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Small Endemic Birds and Hot Climate: Avian and Environmental Predictors of Avifauna Road Mortality in Santa Cruz Galapagos

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Simple Summary: Simple Summary: Many bird species in the Galapagos Islands are killed on the roads by cars that transport citizens and tourists to their daily activities. This study reports the number of wild bird species killed near roads in 2004, 2005, 2006, and 2018 and uses a statistical analysis (PRIDIT) to rank the main intrinsic (avian) and extrinsic (environmental) predictors of mortality. About 250 birds (21 species) were found dead each year on the road. Our results show that for all studied years, small-endemic birds are especially at risk of roadkill during hot days on the main road of Santa Cruz. The Yellow Warbler *Setophaga petechia aureola* is the most affected species, particularly during the hot season. On the other hand, owls are a bigger species than the Yellow Warbler and, therefore, are less affected. However, the impacts of vehicle strikes are important to follow up on because owls are endangered. Although controlling the factors affecting bird mortality is complex, our results can inform management actions to mitigate avian mortality resulting from collisions with vehicles and other human activities.

Abstract: In the Galapagos Islands, the main road in Santa Cruz is one of the elements involved in bird road mortality along with vehicles and the impacted species. This study reports the number of roadkilled birds found on the road from the Itabaca Channel to Puerto Ayora, and the main factors, whether avian or environmental, involved in bird roadkill mortality. We collected individual carcasses in 2004, 2005, 2006, and 2018 with a prevalence of 278, 252, 265, and 294, respectively, across 21 species. The endemic Yellow Warbler *Setophaga petechia aureola* was the most affected bird. We used a PRIDIT model to rank the top avian and environmental predictors of road mortality. We found that for the sampled years, bird body size (i.e., 8–35 g) and the endemism status (i.e., endemic/native) were the main predictors of roadkill mortality, along with seasonality (i.e., hot season). Weaker predictors related to the bird (i.e., age and sex) and the environment (ecosystem, road slope, vegetation, or precipitation) are also reported as determinants of roadkill mortality. This study on avian mortality aims to inform conservation strategies to reduce the rate of wildlife avian roadkill on Santa Cruz Island and other islands with similar problems.

Keywords: bird species; conservation; prevalence; roadkill; vehicles

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1. Introduction

The avifauna on the Galapagos Islands is characterized by a small number of species and a high level of endemism [1]. According to The Encyclopedia of Conservation, endemic species in the Galapagos are unique to these islands. Additionally, native species are defined as being found on the islands and other regions, or even the mainland [1]. Out of the 169 species of birds recorded in the Galapagos Islands (including endemic species and subspecies, native residents, migrants, vagrants, and introduced species, except fossil, hypothetical, intercepted, and eradicated species), 72 are found on Santa Cruz Island. Among these, there are 20 endemic species (27.78%), 12 endemic sub-species (16.67%), nine native (12.50%), 22 migrants (30.56%), and nine introduced species (12.50%) [1,2]. Many birds die due to anthropogenic influences such as collisions with human-made infrastructure such as vehicles (i.e., sedans, pickups, vans, buses, trucks, or trailers) [3].

Some islands of the Galapagos have experienced demographic growth in the past decades, increasing the demand for vehicles, mainly pickup trucks, that transport tourists and citizens [4,5]. There are estimated to be more than 200,000 visitors per year (with some seasonal variations), in addition to the more than 30,000 people living on the islands. This population growth has resulted in increased vehicle traffic over the years [1,6], and it is expected to continue rising [6]. Expanding the road network is critical to respond to the demands of the growing population in terms of economic, social, and institutional development [4,5]. Paradoxically, vehicles are used on the island for the comfort of humans at the cost of avian well-being, contrary to the one-health concept that safeguards the health of humans, animals, and the environment together [7]. There are several adverse effects of road use on habitats and species, such as (i) a barrier effect that decreases the mobility of organisms and divides large populations into sub-populations, (ii) a border effect in which the behavior of birds is modified by the changes in the biotic and abiotic environment, (iii) fatalities by the collisions of birds with vehicles, (iv) indirect impacts, such as the introduction of invasive species, soil, and (v) environmental pollution resulting from water runoff, fuel spills, noise, and dust [8,9]. However, birds use the roads to obtain food (invertebrates or seeds), grab small stones, drink accumulated rainwater, thermoregulate their bodies, rest, and use the open space to fly, sometimes as a migration route.

