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Long-term data reveals increase in vehicle collisions of endangered birds in Hokkaido, Japan

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Abstract

Wildlife-vehicle collisions have significant consequences for both humans and animals, including injuries, deaths, and vehicle damage. Therefore, analysis of accident data is important for planning countermeasures and appropriate wildlife management. In this research field, roadkill incidents have been extensively studied in many taxa, while railway accidents have received less attention despite their obvious impact on wildlife. Here we applied a Bayesian state-space model to 31 years of collision data, both on railways and on roads, collected by the Ministry of the Environment in Hokkaido prefecture, Japan, to reveal the spatiotemporal dynamics of accidents for white-tailed eagles, Steller's sea eagles, and red-crowned cranes, for which over hundred accidents were reported in the data. Our analysis suggested that the mean annual number of individuals collected per collision site across Hokkaido increased 47,377-fold in the white-tailed eagle, 40,277-fold in the Steller's sea eagle, and 50,584-fold in the red-crowned crane between 1991 and 2021. There have been concerns about the impact of traffic accidents on the population dynamics of these endangered birds, but no formal analyses have been conducted. Our analysis showed numerically that the negative impact has been increasing annually. These results suggest that long-term data accumulation over large spatial scales allows us to understand the dynamics of accidents and predict potential factors underlying collision risks.

KEYWORDS

Grus japonensis, *Haliaeetus albicilla*, *Haliaeetus pelagicus*, seasonality, time-series analysis, wildlife-vehicle collisions

1 | INTRODUCTION

Wildlife-vehicle collisions account for deaths of millions of animals across the globe. In the United States, it is estimated that at least 350 million vertebrates are killed

Kazuya Kobayashi and Annegret Moto Naito-Liederbach equal contribution.

every year on the road (Forman & Alexander, 1998; Seiler & Helldin, 2006), and in Europe 194 million birds and 29 million mammals are killed annually on the road (Grilo et al., 2020). Although raw counts of roadkilled corpses are thought to grossly underestimate the actual number of animals killed (Slater, 2002), such data can inform conservation, behavior, and ecology of affected species (Coffin, 2007). For example, certain taxa, populations, and individuals are more susceptible to vehicle collisions than others (e.g., Ceia-Hasse et al., 2017; Fahrig & Rytwinski, 2009; Grilo et al., 2020). Factors affecting collision risk include population size and density (Ceia-Hasse et al., 2017; Mayer et al., 2021), diet and food availability (Cook & Blumstein, 2013; Ford & Fahrig, 2007; Klöcker et al., 2006), landscape/land use (Fabrizio et al., 2019; Filius et al., 2020), and more.

Moreover, data on wildlife-vehicle accidents can be analyzed to infer spatiotemporal distributional changes and population trends of species (Baker et al., 2004; Canova & Balestrieri, 2019; George et al., 2011; González-Gallina et al., 2015). For example, comparing collision counts within and between years may provide insights into seasonal and long-term changes in population dynamics. Crucial information for extinction risk assessment and conservation management of populations, such as distribution, abundance, and density (McShea, 2014; Pressey et al., 2007), can also be estimated from vehicle-collision data. Such data is increasingly being used by ecologists and conservation practitioners for modeling spatiotemporal trends in various populations, especially because traditional surveys of these indices over long-term and large spatial scales tend to be labor-intensive and costly (Lyra-Jorge et al., 2008).

To date, roadkill has been extensively studied across many taxa (Schwartz et al., 2020). Railway accidents, hereafter railkill, on the other hand, have received less attention in the literature, despite their apparent impacts on wildlife (Dorsey et al., 2015; Nezval & Bíl, 2020; Reck & Schmüser, 2021). Although this lack of research is being increasingly addressed over the last decade, many studies tend to focus on large mammals (Santos et al., 2017). This is not only because they are more easily noticed by their size, but they also are more likely to cause damage to trains, which increases the demand for a better understanding of collisions. Limited research has been conducted on collisions between trains and birds, but several studies point out the variability of risks across ecological contexts (Godinho et al., 2017), and their potential effects on threatened species (Khatri et al., 2020). Studies addressing long-term trends are also scant, especially in the context of railkill, perhaps due to the lack of records and fewer citizen science projects.

In this study, we analyze 31 years' worth of injured and dead bird records on Hokkaido, a large island in northern Japan, to better understand the effect of both roads and railroads on avian populations over spatiotemporal scales. We focus on three endangered species—the white-tailed eagle (*Haliaeetus albicilla*; Accipitridae, Accipitriformes), Steller's sea eagle (*H. pelagicus*), and red-crowned crane (*Grus japonensis*; Gruidae, Gruiformes). The white-tailed eagle has been generally a winter bird of northern Japan, but recently its breeding population is increasing on Hokkaido: About 700–1000 individuals winter in Japan (MoE & WGWS, 2021), and as of 2009, there were 150 breeding pairs, but breeding success remains low (Shiraki, 2013). This species distributes throughout northern Eurasia and is listed as least concern by the IUCN (BirdLife International, 2023a, 2023b, 2023c), but in Japan, it is classified as vulnerable (MoE, 2020). The Steller's sea eagle also winters in Japan, with an estimated wintering population of 1400–1900 individuals mainly on Hokkaido (MoE & WGWS, 2021). They are known to only breed in far east Russia, including Kamchatka peninsula and Sakhalin Island, and are listed as vulnerable by the IUCN (BirdLife International, 2023a, 2023b, 2023c). The domestic population in Japan is also classified as vulnerable, like the white-tailed eagle (MoE, 2020). The red-crowned crane is listed as endangered by the IUCN and vulnerable by the Japanese government (MoE, 2020). The global population is estimated to be around 3000, of which over 1800 individuals reside in Japan (Masatomi & Surmach, 2018; RCC, 2023). The Japanese population, which was thought to be extinct until it was rediscovered in 1924, breeds and migrates only within eastern Hokkaido (Masatomi, 2000). Since its rediscovery, intensive conservation efforts are being carried out, especially in eastern Hokkaido, to monitor and increase the population.

