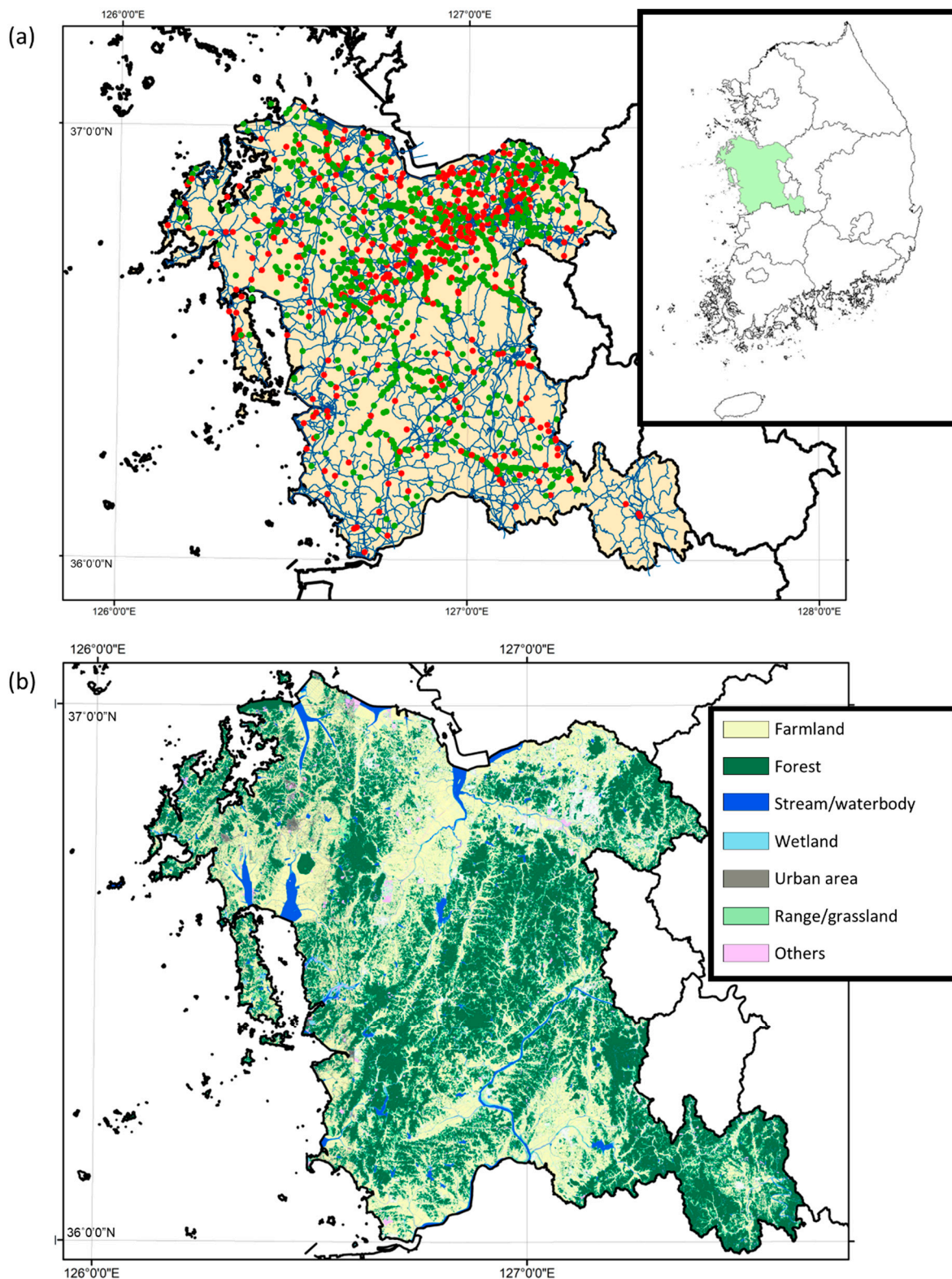


Figure 1. (a) Study area and locations of roadkills and (b) land use of the Province of Chungcheongnam. In panel (a), blue lines indicate the road networks and red and green dots represent water deer and other roadkills, respectively.

