

Disentangling roadkill: the influence of landscape and season on cumulative vertebrate mortality in South Korea

Changwan Seo · James H. Thorne ·
Taeyoung Choi · Hyuksoo Kwon · Chong-Hwa Park

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Abstract This study recorded and analyzed cumulative vertebrate roadkill data on 107 km of roads in rural South Korea and reports the first intensive roadkill study results from Asia. Over 30 months, roadkill strikes and adjacent landscape factors were recorded daily or every other day on three types of roads: highway, local, and riverside. For analysis, roads were segmented into 250-m units, and roadkill hotspot segments were calculated with the Getis–Ord G_i^* statistic. Eighteen road characteristics and landscape factors were correlated to roadkill hotspots using multiple logistic regression analysis. Mammal mortality increased from spring to fall, whereas bird mortality peaked in summer. Reptile and amphibian mortality peaked during fall. Seasonal focal species' mortality tracked the taxonomic groups they represent, except oriental scops owl (*Otus scops*), for which yearly mortality peaked 2 months earlier than for most birds. Mammal and bird roadkill hotspots were concentrated on the highway,

which passes across mountains, whereas amphibian and reptile hotspots were on the riverside road because of movements related to breeding, juvenile dispersal, and hibernation. However, many species used the spatially complex agricultural fields along the local road, especially during harvest season. The significant site and landscape factors that influenced overall roadkill hotspots were a high landscape percentage of water and rice paddies, low traffic volumes, high percentage of natural vegetation, an absence of road banking, high roadside grass presence, and an absence of drainage. South Korea has an active wildlife-crossing management program, and these findings can inform avoidance, minimization, and mitigation strategies and practices.

Keywords Roadkill landscape modeling · Roadkill hotspots · G_i^* statistic · Logistic regression · Roadkill phenology · South Korea

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C. Seo (✉)
Environmental Planning Institute, Seoul National University,
1 Gwanak-ro, Gwanak-gu, Seoul 151-742, Republic of Korea
e-mail: dharmascw@gmail.com

J. H. Thorne
Department of Environmental Science and Policy,
University of California, Davis, CA 95616, USA
e-mail: jhthorne@ucdavis.edu

T. Choi
Nature Assessment Research Team, National Institute
of Environmental Research, Kyungseo-dong, Seo-gu,
Incheon 404-170, Republic of Korea
e-mail: gumiran@gmail.com

H. Kwon
Nature Conservation Research Division, National Institute
of Environmental Research, Kyungseo-dong, Seo-gu,
Incheon 404-170, Republic of Korea
e-mail: ulmus1@korea.kr

C.-H. Park
Department of Landscape Architecture, The Graduate School
of Environmental Studies, Seoul National University,
1 Gwanak-ro, Gwanak-gu, Seoul 151-742, Republic of Korea
e-mail: rsgis@snu.ac.kr

Introduction

Despite economic, quality of life (QOL), and other benefits of roads to humans, there is widespread recognition of the adverse impacts of roads on natural environments (National Research Council 2005; Forman et al. 2003; Trombulak and Frissell 2000). These impacts include direct and cumulative mortality to species hit by vehicles along roads (Forman et al. 2003; Riley et al. 2006; Grilo et al. 2009), reduced dispersal capacity (Forman and Alexander 1998) and associated impediments to gene flow (Epps et al. 2005; Riley et al. 2006; Balkenhol and Waits 2009), increased spread of invasive species (Gelbard and Belnap 2003), disturbance effects such as traffic noise that can affect breeding birds (Reijnen and Foppen 1995; Reijnen et al. 1995), impedance to recolonization of depopulated habitats, and indirect effects including but not limited to the road-effect zone (Bissonette and Rosa 2009), landscape fragmentation (Jaeger et al. 2005; Girvetz et al. 2008) and greenhouse gas emissions (Fuglestedt et al. 2008).

Roadkill studies have focused on a wide range of vertebrate species (Finder et al. 1999; Nielsen et al. 2003; Glista et al. 2007; Gunson et al. 2009; Grilo et al. 2009; Gomes et al. 2009; Langen et al. 2009). However, few studies have examined multiple taxonomic vertebrate groups across time periods long enough to determine predictive landscape factors by taxonomic group or season (e.g., Farmer and Brooks 2012).

The tremendous expansion of roads associated with human population growth increases the need to understand their impact on ecosystems and wildlife. Recognition of this need has led to the development of the subdiscipline of road ecology, recognized by textbooks (Forman 1995; Turner et al. 2001; Havlick 2002; Forman et al. 2003), conferences (Forman et al. 1997; West 2006) and >20 years of publications (Harris and Scheck 1991; Crist and Wilmer 2002; Johnson et al. 2002; Smith et al. 2005). Areas of research interest include developing landscape-scale metrics of fragmentation due to roads (Jaeger et al. 2005; Li et al. 2010), landscape-connectivity studies (Alexander and Waters 2000; Donaldson 2007; Crooks et al. 2008; Beier et al. 2008), and predictive assessments of the impacts of new roads (Thorne et al. 2009). Much of this research is meant to support actions to reduce the negative effects of roads through infrastructure alterations such as wildlife-crossing structures, fencing, decommissioning of roads, and optimizing the alignment of new roads (Fahrig and Rytwinski 2009; Gunson et al. 2011). Efforts that monitor roadkill of multiple taxa can provide information to transportation planners on where to place modifications to roads in order to minimize roadkill (e.g., Clevenger et al. 2003).

This study analyzed roadkill-monitoring data from three types of roads in southern South Korea and is the first to report results of multiple roadkill taxonomic groups and species from eastern Asia. The study investigated three questions: What are the rates of roadkill for different taxonomic groups and focal species on the Korean peninsula, and does this mortality vary by month? What are the spatial and seasonal patterns of roadkill hotspots for the four different taxonomic groups (mammals, birds, amphibians, and reptiles) and their representative focal species? What landscape and site-level factors contribute to roadkill hotspots?