For all three of these species, vehicle collisions are identified as a conservation threat by the Ministry of the Environment, but accurate quantification and utilization of road/railkill data are still limited. The aim of this study is to (1) estimate the rates of vehicle-collision incidents of each species during the past 31 years, (2) detect and predict the locations and seasons of wildlife-vehicle accident occurrences, and (3) understand interspecific differences and common tendencies by adapting the same model to the ecologically distinct three species.

2 | MATERIALS AND METHODS

To address these aims, we analyzed data on rescued live birds and recovered dead birds (henceforth, "collected," to refer to both live and dead individuals) on Hokkaido

Island. The dataset, provided by the Ministry of the Environment Hokkaido branch, includes road and rail accidents that occurred from January 1991 to November 2021. For each of the species of bird collected, location and date data were used for Bayesian modeling in R (ver.4.2.1) and CmdStan (ver.2.32.2) via cmdstanr (ver.0.5.3). To investigate the relationship with the surrounding land use, the location data was transformed into grid data. Each grid has a latitude difference of 5 min and a longitude difference of 7 min and 30 s, so the length of one side is about 10 km. This method divided Hokkaido Island into 970 grids. For the analysis of spatial patterns, we used the land use data as explanatory variables, with road length and railway area as offset terms. The data was obtained from the website of National Land Information Division, National Spatial Planning and Regional Policy Bureau, Ministry of Land, Infrastructure, Transport, and Tourism of Japan (https://nlftp.mlit.go.jp/ksj/gml/datalist/KsjTmplt-N04.html, N04-10 series, accessed 8 December 2023, and https://nlftp.mlit.go.jp/ksj/gml/datalist/KsjTmplt-L03-a-v3_1.html, L03-a-16 series, accessed February 6, 2023), and consisted of road length (m) and area (m^2) of forests, wastelands, paddy fields, farmlands (excluding paddy fields), buildings, rails, lakes, beach, sea, golf courses, and other sites. These areas were summed for each of the above grids. In addition to the land use data, latitude, longitude, distance to the sea for each of the grid, and 14 regional divisions of Hokkaido as dummy variables, were also used as explanatory variables to detect regional characteristics that cannot be explained by the land use data alone. Thus, we used 27 explanatory variables to estimate the location effect. Because these explanatory variables were in different units and greatly differed in their means and variances, the data was standardized to mean = 0 and variance = 1, respectively. The length of roads was used as an offset term in the analysis of roadkill data. Similarly, the area occupied by railways was used as an offset term in the analysis of railkill data. This resulted in the exclusion of 22 grids containing neither roads nor rails, leaving us with 948 grids with roads and 264 grids with railways in the analysis. All grids containing railways also contained roads, while no grids contained only railways. Before analyzing these data, we checked collinearity among the explanatory variables. In descending order of absolute values, the correlations were between forest and sea (−0.6812), buildings and others (0.5628), and latitude and the Soya region (0.5628). These correlation coefficients suggested that including these variables in the analysis would not greatly misinterpret the effect size of the analysis. All of the data we used are provided as (Appendices S1 and S2).

These data were analyzed by a Bayesian hierarchical Poisson model. By using the constraint that the rate of an accident in a given year is close to that of the previous year, we estimated the annual accident rates while minimizing the difference between the estimated rate and the actual number of accidents observed per year. In addition, this time-series annual rates are constant regardless of location, and the spatial variation is estimated based on information such as land use, allowing us to estimate the temporal and spatial trends in a single model. Based on these constraints, accident rates were estimated for all grids including regions where no incidents were observed during the 31 years, without having to consider population dynamics.

Let $N_{t,g}$ be the number of collected individuals at time t ($t = 1, \ldots, 370$, corresponding to elapsed months since January 1991 to November 2021) in a grid g ($g = 1, \ldots, 948$), and expressed as follows:

$$N_{t,g} \sim \text{Poisson\_log}\left(\alpha_{t,g,\text{road/rail}}\right),$$

$$\alpha_{t,g,\text{road}} = P_y + S_t + L_g + \log(L_{\text{road}}).$$

$$\alpha_{t,g,\text{rail}} = P_y + S_t + L_g + \log(A_{\text{rail}}).$$

where $\alpha_{t,g,\text{road}}$ and $\alpha_{t,g,\text{rail}}$ is the logarithm of the mean number of collected individuals in each grid each month on roads and on rails, respectively, P_y is the effect of the year y ($y = 1, \ldots, 31$, corresponding to elapsed years since 1991–2021), S_t is the seasonal effect at time t, and L_g is the location effect on grid g. $\log(L_{\text{road}})$ and $\log(A_{\text{rail}})$ are the offset terms to account for road lengths and railway area, respectively, in each grid. We used a first-order autoregressive model for P_y as follows:

$$P_y \sim \text{Normal}\left(P_{y-1}, \sigma_p\right),$$

where σ_p is the scale of change in the time-series data. Prior distributions of any σ in this paper, such as σ_p, are assigned a half-Student-t distribution, i.e., $\sigma \sim$ student_t (4, 0, 1), $\sigma \in \mathbf{R}+$. Incidents were not recorded before 1991, which suggests very low probability of incidents for this time period; thus we assigned a normal prior distribution with a negative mean and sufficiently large variance to the first data point P_1, i.e., $P_1 \sim \text{Normal}(-15, 10)$, which gives about a 6.6% chance that P_1 is positive. Note that a positive P_1 means that one or more incidents are reported on each grid on average in 1991. S_t was modeled as the effect of the month regardless of the year, and the difference from the next month and the total of the effects follow the standard normal distribution, that is.