In this study, we used a novel approach to analyze a set of qualitative and quantitative indicators of avifauna roadkill mortality using Principal Component Analysis (PCA) and Relative to an Identified Distribution (RIDIT), resulting in transformations from the cumulative distributions of the original variables to a scoring system [10]. Based on field observations, we initially assumed that seasonality affected roadkill mortality, and we hypothesized that specific bird traits and environmental factors would show a stronger relationship with roadkill mortality. Applying these two techniques, we ranked the top predictors involved in roadkill prevalence for different years to inform management strategies. The generated ranking can be used as a robust predictor of avian road mortality, compared to field observations. Our results aim to contribute to mitigating roadkill of unique avifauna in the Galapagos Islands. The applied methodology can be used to study roadkill mortality in other islands where qualitative and quantitative data are available, or data can be collected using the same a priori classifications.

2. Materials and Methods

2.1. Study Area

The Galapagos Islands are located in the Eastern Pacific Ocean along the equator, about 960 km west of mainland Ecuador (Figure 1). In total, there are 17 major islands, four of which are inhabited by humans (Santa Cruz, San Cristóbal, Isabela, and Floreana), and one (Baltra) that serves as an airport and military base with humans activity, but no human settlements as cities [11].

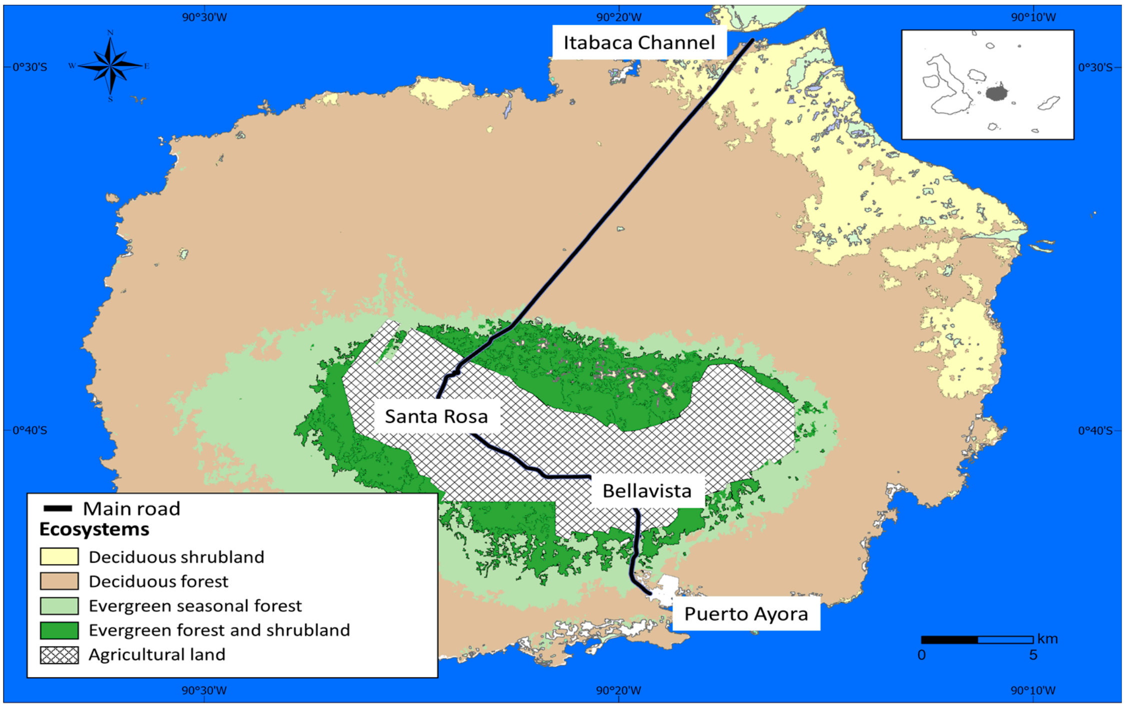

Figure 1. Galapagos Islands and the study area. Santa Cruz is located at the center (−1°37.50′ S and −90°21.00′ W) of the archipelago. The main road (dark black line) from Itabaca Channel (in the north) to Puerto Ayora (in the south) crosses five ecosystems and two settlements (Santa Rosa and Bellavista).

The five islands listed contain numerous roads, with Santa Cruz featuring the longest road with the heaviest and fastest traffic compared to the other islands, and it is, therefore, the focus of this study (Figure 1). Santa Cruz Island receives significantly more tourists than the other islands [5,12] and has a higher number of permanent residents. The road construction in Santa Cruz began in 1972, and it has been functional since 1974. In 2000, it was extended and lined with concrete, and in 2016, a bike path was constructed from Puerto Ayora to *Los Gemelos*. The vehicle flow on the island has increased exponentially, from only one vehicle in 1959 (a small tractor owned by Forest Nelson) to 20–30 units in the 1980s, to 1074 vehicles in 2009 [13]. Currently, substantial restrictions regulate vehicle imports, even electric vehicles with silent engines. The current legislation limits the imports to a maximum number of vehicles per year that should have been manufactured the last 5 years before import, and the use is restricted to local people for their agricultural or tourist activities or public and private local institutions. The special regime of the Galapagos government is in charge of regulating and controlling the import of all vehicles [14].