Materials and methods

Study area

To address these questions, we monitored roadkill strikes for 30 months from 1 July 2004 to 10 January 2007 on a 107-km stretch of road in a rural region of southern South Korea comprising three types of construction. The road studied forms a semicircle around the northern and western sides of Jirisan National Park (JNP) and is a barrier between

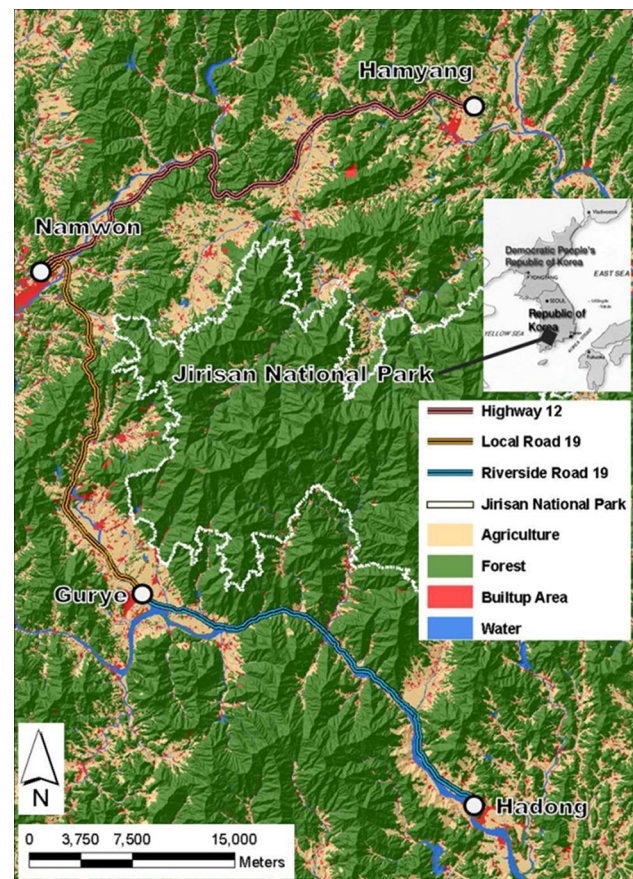


Fig. 1 Study area

the park and mountainous areas further west. The study road passes through natural and seminatural landscapes (Fig. 1).

There are three types of roads in the study area: (1) A two-lane, undivided express highway (highway 12, herein called the highway), 44 km in length with an 80-km/h speed limit and in mountainous terrain. This road is located north of JNP and passes through forest and agriculture lands. It traverses the Baekdu Daegan, the central mountain range of South Korea, which is the main ecocorridor for wildlife movement in Korea. (2) National road 19 is the second type (herein called the local road). It is a four-lane divided national road 30 km long with an 80-km/h speed limit. It passes through hilly terrain and agricultural lands including rice paddies and vegetable and orchard crops interspersed with hedgerows and small water courses in a wide valley west of JNP. Adjacent hill slopes have limited tree cover and some shrublands. Where the road passes through these hills, it was created using a cut-and-fill technique. (3) The third is another section of national road 19 comprising a two-lane, undivided road 33 km long, with a 60-km/h speed limit. It runs parallel to the Sumjin River (herein called the riverside road). The riverside road passes through stands of mature upland trees and riparian forest, through some settlements, and follows the natural topography about 20 m above the river.

Data collection

Roadkill surveys were conducted daily from 1 July 2004 to 30 June 2005 and every other day from 1 July 2005 to 10 January 2007, for a total of 559 road surveys (Choi 2007). After 1 year of daily surveys, it was determined through statistical analysis that all roadkill strikes could be uniquely identified using every-other-day surveys (Bager and Rosa 2011). Corpses were removed after counting, and the strike location was spray painted to avoid duplicate counts. At each observed roadkill site, we recorded location, species, and date, as well as 18 different landscape and site variables such as fencing, road dividers, drainage culverts, and roadside vegetation (Table 1). Data were collected on four taxonomic groups: mammals, birds, amphibians, and reptiles. Each taxonomic group was further represented by an endangered species list, which was independently analyzed: leopard cat (*Prionailurus bengalensis*), oriental scops owl (*Otus scops*), Asiatic toad (*Bufo bufo gargarizans*), and red-sided water snake (*Rhabdophis tigrinus*).

Summary of roadkill statistics

We summed annual, monthly, and seasonal mortality by taxonomic group and focal species. We examined rates of roadkill for the three types of roads and assessed temporal variations for taxonomic groups and focal species.

Table 1 Definition and description of variables used in the analysis of factors explaining roadkill occurrence

Variable name	Definition
Continuous variables	
Traffic lane	Number of traffic lanes
Vehicle speed	Speed limit
Traffic volume	Average annual daily traffic
Paddy field	Proportion of rice paddy fields within 500 m from road center line
Dry field	Proportion of dry fields within 500 m from road center line
Vegetation	Proportion of natural vegetation area within 500 m from road center line
Built up	Proportion of built-up area within 500 m from road center line
Water	Proportion of water-body area within 500 m from road center line
Categorical variables	
Tree	Tall tree present (1) absent (0) at roadside
Shrub	Shrub present (1) absent (0) at roadside
Grass	Grass present (1) absent (0) at roadside
Mowing	Roadside mowing good (1) poor (0)
Median	Median present (1) absent (0)
Guardrail	Guardrail present (1) absent (0) at roadside
Drainage	Drainage present (1) absent (0) at roadside
Road type	Curvature of road curve (1) straight (0)
Road slope	Slope (1) flat (0)
Topography	Roadside topography banking (3) cutting (2) mixed (1) flat (0)