The climate of the Province of Chungcheongnam is classified as a humid continental climate with dry winter. The average temperature and annual precipitation (1981–2010) of the province are 12.2 °C and 1310 mm [28]. The highest average monthly temperature was

recorded in August (25.3 °C) and the lowest in January (−1.7 °C). The annual precipitation is more than 50% in summer, and less than 10% in winter.

2.2. Data Acquisition, Processing, and Analyses

The data regarding roadkill (2010–2020) of water deer analyzed in this study were acquired from the wild animal rescue database of CWARC. Roadkill cases with the Global Positioning System coordinates were extracted as point data (RD_KILL) from the rescue database. A total of 1541 roadkill cases were reported from 70 species, including mammals, birds, and reptiles. There were 419 cases of water deer roadkills (Figure 1). Digital maps constructed by the Korea National Geographic Information Institute were used for geographical and demographical variables (Table 1); they were digital elevation model, roads and water channels, and human population. Layers of distance to the water channel (D_WAR), elevation (ELEV), road-side slope (SLOPE), human population density (POP_DEN), road density (RD_DEN), speed limit (RD_SPD), and road width (RD_WID) were created.

Table 1. Description of variables for model construction.

Variables	Unit	Notation	Note	Source ¹
Roadkill		RD_KILL	point data	CWARC
Area of the nearest forest	m ²	F_AREA	log-transformed	KFS
Diameter class		D_CLS	categorical data	KFS
Distance to the forest edge	m	D_FOR	log-transformed	KNGII
Distance to the water channel	m	D_WAR	log-transformed	KNGII
Elevation	m	ELEV	log-transformed	KNGII
Road-side slope	%	SLOPE	log-transformed	KNGII
Human population density	people ha ^{−2}	POP_DEN		KNGII
Road density	road ha ^{−2}	RD_DEN		KNGII
Road speed limit	km h ^{−1}	RD_SPD		KNGII
Road width	lanes	RD_WID		KNGII
Water deer occurrence	points ha ^{−2}	WD_KER	kernel density	CI

¹ CWARC: Chungnam Wild Animal Rescue Center; KFS: Korea Forest Service; KNGII: Korea National Geographic Information Institute; CI: Chungnam Institute.

The digital forest cover type map (Korea Forest Service) was used to obtain information on the nearest forest from roadkill occurrence points. Forest area (F_AREA), tree diameter class (D_CLS; categorical data), and distance to the nearest forest edge (D_FOR) were exported. Mammal survey data collected from the Biotope Mapping Project (2008–2014; Chungnam Institute) in the Chungcheongnam Province was used to account for the probability of water deer occurrence. The biotope mapping project was an intensive and extensive survey campaign, covering the entire province. Traces of water deer were observed from 1222 out of 1483 randomly selected plots, and kernel density of water deer detection points (WD_KER) was calculated. All variable layers except the point data (i.e., RD_KILL) were rasterized with a resolution of 100 m X 100 m using ArcGIS Desktop (ver. 10.8.1 ESRI Inc. Redlands, CA, USA).

The intensity (λ ; density of points per unit area) of observation points (i.e., roadkill occurrence; sensu [17]) was modeled through PPM. The intensity is the expected number of points per unit area:

$$\lambda = \frac{n(X)}{|W|}, \quad (1)$$

where, $n(X)$ is the number of points in the dataset X in the area W . Then, a log-linear function with n explanatory variables can model the intensity of location s within bandwidth τ through kernel weighting function $k()$:

$$\hat{\lambda}(s) = \sum_{i=1}^n \frac{1}{\tau^2} k\left(\frac{s - s_i}{\tau}\right), \quad (2)$$

Then, the log-linear function with l explanatory variables estimates the intensity of each location i (s_i):

$$\log\lambda(s_i) = \beta_0 + \sum_{j=1}^l x_{ij}\beta_j, \quad (3)$$

where β s and x_i s are the estimated parameters and explanatory variables, analogously interpreted as generalized linear models [18,29]. Poisson distribution was assumed to estimate the probability of the number of observation points (i.e., water deer roadkill in this study).