The main road on Santa Cruz connects the Itabaca Channel to Puerto Ayora and serves tourists and citizens, especially as they travel to and from the airport on Baltra. It is also used by buses and trucks to transport people and goods. The referred road is 39.5 km long and approximately 12 m wide with two lanes. The route crosses through major vegetation zones found on the island i.e., deciduous shrubland, deciduous forest, evergreen seasonal forest and shrubland, evergreen forest and shrubland, and agricultural land [15], and some small towns such as Bellavista (−0°41.672′ S & −90°19.524′ W, 186 m), El Carmen (−0°40.560′ S and −90°22.872′ W, 349 m), and Santa Rosa (−0°39.190′ S and −90°24.322′ W, 428 m), and few National Park areas (Figure 1). The road reaches an altitude of 614 m at a tourist site called "Los Gemelos" (−0°37.590′ S −90°23.132′ W, 614 m) located in the National Park. The vehicle speed limit is 70 km/h from Itabaca Channel to Bellavista, and 50 km/h from Bellavista to Puerto Ayora, but the speed limit is not controlled [16].

2.2. Data Collection

Before data were collected, the protocols were revised and approved by the Galapagos National Park in 2004, 2005, 2006, and 2018. The principal investigator has a research permit to work on avian health. No animals were injured from the study, and carcasses were disposed of following the Charles Darwin Foundation Protocol.

Data collection involved a sampling road trip led by the principal investigator, accompanied by three local assistants and a driver. The team used a pickup truck as a means of transport. The road survey traveled from the north (Itabaca Channel) to the south (Puerto Ayora) to collect roadkill bird samples in the years 2004, 2005, 2006, and 2018. A limitation of the study is that in 2004, data collection was not conducted during February, May, September, October, and December. Therefore, data for 2004 were used as a pilot study. In 2005, data were not collected during February and March because of financial limitations, and in July 2018, the road trip was not organized due to the lack of vehicles. Data collection was structured in two phases for each year and conducted consecutively, according to the following protocol. Phase 1 involved cleaning the road (to start the count from zero). The assistants were transported in the back of the pickup truck (speed ~20–30 km/h) and observed the road to collect all carcasses (regardless of the species). Birds were removed from the road, along roadsides, and in road gutters [17]. Consecutively, Phase 2 was conducted 24 h after Phase 1, which included the collection and count of each bird carcass found on the road during the sampling trip. The latter involved multiple stops (as many as necessary) to collect all carcasses on the road. Results show the number of carcasses found during Phase 2 of the protocol as a roadkill index per 24 h.