Continuous variables were generated from a geographic information system or other source; categorical variables were obtained from field notes

Roadkill hotspot analysis

We expected roadkill hotspots to be nonrandom and to have a high spatial association with neighborhood type. It was therefore necessary to use local measures to depict the variability of spatial autocorrelation (Anselin 1995; Ord and Getis 1995). Using the Getis–Ord G_i^* statistic (Ord and Getis 1995; Baruch-Mordo et al. 2008), we identified clusters of roadkill of higher magnitude than expected by random chance. To do this, we used road segments as units of analysis for all tests and described roadkill data, roadside variables, and landscape variables within each segment. We divided the road into 429 segments of 250 m in length and measured G_i for each road segment. The delineation of 250 m resulted in an average number of roadkill strikes of 12 per segment overall and of four per segment for focal species. Road segments shorter or longer

than 250 m were also examined, but they either reduced or increased the number of roadkill occurrences in each segment to the point where we could not identify hotspot patterns. We used the fixed distance option (500 m; two road segments) for calculating hotspots and set a Z value of 2 from Gi scores to identify hotspot segments (Anselin 1995). Spatial and seasonal patterns of roadkill hotspots were examined for each taxonomic group and focal species. We used ArcGIS 9.3 for hotspot analysis (ESRI Inc. 2009).

Driving factors for roadkill

We examined 18 predictor variables in a multiple logistic regression framework to identify roadside and landscape factors consistently present at roadkill hotspots (Table 1). Thirteen variables were collected at each roadkill reported. Five landscape variables, consisting of general landcover categories, were sampled using a 500-m buffer from the road center line, and the percentage of each landcover type was summarized for every 250 m of road segment. The 500-m buffer distance was selected after a sensitivity analysis on a range of buffer sizes because it best captured the distribution of landcover types in our study area. The pattern of roadkill hotspots from the previous analysis (above) identified each road segment as having (1) or not (0) a hotspot. This pattern was used as the response variable. Logistic regression was selected because we used continuous and categorical data for explanatory variables (Press and Wilson 1978). The 18 predictor variables were quantified for each road segment. We analyzed roadkill hotspots for the four taxonomic groups and focal species.

All roadkill hotspot segments were used, but only twice as many randomly selected nonroadkill hotspot segments were included (rather than all nonhotspot locations) (Kvamme 1985). We used two analyses to evaluate each model. First, we used AIC to assess goodness of fit. Second, to assess model accuracy, we used three procedures: area under the relative operating characteristic curve (AUC, Hanley and McNeil 1982), Cohen's *K* (Monserud and Leemans 1992), and true skill statistics (TSS, Allouche et al. 2006). Used in combination, these three procedures can provide more ways to assess the accuracy of each model. We therefore provide all three results. We assessed the relative importance of each predictor variable within each model by comparing Pearson correlation between standard predictions and predictions with the randomly permuted investigation variable. We also validated each model using 100 bootstrapping runs of a cross validation with a 70 % training set and a 30 % test set. We used BIOMOD in R 2.13.2 for all analyses (Thuiller et al. 2009).

Results

Summary statistics by taxonomic group, season, and road type

Road surveys totaled 59,813 km (559 surveys), and recorded 5,715 fatal road strikes. We used 5,044 records, and excluded 145 recorded strikes of invertebrates including crustaceans and millipedes and 526 locations with GPS error above 10 m from a roadside. Roadkill yearly totals were 2,532 (July 1, 2004–June 30, 2005), 1,655 (July 1, 2005–June 30, 2006), and 857 (July 1, 2006–January 10, 2007) (Table 2). A total of 5,044 vertebrates were killed during the study, comprising 1,582 mammals (1.71/day), 1,205 birds (1.3/day), 1,394 amphibians (1.5/day), and 863 reptiles (0.93/day) (Table 2). Roadkill species richness totaled 101 vertebrates, comprising 22 mammals, 59 birds, 6 amphibians, and 14 reptile species (Supplementary Appendix 1). Among these are 15 which have both national monument status (species designated by the Cultural Heritage Administration of South Korea for their significance), and endangered species status in Korea.

Unspecified rodents were the most frequently struck mammals, followed by the focal species raccoon dog (*Nyctereutes procyonoides*) (86.7/year) and water deer (*Hydropotes inermis*) (62.5/year). Mortality for the focal species leopard cat was 37.6/year (see all impacts in Supplementary Appendix 1). Mammal mortality increased in the spring and fall and peaked in October (Fig. 2). Maximum bird strikes were on ring-necked pheasant (*Phasianus colchicus*) (138.1/year), with 37.2 strikes/year on the focal species, oriental scops owl. Bird mortality peaked in summer. Reptile mortality peaked in the fall. Among reptiles, snakes were most affected; the focal species, red-sided water snake, was hit 116.3 times/year. The Asiatic toad had the dubious distinction of most frequently killed species, with 523.9 strikes/year. Amphibian mortality peaked during fall, and there were 3 months with peak strikes: March, June, and October (Fig. 2). All taxonomic groups had minimal mortality during the winter due to hibernation and inactivity.