The candidate variables were tested as a manner of a forward selection at an alpha level of 0.05. A maximum likelihood ratio test was used to test the significance of each candidate explanatory variable. The Akaike information criterion (AIC) was used to evaluate the superiority of model fit between two candidate models. The cut-off AIC value of 4 (i.e., $|\Delta AIC| \geq 4$) was used as a threshold for selection of the more complicated model than the simpler one in this case [30]. All statistical analyses were performed using spatstat package (ver 2.2-0 [29]) in the statistical software R (ver 4.1.0 [31]).

3. Results

Approximately 50% of the reported roadkill cases consisted of mammals, while birds and reptiles occupied 44 and 7%, respectively. The water deer roadkill was the most frequent among the mammal species (approx. 38% of mammal roadkills). When compared with the overall means of the province, water deer roadkill tended to occur in the places with lower elevation and more gentle road-side slope (Table 2). A distinctly higher human population and road density were observed for the water deer roadkill points. A higher proportion of the water deer roadkills were observed for sites with higher water deer detection density during the wildlife survey of the Biotope Mapping Project (Table 2).

Table 2. Description of water deer roadkill reporting sites.

Variables	Unit	Mean	Mean of the Province
Distance to the forest edge	m	227	202
Distance to the water channel	m	1730	1789
Elevation	m	52	98
Road-side slope	%	4.3	7.2
Human population density	people km ⁻²	737	248
Road density	road ha ⁻²	3.6	2.4
Road width	km h ⁻¹	2.14	2.0
Water deer occurrence	points ha ⁻²	0.13	0.07

The PPM results supported the general tendency. The model with RD_DEN, POP_DEN, SLOPE, RD_WID, WD_KER, and ELEV exhibited the best fit to the roadkill data (AIC = 14,537; Table 3). RD_DEN, POP_DEN, RD_WID, and WD_KER showed a positive association with water deer roadkill events (Table 4). In contrast, SLOPE and ELEV showed a negative association with water deer roadkills. Forest area (coefficient: -0.181), distance to the nearest forest edge (coefficient: 0.162), distance to the nearest water channel (coefficient: -0.069), and road speed limit (coefficient: 0.004) were significant when they were tested alone (i.e., single predictor model); however, they were not included in the final model.

Table 3. Evaluated candidate models (top 5) for water deer roadkill. Variable notations are described in Table 1.

Rank	Model Form	AIC
1	RD_DEN + log(POP_DEN) + SLOPE + RD_WID + WD_KER + ELEV	14,537
2	RD_DEN + log(POP_DEN) + SLOPE + RD_WID	14,576
3	RD_DEN + log(POP_DEN) + SLOPE + RD_WID + log(D_WAR)	14,576
4	RD_DEN + log(POP_DEN) + SLOPE	14,580
5	RD_DEN + log(POP_DEN) + log(D_FOR)data	14,593

Table 4. Estimated model parameters for water deer roadkill (***: $p < 0.001$; **: $p < 0.01$; *: $p < 0.05$).

Variable	Estimates	SE	z Value	
Intercept	−18.604	0.273	−68.099	***
RD_DEN	0.070	0.025	2.820	**
log(POP_DEN)	0.273	0.047	5.819	***
SLOPE	−0.037	0.015	−2.546	*
RD_WID	0.211	0.084	2.505	*
WD_KER	3.209	0.560	5.728	***
ELEV	−0.004	0.001	−4.068	***

4. Discussion and Conclusions

The results of our study of water deer were consistent with results from published research findings showing that the configurations of the road network and traffic load are the key factors affecting roadkill occurrences [6]. For example, road density has been demonstrated as the main driver in increasing the roadkill of ungulate species in Slovenia [32]. Positive associations of human population density and road width with water deer roadkill imply that traffic volume is also a dominant factor determining the deer roadkill risk [5,33]. Choi [34] found that four-lane roads had 40% of additional water deer roadkills compared with two-lane roads in Korea.