Data collection also involved documenting a list of traits for each dead bird on a printed datasheet. The traits were selected after a literature review on avifauna road mortality because these have been widely reported to be associated with higher ratios of car-collision avian mortality [3,8,9,18]. Avian traits included identifying the species, scientific name, age, sex, size, and endemism.

Environmental variables included date and time (using a SmartWatch), GPS position and slope (using a handheld Garmin 60CSx), road distance from the Itabaca Chanel (using the car odometer), daily precipitation and station (data from the meteorological station at CDF), ecosystem (from the latest National Park report), and Normalized Difference Vegetation Index (NDVI) (computed using MODIS). The season was categorized into three groups, assuming birds are more active on hot days, followed by a transition period and cold weather. Seasonality affects the reproductive and eating behavior of birds during dry or rainy seasons and is, therefore, essential to explore [18]. Precipitation was included because, during rainy days, there are more food and water drops on the road to drink [19]. The vegetation zone around the road is critical because birds fly differently according to the trees and altitude of the vegetation, and the vegetation communities provide food and habitat for a range of species [15,20]. The NDVI was computed for every year from the 15-day average that was closest to the sampling day, per 250 m cell size from the MODIS project using the GPS coordinate for each collected carcass [21,22]. NDVI was helpful because it has been demonstrated to be linked to birds' food abundance and habitat variability [23]. The slope was derived from the 30 m DEM of the SRTM [22] because road transects with higher slopes would require vehicles to slow down on their way up and allow them to travel at higher speeds as they descend.

2.3. Data Analysis

We conducted a series of analyses, both qualitative and quantitative, from the carcasses collected from Phase 2. Quantitative analysis was done using RStudio (Version 2024.04.1+748; RStudio Team, 2024) and R (version 4.3.2; R Core Team, 2023). Descriptive statistics were generated to report the number of carcasses found on the road per species and merged the count into the prevalence per year. Data for 2004 were used as a baseline and to train the assistant researchers to refine each protocol's phase. Qualitative analysis was conducted to enlist the reported species according to the Red List Threatened Species at UICN [24]. Certified ornithologists identified the reported species using the full local name and the scientific name of the bird, in addition to the acronym for the RED List ECU for Endangered (EN), Vulnerable (VU), Near Threatened (NT), and Least Concern (LC). Scientific names were validated by the principal investigator using the regional red list of birds [24]. The number of collected bird species from Phase 2 was listed as part of the main results and ordered by increasing prevalence. Other vertebrates recorded in Phases 1 and 2 were reported qualitatively as additional findings and organized by taxa-alphabetical order.

Data for 2005, 2006, and 2018 were used for the predictive analysis, which only included 9 months per year (because missing data were excluded). We did not input data for the missing months because the variation of each species per month was too high, and imputed values can affect the model as it is sensitive to each bird species' distribution [17]. PCA and RIDIT were applied to rank a list of avian and environmental road mortality, on a combined PRIDIT model to identify the top predictors. This method requires a priori classifications for the categories group, which were grounded on literature and field observations. The order of the categories was organized according to the initial hypothesis. The latter assigned the first category to the most affected group. For example, categories for age are juvenile, adult, or indeterminate (when the carcass is ruined and it is difficult to determine its age). According to our hypothesis, juveniles are naiver and tend to be impacted by vehicles, compared to adults, and, therefore, juveniles were assigned to the first category and adults to the last. Table 1 shows the organized categories built for each variable.