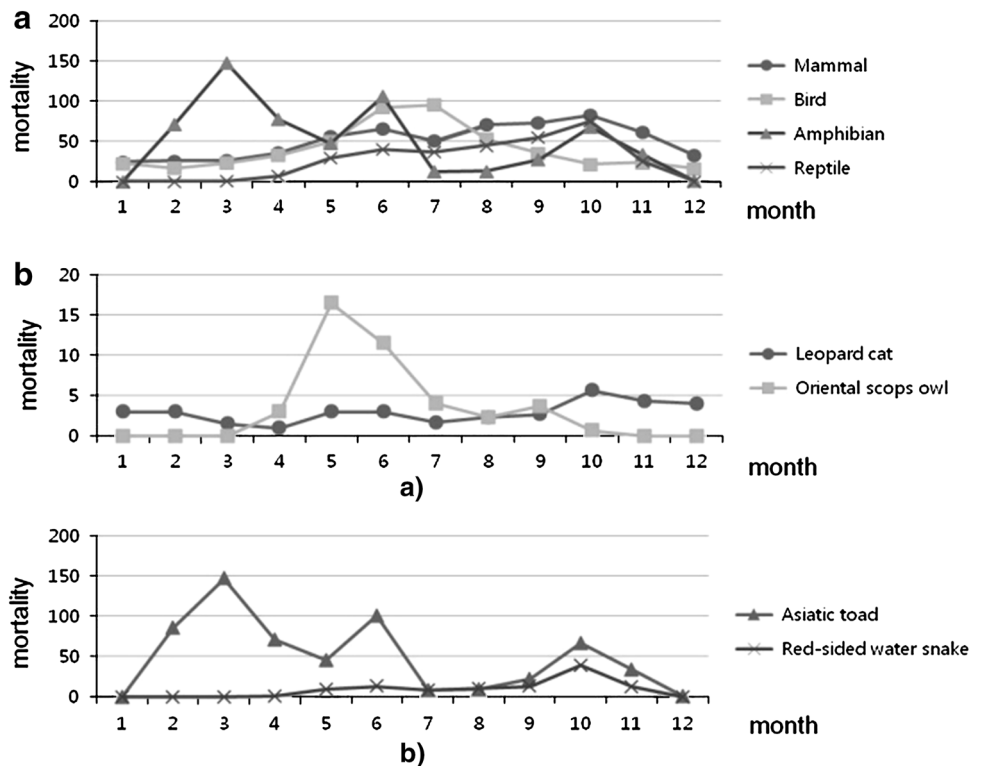
Roadkill hotspot analysis

The distribution of yearly roadkill strikes across the study area for all species and taxonomic groups was non-random. For all species combined for the entire year, six roadkill hotspots were identified with a mean length of 1.2 km and a Gi Z statistic value > 2 (Fig. 3a). However, mammals and birds each had eight yearly hotspots, with an average 0.8-km kill zone for mammals and 1.2-km zone for birds. There were similar numbers of hotspots

Table 2 The number of individuals killed by roads according to taxonomic group and year

Road	Length (km)	Lane	Speed limit (km/h)	Taxa	1 July 2004–30 June 2005		1 July 2005–30 June 2006		1 July 2006–10 January 2007		Total	
					N	Kill per km	N	Kill per km	N	Kill per km	N	Kill per km
Highway 12 (expressway)	44	2	80	Mammal	323	7.3	216	4.9	145	3.3	684	15.5
				Bird	350	8.0	186	4.2	143	3.3	679	15.4
				Amphibian	49	1.1	9	0.2	13	0.3	71	1.6
				Reptile	131	3.0	81	1.8	59	1.3	271	6.2
				Subtotal	853	19.4	492	11.2	360	8.2	1705	38.8
National road 19 (rural area)	30	4	80	Mammal	134	4.5	172	5.7	74	2.5	380	12.7
				Bird	80	2.7	91	3.0	41	1.4	212	7.1
				Amphibian	19	0.6	9	0.3	11	0.4	39	1.3
				Reptile	24	0.8	48	1.6	24	0.8	96	3.2
				Subtotal	257	8.6	320	10.7	150	5.0	727	24.2
National road 19 (riverside)	33	2	60	Mammal	245	7.4	166	5.0	107	3.2	518	15.7
				Bird	157	4.8	106	3.2	51	1.5	314	9.5
				Amphibian	802	24.3	387	11.7	95	2.9	1,284	38.9
				Reptile	218	6.6	184	5.6	94	2.8	496	15.0
				Subtotal	1,422	43.1	843	25.5	347	10.5	2612	79.2
Total	107				2,532	23.7	1,655	15.5	857	8.0	5,044	47.1

Fig. 2 Cumulative monthly roadkill for four taxonomic groups and for focal species; results of 2.5 years of monitoring (1 July 2004–10 January 2007). **a** Mammal, bird, amphibian, reptile. **b–a** Leopard cat (*Prionailurus bengalensis*), oriental scops owl (*Otus scops*), **b–b** Asiatic toad (*Bufo bufo gargarizans*) and red-sided water snake (*Rhabdophis tigrinus*)



for amphibians (6) and reptiles (7), but these were longer kill zones, averaging 1.7 km for each taxonomic group (Fig. 3b).

The number and location of all-taxa hotspots varied by season, with fall having the most (11, averaging 727 m in hotspot length), followed by summer (7 hotspots, averaging