The significant factors with regard to landform (i.e., road-side slope and elevation) might imply an association of water deer roadkill with habitat preferences and traffic characteristics. There is a general agreement that water deer prefer a habitat of lowlands with gentle slopes [35]. The habitat preference presumably attributes to the abundant food source (e.g., crops in farmlands) and to avoidance of other mountainous carnivores, such as leopard cats (*Prionailurus bengalensis*), raccoon dogs (*Nyctereutes procyonoides*), martens (*Martes flavigula*), Eurasian eagle-owls (*Bubo bubo*), and feral dogs [10]. However, equivocal results regarding the association between road-side slope and deer roadkill have also been reported (e.g., [36]). Gunson et al. [6] suggested that the road-side slope effect might confound and interact with other factors such as types of roads and habitat. In addition, significant associations with elevation were reported primarily from small mammals and birds (e.g., [37–39]), which presumably have stronger habitat preference of the small vertebrates at lower elevation sites rather in comparison with ungulate species [6]. Therefore, the significant negative associations of two explanatory variables in this study may be attributed not solely to the factors related to habitat types, but to those with road networks and traffic. For example, roads at lower elevations and with flatter road-sides tend to be wider and have higher speed limits [40].

According to several reports, a large local herbivore population leads to a higher roadkill rate [6,8]. The positive relationship of water deer detection point density supports this assertion by assuming the density as a proxy of water deer population abundance. However, Saint-Andrieux et al. [8] emphasized the inter-specific differences in roadkill events. For example, the species with a larger home range would exhibit a stronger association between wildlife population size and roadkill density. Yet, our understanding of the distribution of water deer, population size, habitat use, and home range are still insufficient [10]. Therefore, an accurate estimate of water deer population abundance

around the road network and a better understanding of deer ecology might be the most critical factors for development of successful mitigation measures [41].

Although the area of the nearest forests and distance to the nearest forest edge were not included in the final model, their negative and positive associations in other candidate models might imply that the intensified forest fragmentation would link to increased water deer roadkills. Forest fragmentation reduces the area of forest as well as increases the distance of commute among forest patches [8]. Furthermore, the negative association of the distance to the nearest water channel indicates that roadkills of water deer occur more frequently near water channels. This result may be attributed to the road crossing pattern of water deer, crossing under bridges instead of other road crossing structures, such as underpasses and culverts [42].

The findings of our study demonstrated the potential usefulness of PPM for interpreting the association between road network and traffic characteristics and water deer roadkill occurrences. The PPM approach enables planners and wildlife managers to test how those variables (in conjunction with other environmental/human variables) affect the target species' roadkill pattern, resulting in the spatially explicit assessment of roadkill risk. This study also implies the benefits of PPM for analyzing surveys or monitoring data collected by citizen scientists, which are extensive data collections exceeding the limits of traditional surveys and experiments [43]. Therefore, the PPM approach can help to make cost-effective decisions for mitigation.

However, it should be stressed that roadkill is an event that occurs on a network (e.g., road, river, power line network [44]). Unfortunately, a general agreement regarding the analytical approach of point patterns on a linear network is still lacking [45,46]. Although the interpretation regarding the association between point patterns and explanatory variables on a linear network can be made analogously with those of two-dimensional spaces, the additional assumption involves careful attention for inferences [22]. Therefore, it is recommended that the result of this study and an analytical approach should be limited to identifying the potential factors associated with roadkills rather than predicting the roadkill rates at a certain point. The introduction of more rigorous and reliable analytical techniques together with elaborated sampling efforts for the water deer population would be required in order to obtain a better understanding of water deer roadkill.

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