For both continuous and categorical variables, the RIDIT model assigns a score to the ordinal values of each variable through its distribution function [25], so that, as a first step, the distribution function of each variable is calculated, and then its corresponding scores are calculated using the "B_{ij}" scores are calculated using Formula (1).

$$B_{ij} = F_j^-(i) - \left(1 - F_j(i)\right) \tag{1}$$

where: B_{ij} = Ridit score matrix. i = 1, 2, . . ., n. are the n individuals analyzed. j = 1, 2, . . ., p. are the p variables considered to construct the indicator. $F_j^-(i)$ = is the value of the cumulative distribution function of Variable j for the individual ranked one point below that individual. $F_j(i)$ = is the value of the cumulative distribution function of Variable j for the individual i ranked.

A table of indicators (Table 1) was constructed for the PRIDIT model, using both qualitative and quantitative variable types, including both avian and environmental indicators, and assigning numerical scores to the categories. This technique was used because it is based on unsupervised learning, is non-probabilistic, and can analyze data that are not continuous and not normally distributed.

The PRIDIT model computed a ranking value for each dead bird, which was used to predict the bird's tendency to be roadkilled, and, consequently, the predictor was analyzed for all species merged. The indicator for each individual is a ranking value from −1 (high tendency) up to 1 (low tendency). For categorical variables, the higher the category, the higher the chance to be roadkilled, and for continuous variables, the higher the value of the variable, the higher the chance to be roadkilled. For all species merged, stronger predictors have values higher than 0.4, considering their absolute value (PRIDIT $\geq$ |0.4| [10]. The sign of the value serves to validate the categories assigned by the initial hypothesis, and when the sign is positive, it means that the first category differs from the initial hypothesis, and it does not correspond to the group with a high tendency to be roadkilled.

Table 1. Qualitative and quantitative indicators of avifauna road mortality, both avian and environmental, were used for the PRIDIT model with the categories used for the scoring.

Variable Type	Indicator	Description	Category
Qualitative-Avian	Age	Age Group	1: Juvenile 2: Indeterminate + 3: Adult
	Sex	Bird's Sex	1: Female 2: Male 3: Indeterminate +
	Endemism	Origen of the bird in the Galapagos Islands	1: Endemic ++/Native +++/ 2: Introduced * 3: Migrant **
	Size	Bird Size in relation to weight (grams)	1: Small (8–35) 2: Medium (36–100) 3: Heavy (200–650)
Qualitative-Environmental	Ecosystem	Ecosystem surrounding the road	1: Agricultural Land 2: Deciduous Forest 3: Forest and Shrubland and Evergreen forest 4: Evergreen seasonal forest 5: Deciduous Shrubland
	Season	Climatic Season during data collection	1: Hot 2: Transition 3: Cold
	Slope	The slope of the road (%)	1: Very Strong (25–55) 2: Strong (12–25) 3: Moderate (7–12) 4: Gentle (3–7)
Quantitative-environmental	NDVI Normalized Difference Vegetation Index	Value of green color in relation with vegetation	Continuous Variable (from 0 to 8875)
	Precipitation	Sum of rainfall of two days during data collection (mm)	Continuous Variable (from 0.0 to 2.0)

First category assigned according to the hypothesis (assumed higher tendency to be roadkilled). + Indeterminate: Age or sex could not be determined. ++ *Endemic:* species that are unique to geographic location (i.e., Galapagos Finches). +++ Native: species found in various regions (in and out of the Galapagos, i.e., Paint-billed Crake). * Introduced: species that arrived on purpose or accidentally in the Galapagos for human interaction (Smooth-billed Ani). ** Migrant: species that move from one habitat to another during different times of the year (i.e., Phalarope).

Additionally, qualitative analysis was conducted to analyze the determinants of avifauna roadkill mortality for the species with less abundance (Owls). This analysis was based on the sum of roadkill per species for each variable, and the label of the category per indicator was used. The latter was done because species that were less present on the roads might be of conservation importance (endangered species), and, therefore, it is essential to know when and where the carcasses were found.