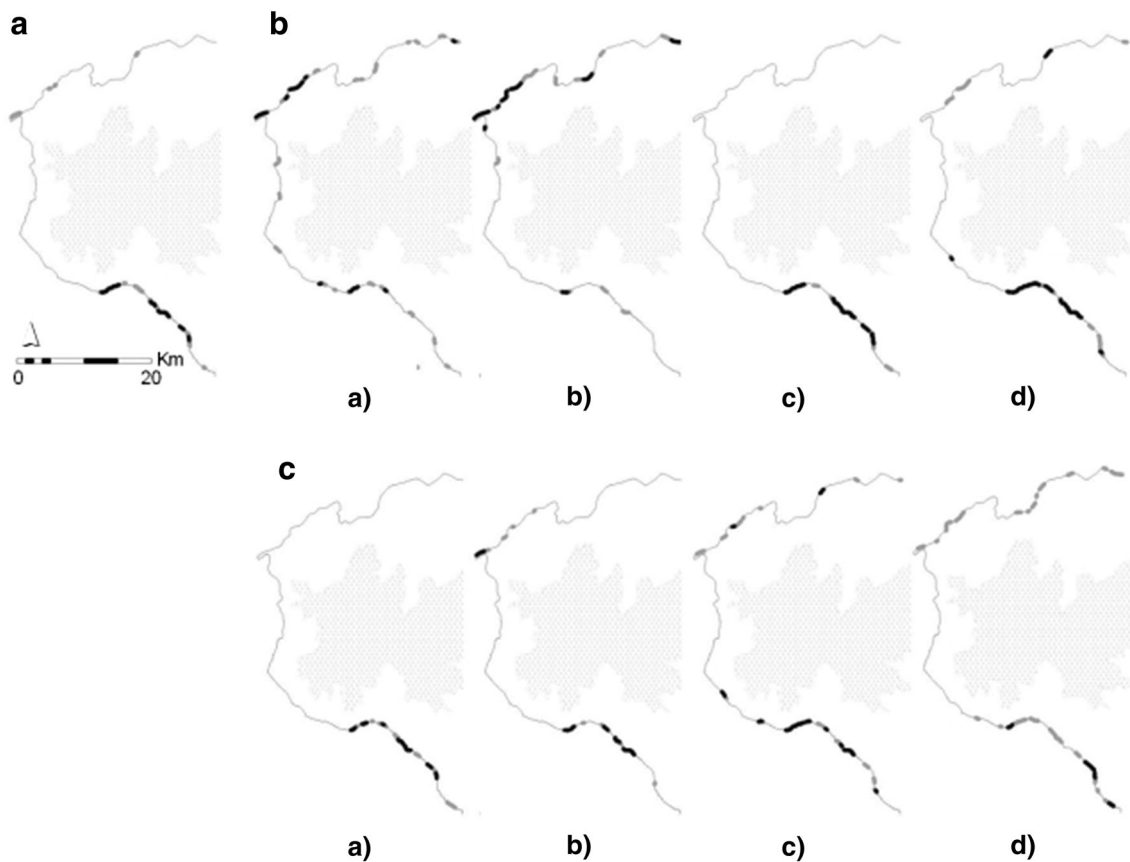


Fig. 3 Roadkill hotspots of four taxonomic groups and four seasons. **a** Total, **b–a** mammal, **b–b** bird, **b–c** amphibian, **b–d** reptile, **c–a** spring, **c–b** summer, **c–c** fall, **c–d** winter. *Grey segment* means

less aggregated.; *black segments* show where roadkill hotspots are more spatially clustered ($Z \geq 2$); *grey segments* are less clustered ($1 \leq Z \leq 2$)

500 m). Spring and winter had six and five hotspots, respectively, but they were longer (1,000 and 900 m, respectively) than summer hotspots (Fig. 3c). There were nine yearly roadkill hotspots for leopard cat, with a mean road length of 611 m. This number doubled in the summer to 16 (Fig. 4a), and the hotspot length for this species was longest in spring, at 844 m ($n = 8$), and shortest in winter, at 406 m ($n = 8$). Mean roadkill hotspot length (875 m, $n = 7$) for oriental scops owl (Fig. 4b) was shorter than for all birds, and the number of hotspots was constant (10) in spring, summer, and fall; there was no mortality in winter. Hotspots lengths for this species varied slightly by season through spring, summer, and fall, at 450, 600, 800 m, respectively. For the Asiatic toad (Fig. 4c), the mean roadkill hotspot length (786 m, $n = 7$) was shorter than for all amphibians combined; the number of hotspots in spring and fall was similar (6 and 7, respectively) but was halved in summer, likely due to seasonal movement because Asiatic toads move from mountain to river habitats in spring for breeding and in the opposite direction in fall for hibernation. The length of hotspots for this species was longest in fall (1,036 m). Mean hotspot length (615 m,

$n = 13$) for the red-sided water snake (Fig. 4d) was shorter than for all reptiles combined and was longest in spring (958 m); from spring to fall, hotspot length was 11 and 13 m, respectively, with none in winter due to hibernation.

The spatial pattern of hotspots varied by season and by taxonomic group and focal species (Figs. 3, 4), with hotspots most prevalent along the riverside road due to the many roadkill occurrences of amphibians and reptiles. However, spatial distributions of mammal and bird fatalities were concentrated on the mountainous highway. Roadkill occurrences on the local road were few compared with highway and riverside roads. Across the year, roadkill hotspots for the leopard cat occurred primarily on the local road and were widespread in summer but more spatially clustered in winter; occurrences were concentrated on the local road in fall. Roadkill hotspots of oriental scops owl were concentrated on the highway; those of the Asiatic toad were concentrated on the riverside road with more hotspots found in spring and fall. Hotspots of the red-sided water snake mostly concentrated on the highway and riverside road across the entire year but were widespread in spring.