$$S_t = M_{((t-1)\%12)+1},$$

$$M_{1,\ldots,12} \sim \text{Normal}(0, \sigma_m),$$

$$M_{1,\ldots,11,12} - M_{2,\ldots,12,1} \sim \text{Normal}(0, 1),$$

$$\Sigma M \sim \text{Normal}(0, 1),$$

where $M_{1,\ldots,12}$ is the seasonal effect corresponding to each month (January to December) and σ_m is the scale of seasonal variation. L_g was modeled by a simple linear regression as follows:

$$L_g = \boldsymbol{x}_g \boldsymbol{\beta},$$

where $\boldsymbol{x}_g$ is a row vector consisting of 29 explanatory variables for the grid g and $\boldsymbol{\beta}$ is a vector of coefficients and assigned a normal prior distribution, $\boldsymbol{\beta} \sim \text{Normal}(0, \sigma_b)$. In practice, we used $\boldsymbol{L} = \boldsymbol{x}\boldsymbol{\beta}$, where $\boldsymbol{L}$ is a vector representing the location effect of 970 grids and $\boldsymbol{x}$ is a matrix with 970 rows corresponding to grids and 29 columns corresponding to the explanatory variables. The source code of this model and commands for R are available in Appendices S4 and S5, respectively.

For Bayesian inference, we used the Markov Chain Monte Carlo (MCMC) method through the CmdStan. We ran four parallel MCMC chains, retained 1000 sample iterations after an initial warmup of 5000 iterations, and set adapt_delta as 0.95. Other parameters were left as default. Convergence of MCMC sampling was judged by Rhat values (Vehtari et al., 2021) and by a check of the MCMC trace plots. The Rhat values of our estimated parameters were all under 1.01.

3 | RESULTS

The data provided by the Ministry of the Environment included a total of 465 individuals collected: 150 white-tailed eagles, 102 Steller's sea eagles, 198 red-crowned cranes, and 15 individuals of other species. For each data, the date and time of collection, longitude, latitude, species name, incident type (road/rail), alive/dead at time of discovery, age (adult/nonadult), and sex were recorded. Because detailed habitat information of these endangered species cannot be disclosed, latitude and longitude were replaced by grid indexes in Appendix S1. Roadkill and railkill were reported in 77 and 73 cases for white-tailed eagles, 33 and 68 cases for Steller's sea eagles, 123 and 75 cases for red-crowned cranes, respectively. All three species were collected mainly in eastern Hokkaido (Figure 1). In particular, the red-crowned cranes were highly skewed toward Tokachi and Kushiro regions.

Bayesian models showed a general increase in the number of collected individuals over time for all three of the species analyzed, although the rate of increase varied by species (Figure 2). Posterior means and 95% credible interval (CI) estimates on a natural logarithmic scale for the effects of 1991, P_1, and those of 2021, P_{31}, were -24.136 (-26.686 to -22.229) and -13.370 (-18.003 to -6.997) for the white-tailed eagle (*H. albicillus*), -25.151 (-27.775 to -23.182) and -14.548 (-19.607 to -7.972) for the Steller's sea eagle (*H. pelagicus*) and -25.053 (-27.109 to -23.524) and -14.222 (-19.717 to -7.197) for the red-crowned crane (*G. japonensis*), respectively. In other words, in the case of the white-tailed eagle, for example, the estimated mean number of collisions per site, per month, per unit road length or rail area increased from about 3.295×10^{-11} in 1991 to about 1.561×10^{-6} in 2021. These estimates indicate that the posterior mean number of annually collected individuals in Hokkaido increased 47,377-fold (95% CI: 247.7–3.070×10^7) in the white-tailed eagle, 40,277-fold (140.6–3.558×10^7) in the Steller's sea eagle, and 50,584-fold (209.4–5.085×10^7) in the red-crowned crane between 1991 and 2021. A more detailed list of estimates is provided in Appendix S3.

For the seasonal effects, posterior mean and 95% CI estimates showed relatively similar patterns between the two eagle species compared to the red-crowned crane (Figure 3). The estimates of white-tailed eagles, which are mostly winter birds in Japan but also breeding on Hokkaido (Shiraki, 2013), showed that the collection rate increased in the winter, December to March, and decreased in May, June, September, and October. The Steller's sea eagles, which are also winter birds and have no breeding populations on Hokkaido (Meyburg et al., 2020), were estimated to be collected at higher rates in the winter, December to March, and at lower rates in the summer, June to October. Estimates for red-crowned cranes, which have little seasonal migration, were largely non-seasonal, with slightly increased collection rates in October.