We illustrated the distribution of the total number of roadkill birds for each year using the GPS coordinates in Rstudio using available shape files [21]. The latter was done for the most prevalent roadkilled bird species (three Passeriformes), and prioritized birds (two Strigiformes) were included because these are endangered species according to the Red List ECU [24]. The maps used round spheres for four ranges of roadkilled birds (i.e., 5–9, 10–14, 15–19, and higher or equal to 20). Additionally, heat maps were generated using Power BI (version 2.131.11260, and ArcGIS 2024. 400) to illustrate the intensity of total deaths for each year using colors from high (yellow) to low (white). These graphs are available as Supplementary Material.

3. Results

The prevalence of dead birds collected throughout the road was 278 in 2004, 252 in 2005, 265 in 2006, and 294 in 2018. Figure 2 shows the number of roadkill birds geographically on the road of the three most prevalent species and the two endangered, according to the Red List ECU [24]. Supplementary maps show the geographic location of each roadkilled species. The ecosystem where most of the roadkill prevalence was found is in the Deciduous Forest for all studied years and Agricultural Land for 2004. The months with high fatalities were March and April 2004, April and July 2005, April and May 2006, and May and June 2018. Most bird roadkills occurred in the hot season.

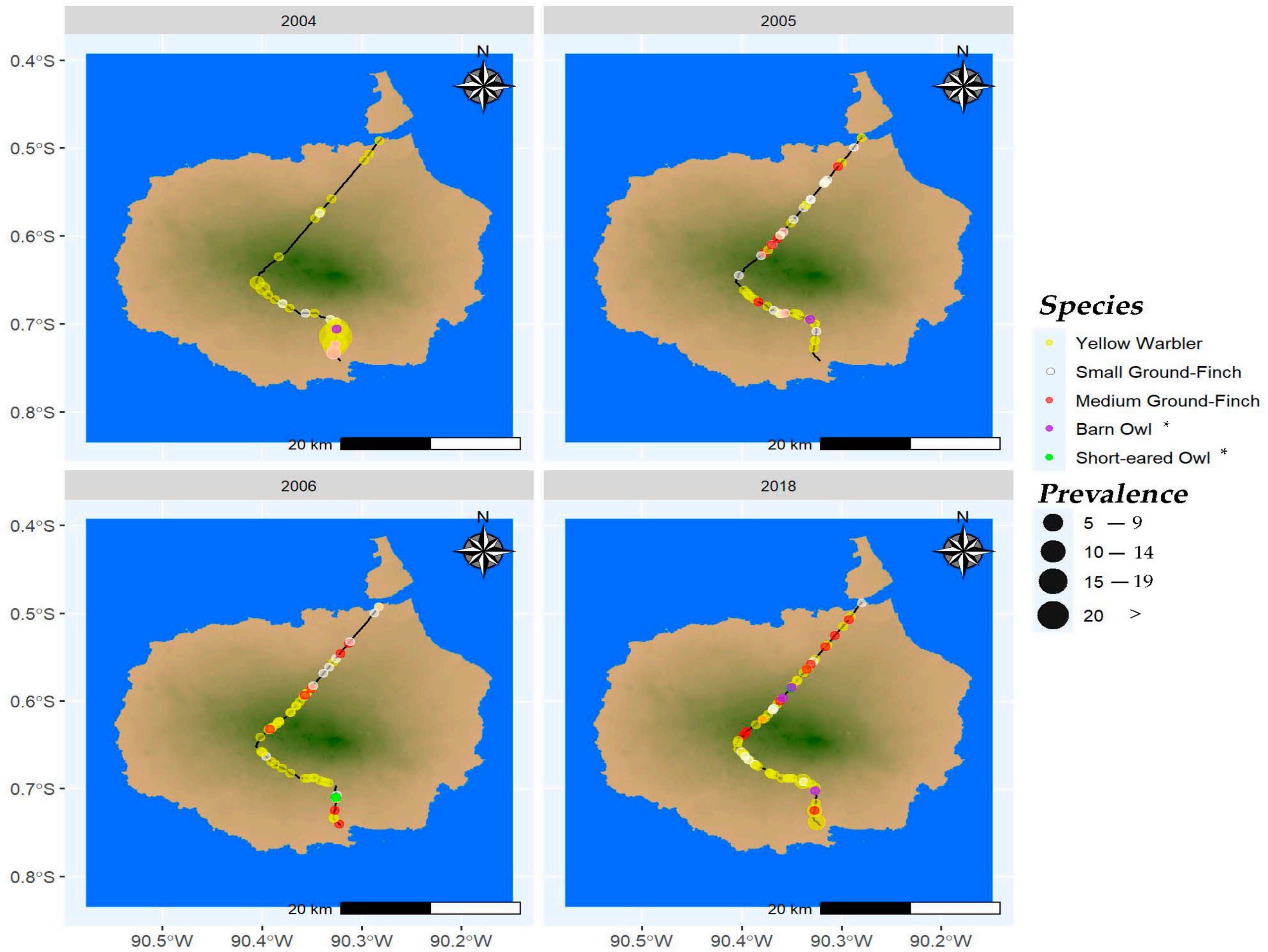

Figure 2. Distribution of five roadkilled bird species, three more prevalent, and two endangered—EN (with *), found on the road from Itabaca Channel down to Puerto Ayora in 2004, 2005, 2006, and 2018.