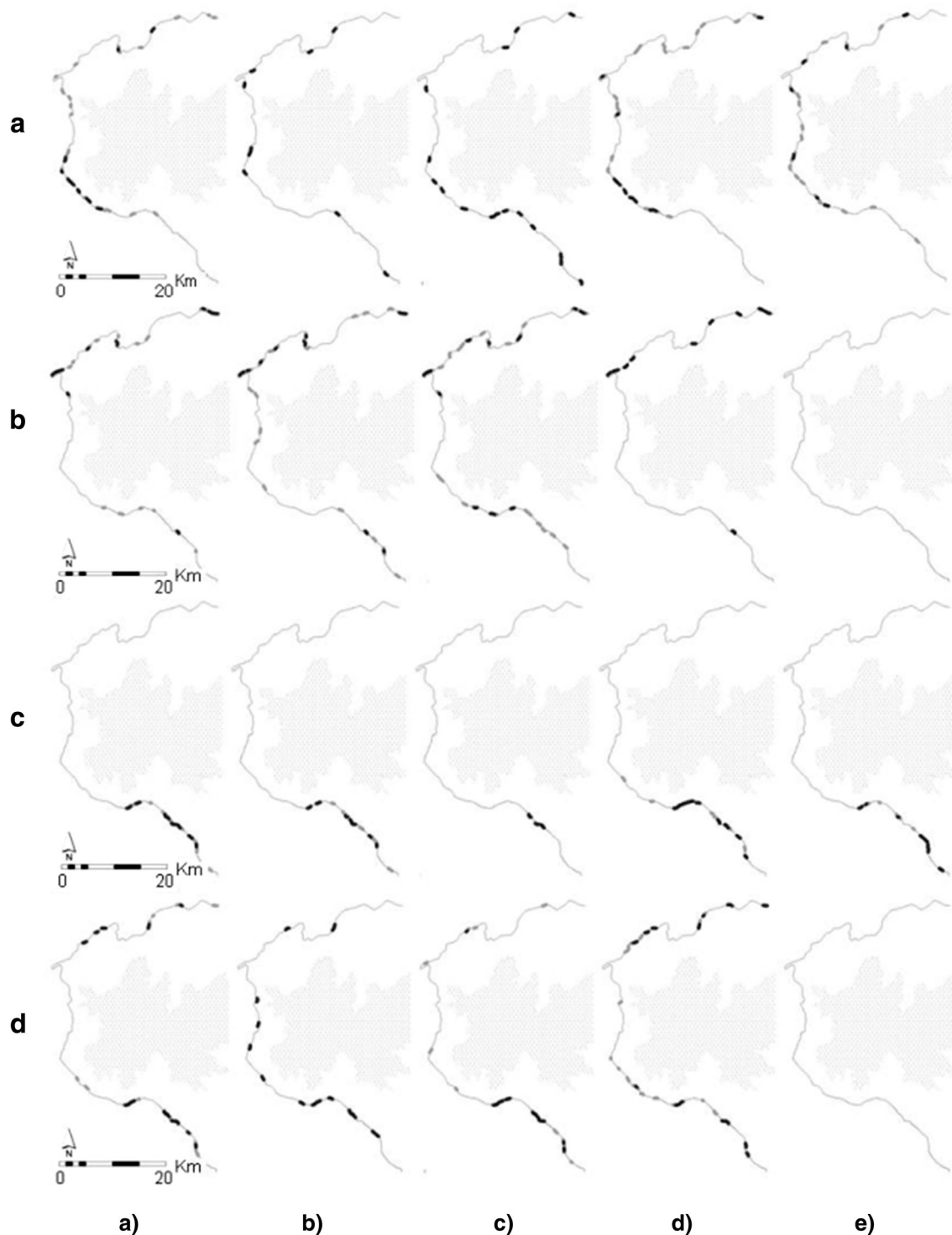


Fig. 4 Seasonal roadkill hotspots of four focal species. **a** Leopard cat (*Prionailurus bengalensis*), **b** oriental scops owl (*Otus scops*), **c** Asiatic toad (*Bufo bufo gargarizans*), and **d** red-sided water snake

(*Rhabdophis tigrinus*). Columns: **a** total, **b** spring, **c** summer, **d** fall, **e** winter. Black segments roadkill hotspots are more spatially clustered ($Z \geq 2$); grey segments are less clustered ($1 \leq Z \leq 2$)

Driving factors for roadkill

Statistically significant site and landscape factors that influence overall roadkill hotspots were a high landscape

percentage of water, low traffic volumes, a high percentage of natural vegetation, a high percentage of rice paddies, an absence of road banking, high roadside grass presence, and an absence of drainage. For mammals,

Table 3 Variable ordering and model assessments

	Total	Mammals	Birds	Amphibians	Reptiles	Leopard cat	Oriental scops owl	Asiatic toad	Red-sided water snake
Number of hotspot road segment	28	28	41	41	50	22	24	22	32
Traffic lane			1–				1–		
Vehicle speed			2+		1–				
Traffic volume	2–	3–		1–				1–	1–
P paddy field	4+		9–	3+	3+	1+	3–		
P dry field		8–			5+			3–	2–
P vegetation	3+				2+		2–		
P built up		6+	8+				5+		4–
P water	1+	1–		5–			4–		
Tree		2+	7+	2+					
Shrub			4+		4+			2+	
Grass	6+	7+	6+			4+			
Mowing		4–	5–		7–				
Median barrier			3+			2+			
Guardrail							7+	4–	
Drainage	7–								
Road curve		10–							
Road slope		5–			5+				
Topography: banking	5–	9–		4–		3+	6–		3–
Topography: cutting									
Topography: mixed									
AIC	29.09	59.33	106.5	69.48	120.9	57.37	60.94	37.92	92.5
CV_ROC (AUC)	0.868	0.798	0.784	0.872	0.833	0.784	0.726	0.849	0.746
CV_kappa (K)	0.715	0.545	0.551	0.730	0.651	0.596	0.491	0.684	0.481
CV_TSS	0.733	0.598	0.579	0.787	0.662	0.590	0.492	0.742	0.499

The number is the sequence of ordering of contribution variables with (+) positive and (–) negative effect

P proportion, *AIC*, *CV*-, *ROC* relative operating characteristic curve, *AUC* area under the ROC, *TSS* true skill statistic

rank-ordered significant factors that increased the risk of roadkill were being far from water, high roadside tree presence, low traffic volumes, less mowing, and low road slopes. A high percentage of rice paddies, median barrier presence, and presence of road banking were the most important roadkill factors for leopard cat. Locations with fewer traffic lanes, high vehicle speed, median barrier presence, high numbers of roadside trees or shrubs in forests and mixed forest–open areas correlated with a high risk of roadkill for birds. Roadkill occurrences of oriental scops owl were correlated with locations where roads crossed lands with less vegetation or rice paddies that had fewer traffic lanes and were close to villages. Amphibian roadkill occurrences were associated with roads near streams, vegetation along the roadside, locations without road banking, near to rice paddies, and areas with low traffic volume. Roadkill of Asiatic toad occurred at similar locations. Reptile roadkill occurrences were correlated with roads having low vehicle speeds and

roadside shrubs that were nearby to forest and agriculture land. Roadkill occurrences of the red-sided water snake were correlated with roads with low traffic volume, far from villages, and without road banking (Table 3).