Collection rates of all three species were greater at higher longitudes, while latitudes did not appear as an evident effect. Distance to the sea had a strong negative effect (Figure 4a–c). A slight positive effect of lakes, slight negative effects of paddy fields, farmlands, and buildings were observed for the white-tailed eagle (Figure 4a). For the Steller's sea eagle, paddy fields and areas designated as "other" by the National Land Information Division database (i.e., land use types not corresponding to the

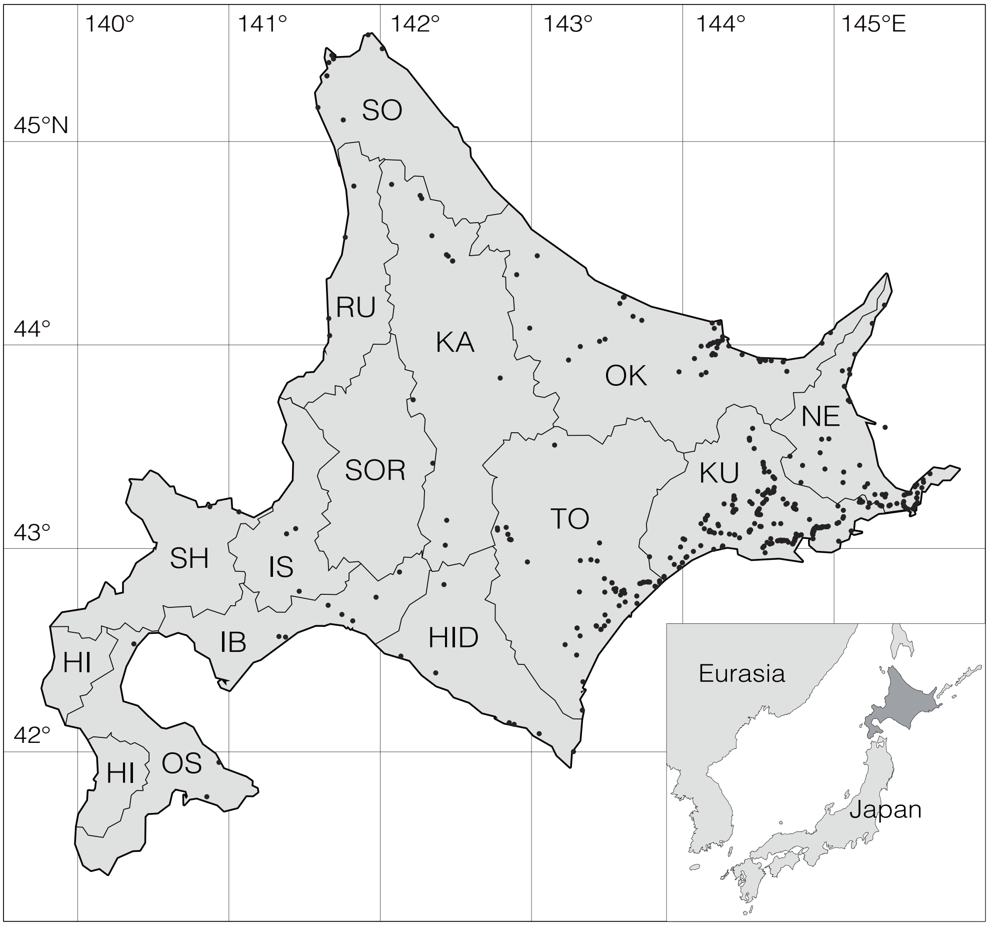

FIGURE 1 Map of Hokkaido Island with collection locations of white-tailed eagles, Steller's sea eagles, and red-crowned cranes involved in vehicle collisions shown as black dots. Abbreviations for each regional division, HI, Hiyama; OS, Oshima; IB, Iburi; SH, Shiribeshi; IS, Ishikari; RU, Rumoi; HID, Hidaka; KA, Kamikawa; SO, Soya; SOR, Sorachi; OK, Okhotsk; TO, Tokachi; KU, Kushiro; NE, Nemuro.

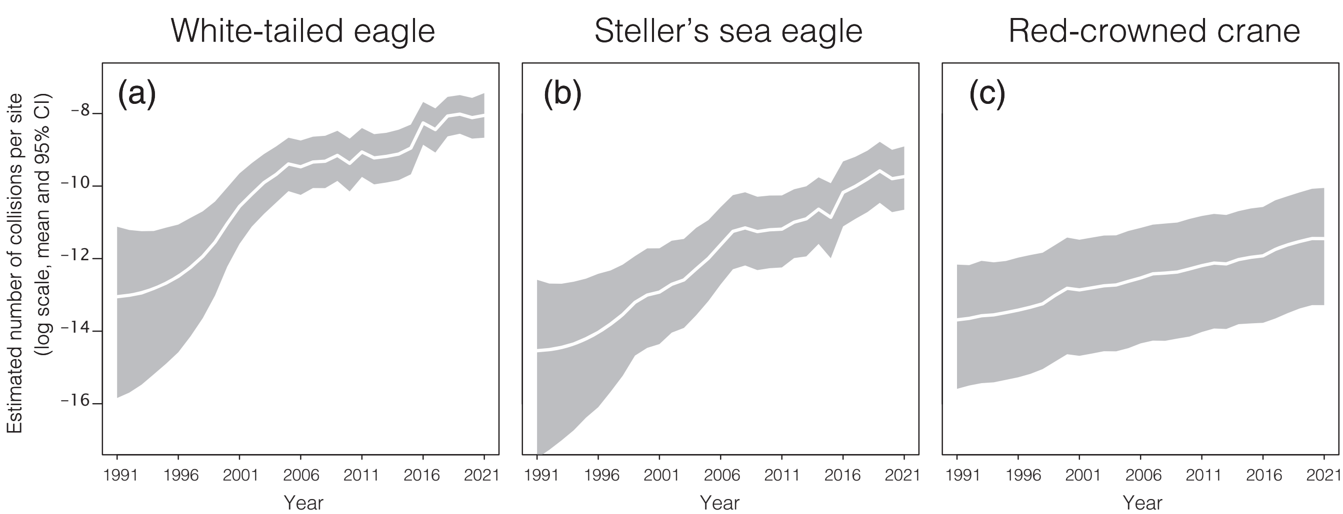

FIGURE 2 Posterior means and 95% CI estimates of the logarithmic number of collected individuals for (a) white-tailed eagles, (b) Steller's sea eagles, and (c) red-crowned cranes over time at log scale (P_y).