The final models for taxonomic groups and focal species were built using a multiple logistic regression model with AIC, and model performance was calculated with AUC, *K* statistics, and TSS (Table 3): overall values for total roadkill hotspots were 0.868, 0.715, and 0.733, respectively, and were highest for amphibians (0.872, 0.730, 0.787, respectively), followed by reptiles (0.833, 0.651, 0.662, respectively), mammals (0.798, 0.545, 0.598, respectively), and birds (0.784, 0.551, 0.579, respectively). The Asiatic toad (0.849, 0.846, 0.742, respectively) had the highest value among focal species. The leopard cat (0.784, 0.596, 0.590, respectively) had similar values to those of the Asiatic toad, followed by the red-sided water snake (0.746, 0.481, 0.499, respectively) and oriental scops owl (0.726, 0.491, 0.492, respectively).

Discussion

Spatial patterns of roadkill varied according to taxonomic group, seasonal pattern, road type, and landscape and site factors. We found the majority of mammals and birds were killed on the highway, which passes across a forested mountain range where these groups are residents and have to move for breeding and migration. On the other hand, amphibian and reptile mortality was higher along the riverside road because of breeding and juvenile dispersal near water (Langen et al. 2009). Whereas some of these patterns are similar to what might be expected in other countries, the magnitude of mortality is higher and the spatial patterns are driven by landscape heterogeneity in South Korea. Measuring the patterns and intensity of mortality hotspots permitted the modeling of their driving factors. The resulting information can be used for making more general models of expected mortality hotspots for various species or taxonomic groups and as a general set of guidelines that could be used in developing mitigation practices to avoid roadkill.

Road characteristics and roadkill

Road density for highway, national, and local roads in South Korea is a little higher than in the USA (1.05 vs. 0.68 km/km²) and much lower than in Japan (3.18 km/km²). However, road length per vehicle (5.88 km/1,000 vehicle) is much lower than in the USA (26.45 km/1,000 vehicle) and Japan (15.85 km/1,000 vehicle) (Statistics Korea 2011, IRF 2010). This means that the probability of roadkill is higher in South Korea compared to other countries because of the higher traffic volume. This high traffic volume is a possible contributor to the high rates of roadkill we recorded (Table 2). Amphibians and reptiles drove the high rates along the river. Roadkill rate on the local road was smallest because four-lane roads in rural areas with high traffic volumes may present greater hurdles and thus fewer animals would attempt to cross them; two-lane roads in forests and along the river have a higher incidence of collisions with animals (Hughes et al. 1996). These rates are much higher than those reported in other, roughly comparable, studies we examined, which range from 1.25 to 5.29/km/year for all vertebrates (Clevenger et al. 2003; Taylor and Goldingay 2004), and 0.47/km/year for mammalian mesocarnivores in a Mediterranean system (Grilo et al. 2009) compared with 1.47/km/year for the mesocarnivores in this study. Possible reasons for the high numbers in this study (in addition to traffic volume) include proximity to a national park; animal abundance levels are higher in South Korea than in locations used for other studies; and other human activities in our study region have relatively low impact on the species studied, leading to a greater abundance of animals.

Characterization of roadkill hotspots

Seasonal patterns of vertebrate roadkill were evident for all four taxonomic groups. These patterns are consistent with species' life history, particularly breeding and juvenile dispersal (Davies et al. 1987; Joyce and Mahoney 2001; Clevenger et al. 2003; Conard and Gipson 2006). For example, the leopard cat is more active in summer, and its roadkill hotspots were widely spread at that time; however, occurrences became concentrated and reached their highest levels on the local road in the fall. This road traverses agricultural lands, which comprise a dense network of small rice paddies and vegetable plots, footpaths, and extensive hedgerows or natural vegetation in patches among a large number of small human-constructed waterways. Increased roadkill for this species is possibly due to their prey species being found on these farmlands during harvest time (Rajaratnam et al. 2007).

Bird mortality peaked in July. The overall pattern is likely driven by juvenile dispersal of ring-necked pheasants (Giudice and Ratti 2001) and seasonal migration of other species. Roadkill of oriental scops owl, the bird focal species, peaked in June and continued in summer and fall due to summer migration (Marshall 1978); most occurrences were on the highway, which is near the forest habitat it requires and that essentially forms a barrier from east to west, across the north/south migration routes for this species (Figs. 4b, 5).

Reptile mortality peaked in the fall, potentially due to seasonal migrations and juvenile dispersal (Brito 2003). Roadkill hotspots of the focal species red-sided water snake were concentrated on the riverside road across the entire year but also occurred on the highway in the fall. Hotspots were widespread in spring because these snakes are active after hibernation, when they migrate downhill on mountain slopes; possibly, fall roadkill on the highway represented a return to nesting sites for hibernation (Fig. 4d).

The tripeaked mortalities for amphibians in March, June, and October (Fig. 2) could be due to seasonal migrations of the Asiatic toad for reproduction, juvenile dispersion, and hibernation (Schmetterling and Young 2008); roadkill was nearly exclusive to the riverside road because Asiatic toads have to move to water for breeding.