other categories are assigned to "other") showed negative effects with relatively broad 95% CI (Figure 4b). For the red-crowned crane, lakes were detected to have the strongest positive effect among land use types, while areas designated as buildingsand beaches had negative effects on collection rates. The effect of regional divisions on collections was obscure for either raptor species (Figure 4d,e), while higher collection rates were detected in Kushiro and Tokachi for the red-crowned crane (Figure 4f).

These patterns correspond to the general spatial patterns shown in Figure 5. For the white-tailed eagle

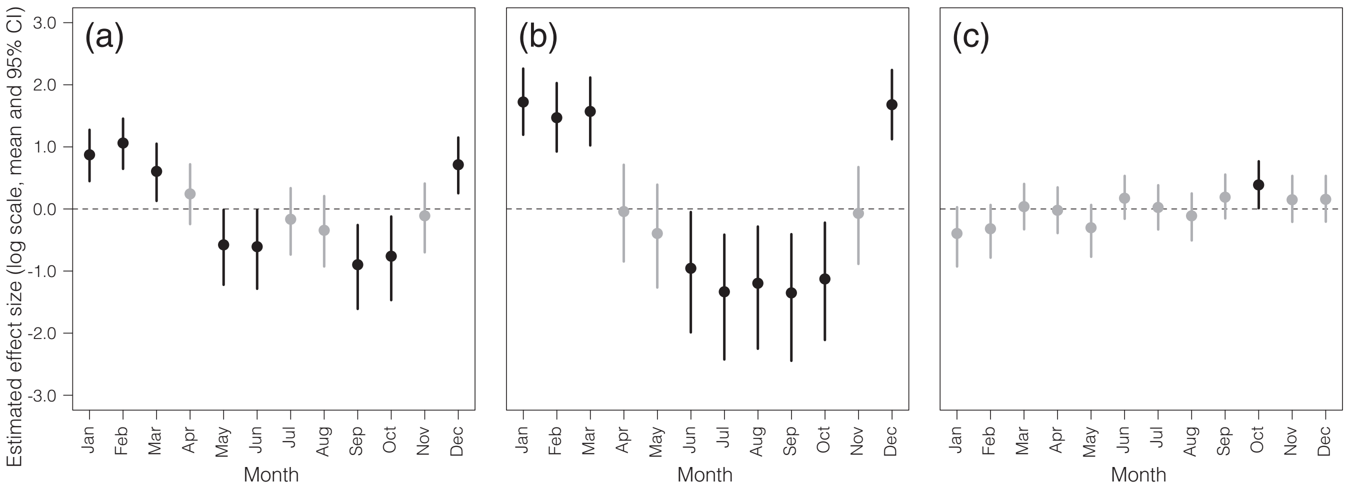

FIGURE 3 Posterior means and 95% CI estimates of collection rates of (a) white-tailed eagles, (b) Steller's sea eagles, and (c) red-crowned cranes in each month (seasonal effects: $M_{1,\ldots,12}$). The difference in color of dots and bars corresponds to whether the respective 95% CI includes zero or not.

(Figure 5a), areas where high collection rates were estimated were concentrated in the east until 1996, but began to spread to north and south Hokkaido from the year 2001. High collection rates in the inland (central Hokkaido) began to increase as well from the year 2006, but to a lesser extent compared to coastal areas. After the year 2011, areas with high collection rates spread across the island, except in several locations in the west. The gradual increase of incident rates west of the Ishikari and Iburi regions (denoted in Figure 1 as IS and IB, respectively) was notable as well. Collection rates of Steller's sea eagle (Figure 5b) followed a similar pattern with that of the white-tailed eagles, but generally had fewer cases, with almost no notable increases in the Oshima peninsula (the region denoted in Figure 1 as OS and HI) and around the Ishikari Plain (around the region denoted in Figure 1 as IS). Another difference with the white-tailed eagle is the disproportionate increase of collection rates of Steller's sea eagles in one area near the northern tip of Hokkaido after the year 2006. Throughout all time points, it appears that raptors are most often collected in eastern Hokkaido. Red-crowned crane incidents also increased spatiotemporally but are mainly restricted to the Pacific Ocean side of eastern Hokkaido (Figure 5c), corresponding to the abovementioned effect of regional divisions (Figure 4f).

4 | DISCUSSION

Our analyses showed that rescued and recovered individuals increased over time for all three species, with species-specific differences in the rates of increase and location effects. Our analysis is based on observational data and does not directly examine causal relationships, thus does not directly identify the causes of accidents, but it may help to infer the underlying reasons.