AUC values of three taxonomic groups were >0.784. This showed that roadkill hotspots of these groups were well detected, and the predictor variables for roadside and landscape factors derived from models described their roadkill characteristics reasonably well. AUC values of three focal species were >0.726 but lower than their respective taxonomic groups, suggesting slightly lower confidence in the results. Roadkill hotspots of the oriental scops owl were found on roads along mountains near villages, but these were not strongly associated with specific predictor variables. Further

studies on the behavioral characteristics of target species and carrying capacity of the land for different species are needed to enhance the low AUC of some target species.

Implications for roadkill mitigation

The importance of reducing the impact of roads on wildlife is well recognized in South Korea. As part of the National Ecological Network Plan (Ministry of Environment 2007), >317 wildlife crossing structures have been built or retrofitted since 1998, including 147 overpasses and 170 underpasses. These crossings were built by three agencies: 153 crossings on the national roads by the Ministry of Construction and Transportation, 119 on local roads by local governments, and 45 on the highways by the Korea Expressway Corporation (Ministry of Environment 2011).

This study shows that ongoing roadkill mitigation efforts can anticipate seasonal patterns of animal movement as they progress through their yearly cycle. These movements are dictated by the Korean Peninsula's strong seasonal weather patterns. For example, considerations about where to place additional wildlife crossing structures or to modify existing infrastructure can use the hotspot analysis to identify locations that optimize safety for multiple taxa or that target specific migration locations (Fig. 5). In addition, predictor variables that proved important in the model should be used to determine crossing locations outside the study area by identifying the types of locations that are most suitable. As long as target species and road types are similar and predictor variables are available or can be measured, a model could be constructed for most of South Korea.

The study also suggests ways in which South Koreans can improve local-level roadkill mitigation practices. Roadkill hotspot locations and identification of disconnected

wildlife habitats can be evaluated in geographic information systems (GIS) by branch offices of the Road Maintenance Bureau to create metrics of road crossing “demand” and

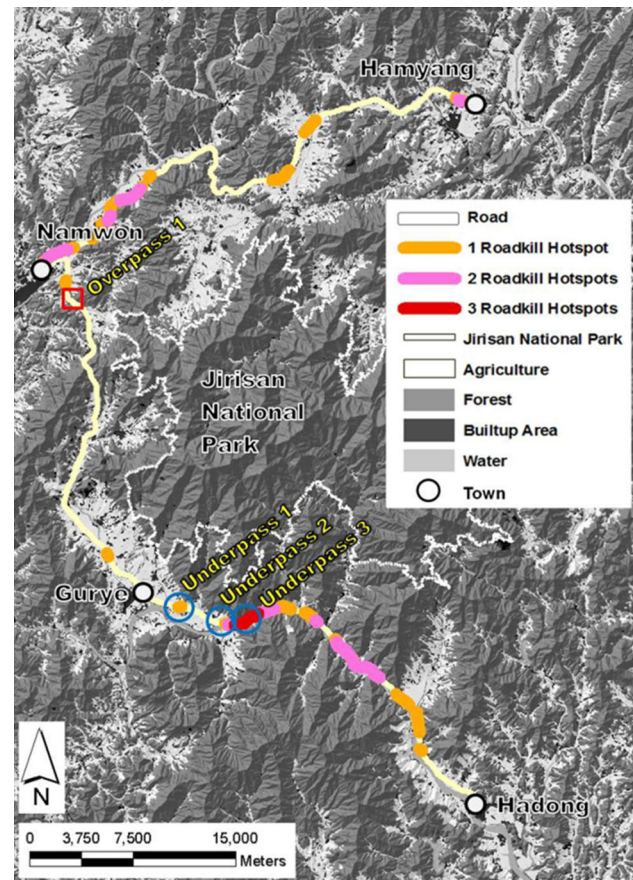


Fig. 5 Congruence map summing roadkill hotspots of the four taxonomic groups and four wildlife crossings, which were constructed by local governments as a result of this research



Fig. 6 Four wildlife crossings constructed as a result of this study: **a** Overpass 1 crosses from hill to hill where a mammal roadkill hotspot occurred on local road 19. **b** Underpass 1, located across the edge of agricultural land and mountains, is under construction. **c** Underpass 2 is a crossing on the riverside road that links the upland,

a habitat to the river, where mammal, amphibian, and reptile roadkill hotspots occurred. **d** Underpass 3 has three subunderpasses that go under a road; an exclusion fence has also been installed along the road to guide wildlife to the underpass

evaluate ongoing mitigation efforts in terms of location and function. In the study area, presentation of these results to transportation officials led to the construction of four wildlife crossing structures on the study road (Fig. 6), one of which is being monitored with heat sensor cameras.

Eight natural monument species and seven endangered species (including five natural monument species) were killed during this study. Mortality totals for two endangered species, the leopard cat and oriental scops owl, were >100, emphasizing a need to consider mitigation options for these protected species, even if background rates of demographic condition are not known. Further studies on these species are needed to determine whether wildlife crossings, exclusion fences, vegetation management, or other mitigation measures are effective.

Conclusion

This study provides roadkill information from an intensive 2.5-year survey near a South Korean national park in north-eastern Asia, a region for which road impacts have not yet been reported. The study represents a significant improvement over previous, presence–absence analysis methods through a roadkill hotspot analysis that used the Getis–Ord G_i^* statistic. However, there were some limitations, including the number of replicates for a comparative study of road types, the use of the same landscape factors for different taxonomic groups, and that few studies were available addressing the phenology of wildlife in South Korea. Future work is necessary to focus on: (1) extending the study to include replicates of the three road types, and possibly other classes of roads; (2) reclassifying landscape factors according to taxonomic groups and habitat types; and (3), improving the roadkill hotspot analysis through the calibration of parameters according to taxonomic groups and species characteristics. Ultimately, we hope these findings can inform countries that have similar landscapes to develop avoidance, minimization, and mitigation practices to lower the impact of roads on wildlife.

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