4.1 | Temporal trends

The increase of collection rates over the 31 years, as shown in Figure 2, can be a result of the following three possibilities: (1) an increased probability of an individual being involved in a vehicle-collision incident, (2) an increased population size, resulting in a higher number of total incidents even without an increase in incident probability per individual, and (3) an increased proportion of incidents reported to the Ministry of the Environment. All three cases are possible and not mutually exclusive, but cannot be disentangled by our analyses. There are, indeed, reports of increasing population sizes of the white-tailed eagles (MoE, 2022; Shiraki, 2013) and red-crowned cranes (Hokkaido Prefecture, 2023). Public awareness may also be increasing (Sueji & Hioki, 2018), which could be resulting in improved road/railkill reporting efforts. If reporting numbers do, in fact, play a significant role in this increase, it would mean that a significant number of collisions went unnoticed over the past decades, and that improvements in reporting efforts by government and citizen science can significantly enhance our understanding of the effects of vehicles on wildlife. Whether the actual probability of accidents per individual increased remains unresolved. However, the prefecture of Hokkaido has reported increased sika deer accidents, especially on

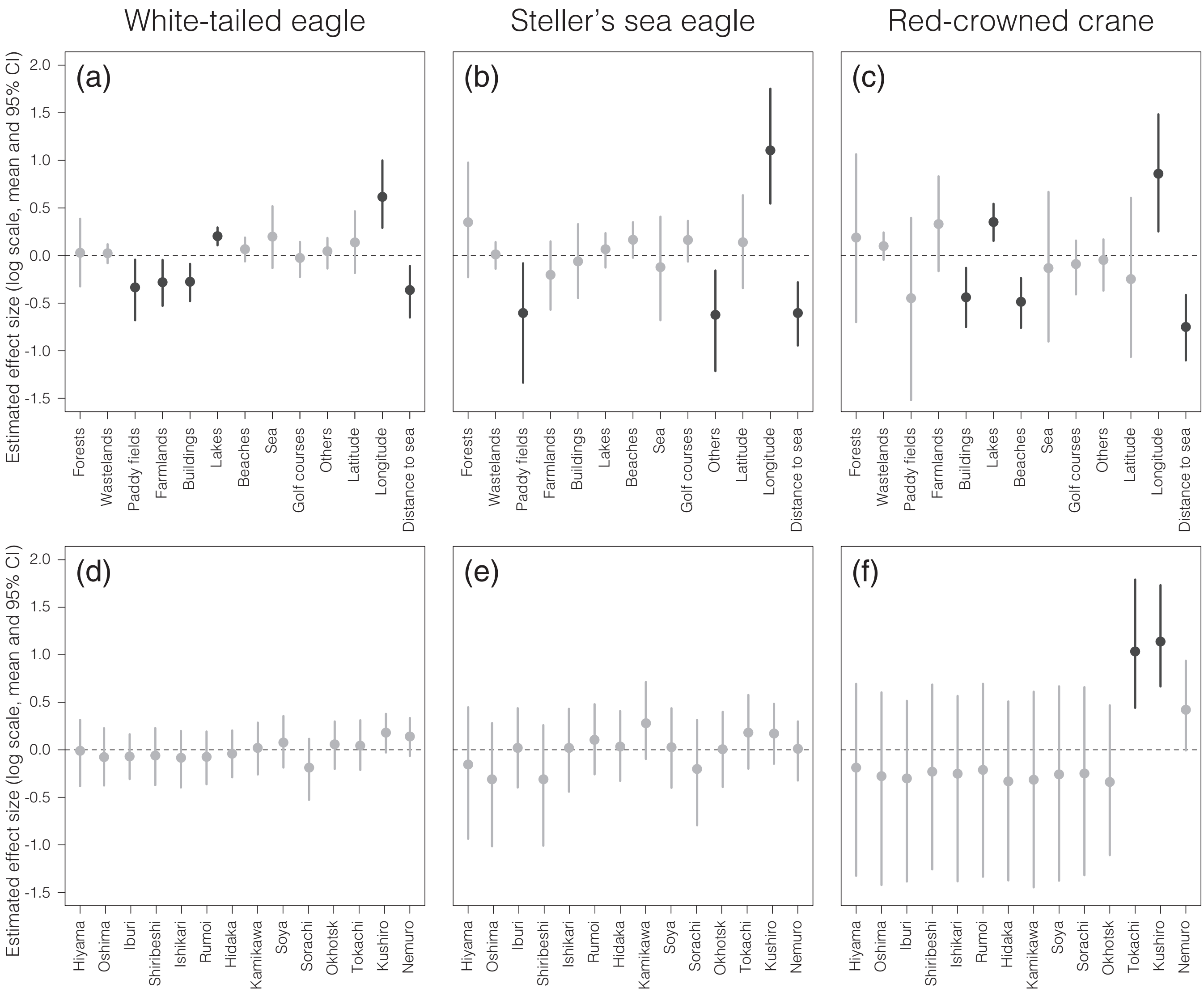

FIGURE 4 Posterior means and 95% CI estimates for the effect of land use types (top row), and regional divisions (bottom row) on the collection rates of (a, d) white-tailed eagles, (b, e) Steller's sea eagles, and (c, f) red-crowned cranes. The difference in color of dots and bars corresponds to whether the respective 95% CI includes zero or not.

railroads (Hokkaido Prefectural Police, 2023), which may be attributed to the increased deer population (Hokkaido Regional Development Bureau, 2011). This is suggested to contribute to heightened rates of secondary railkill for white-tailed eagles and Steller's sea eagles, which are facultative scavengers (MoE, 2022; News, 2023). It has been suggested that aerial predators scavenge on roadkilled carcasses (Hubbard & Chalfoun, 2012), and Cuyckens et al. (2016) found raptors to be the most commonly roadkilled bird in northwestern Argentina, likely due to scavenging. Although empirical studies about secondary railkill are scant, a study from Germany suggested that collisions between trains and white-tailed eagles, which also happens to be the most dominant anthropogenic cause of mortality for this species in Germany, is a result of scavenging on railkilled carcasses (Krone et al., 2002). In Japan, no quantitative evidence is available to explain any relationships between deer populations and eagle-vehicle collisions. To clarify the relative effects of these potential mechanisms, some additional data, such as population count data for three bird species, deer population distribution, and the number of traffic accidents of deers, are useful.

4.2 | Seasonal patterns

The effect of seasons showed species-specific patterns, but relatively similar patterns between the two eagle species compared to the red-crowned crane, as anticipated from the differences in respective breeding and migratory ecology. The two eagles, which winter in Japan, show a

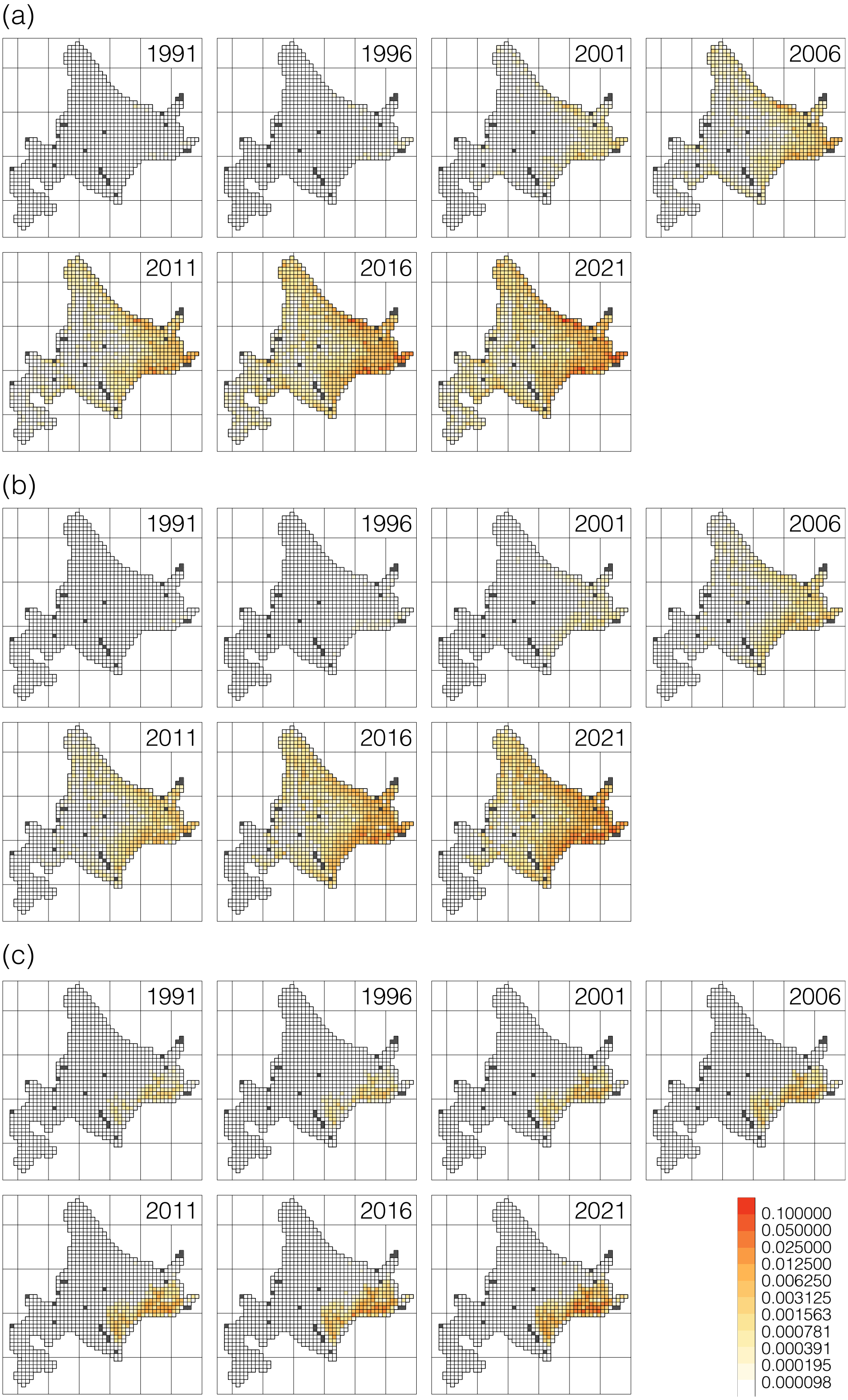

FIGURE 5 Spatial distribution of collection incidents for white-tailed eagles (a) Steller's sea eagles (b) and red-crowned cranes (c) predicted for the years 1991, 1996, 2001, 2006, 2011, 2016, and 2021. Possibilities per month are expressed with colors, as described by the bar on the lower right. Black grids indicate areas without roads and rails.

clear seasonal pattern of the increased collection rates from December to March, possibly due to their high occurrence during this period. That being said, the number of non-migratory white-tailed eagles is increasing on Hokkaido (Shiraki, 2013), and even to areas on Honshu Island, south of Hokkaido (Yoshioka et al., 2017). Although they occur in greater numbers in the winter, the presence of breeding pairs and their offspring could be contributing to some collision incidents in the summer months. This would also explain the slightly higher incident rates relative to the Steller's sea eagle between June and October. In contrast to the eagles, red-crowned cranes are sedentary species in Hokkaido (Archibald et al., 2020), which explains the non-seasonal pattern observed in our analysis. They do, however, migrate within eastern Hokkaido from their breeding to wintering grounds in autumn, and back to their breeding areas in the spring (Archibald et al., 2020). The slight positive incident increased collection rate in October could be highlighting this regional migration of an enlarged population with the addition of individuals born that year.

4.3 | Spatial trends and effects of land use

The spatial increase, mostly for the eagles, may be explained by (1) range expansion, (2) increased population size, and (3) improvements in reporting efforts. Again, these factors are mutually non-exclusive, especially for the first and the second factors, because increased population size could result in greater dispersal to avoid overcrowding of habitats. In the case of the white-tailed eagle, the breeding population is said to have grown (Shiraki, 2013), and the wintering population has also gradually increased over several decades (MoE, 2022). It has also been suggested that the wintering Steller's sea eagles have spread from the coastal regions to interior Hokkaido, especially after 1995, which is attributed to the decline of cod and increased number of sika deer carcasses left by hunters (Nakagawa, 2009; Ueta et al., 2003; WGWS, 1996). These changes in population size and distribution could be contributing to the increase in vehicle accidents of sea eagles.

Our analysis showed that collection rates in all species were positively associated with longitude, and negatively associated with the distance to the sea, indicating the prevalence of cases in eastern Hokkaido, especially along the coast. This corresponds with the reported species distributions—i.e., the chances of encountering an injured/deceased eagle or crane are simply higher than in areas where they do not inhabit in great numbers. This is especially clearly seen in the red-crowned cranes, which mainly inhabit the Kushiro and Tokachi regions, as seen in Figure 3c. The negative effect of paddy fields in the eagles might be explained by distribution as well, because paddy fields are mainly found in western Hokkaido, where the eagles inhibit only at low densities—i.e., the negative effect would be due to a pseudo-correlation, and not reflect a causal relationship between paddy field area and incidents. The same can be said for farmlands in white-tailed eagles. The negative effect of buildings on accident rates of white-tailed eagles and red-crowned cranes may be because both species do not inhabit urban areas, namely in the western areas including the prefectural capital, Sapporo. In contrast, the positive effect of lakes on collision rates of white-tailed eagles and red-crowned cranes may be reflecting their habitat choice—although both species may not directly utilize the lakes, the marshlands, plains, and forests surrounding these lakes may be providing suitable habitats for these species. In fact, there are large lakes in eastern Hokkaido that overlap with both species' distributions. In the case of the Steller's sea eagle, the category of "other" areas had a significantly negative effect size. Although this land use type showed slight collinearity with building area, specific information on the types of landforms/land use is lacking. Therefore, more precise information is necessary to be able to further discuss the implications of this result.

5 | CONCLUSIONS

In this study, we successfully predict spatiotemporal trends of vehicle collisions for three endangered species of birds, the white-tailed eagle, Steller's sea eagle, and the red-crowned crane, using long-term incident records. The vast quantity of records accumulated over 31 years, combined with Bayesian modeling, enabled us to infer patterns and trends of vehicle collisions, despite the low frequency of incidents—only about 1–2 individuals, maximum of 3 individuals, are involved in collisions per month per species. Our study presents a rare example of utilization of multi-decade road/railkill data and complex statistical modeling with practical applications toward ecology and conservation of endangered species. This type of study is especially lacking in Asia. The results also highlight the importance of long-term collection and curation of accurate records.

Although we were unable to discern the exact cause, we found a clear increase in the number of reported incidents for all species. Future research should integrate population dynamics of each species into models to evaluate a relationship between collision rates and the number of individuals in a given area. Combining analyses of deer accidents could also elucidate possible mechanisms of secondary road/railkill, particularly for scavengers. Results also show that land use and seasonal patterns reflected, at least partially, each species' biology, namely habitat use, breeding and migratory behavior, implying the effectiveness of road/railkill data for understanding species distributions and ecology. This aspect of utilizing long-term incident records could potentially be useful for monitoring wildlife, especially endangered species, which are difficult to observe directly over long timescales. Our

Bayesian models are also highly applicable in that they can become a powerful toolkit for conservation practitioners to estimate the relative effects of vehicle collisions on each species' mortality, especially when combining detailed reproduction and survival data.

Furthermore, our results bring to light the significance of bird-vehicle collisions in Hokkaido. High collection rates of injured/deceased birds were not unsurprising in Hokkaido, where multiple roads and train lines pass through the habitats of each species. Our results also align with previous reports of such collisions, especially with trains (Kyodo News, 2023; Yoshino, 2021). Recent advances in citizen science and developments in technology are enabling creation of more complete wildlife-vehicle collision datasets (Asari & Fujiki, 2020; Jingu & Ogawa, 2019; Vercayie & Herremans, 2015; Waetjen & Shilling, 2017), but systems for recording railkill are still limited (Terao et al., 2014), and studies are scant. This is likely a consequence of collisions going unnoticed more often than on roads, especially for smaller animals, due to the high speed of trains (Borda-de-Água et al., 2017). Given the potential applicability of railkill data toward ecology and conservation, as shown through our study, we suggest that records of wildlife-rail collisions be kept and studied to the extent of accidents on roads.

AUTHOR CONTRIBUTIONS

Conceptualization by all authors; Negotiations with the Ministry of the Environment, Government of Japan by TS; Data curation and formal analysis by KK; Supervision by YM and TS; Visualization by YM and KK; Roles/writing – original draft by AMN; Writing – review & editing by all authors.

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SUPPORTING INFORMATION

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