The total number of identified species is 21, and we also found many individual finches that could not be identified with confidence to species (9 species in 2004, 13 in 2005, 14 in 2006, and 17 in 2018). The Yellow Warbler *Setophaga petechia aureola* was the most prevalent species found dead on the road, followed by the Small Ground-Finch *Geospiza fuliginosa* and the Medium Ground-Finch *G. fortis* (Table 2). Of the 21 total identified species, 15 were of endemic status (71.42%), three native (14.28%), one migrant (4.76%), and two introduced (9.52%).

Table 2. Prevalence of dead bird species found on the road starting from Itabaca Channel (north) to Puerto Ayora (south) in 2004–2006 and 2018, according to the endemism and Red List Category.

Bird (Local Name) *Scientific Name*	**Endemism**	**Red List ECU**	**2004** *n*	**2005** *n*	**2006** *n*	**2018** *n*
Yellow Warbler (Canario María) *Setophaga petechia aureola*	E	LC	190	87	122	170
Small Ground-Finch (Pinzón de Tierra Pequeño) *Geospiza fuliginosa*	E	LC	24	61	42	25
Medium Ground-Finch (Pinzón de Tierra Mediano) *Geospiza fortis*	E	LC	22	23	28	32
Unidentified finch (Pinzón no identificado)	E	n/a	18	22	13	17
Smooth-billed Ani (Garrapatero) *Crotophaga ani*	I	n/a	8	17	11	6
Galapagos Mockingbird (Cucuve de Galápagos) *Mimus parvulus*	E	LC	9	4	12	14
Galapagos Flycatcher (Papamoscas) *Myiarchus magnirostris*	E	LC	2	11	15	8
Dark-billed Cuckoo (Cuclillo) *Coccyzus melacoryphus*	N	LC	2	9	7	1
Small Tree-Finch (Pinzón de Árbol Pequeño) *Camarhynchus parvulus*	E	LC	2	8	3	3
Paint-billed Crake (Gallareta) *Mustelirallus erythrops*	N	LC		5	2	5
Cattle Egret (Garza Bueyera) *Bubulcus ibis*	I	n/a			4	
Galapagos Dove (Paloma de Galápagos) *Zenaida galapagoensis*	E	NT		1	2	
Woodpecker Finch (Pinzón Artesano/Carpintero) *Camarhynchus pallidus*	E	NT		1	2	
Large Ground-Finch (Pinzón de Tierra Grande) *Geospiza magnirostris*	E	LC		1	1	4
Barn Owl (Lechuza de Campanario) *Tyto alba punctatissima*	E	EN	1	1		3
Short-eared Owl (Lechuza de Campo) *Asio flammeus galapagoensis*	E	EN			1	1
Yellow-crowned Night-Heron (Huaque) *Nyctanassa violacea pauper*	E	VU		1		
Wilson's Phalarope (Falaropo) *Phalaropus tricolor*	M	LC				1
Green Warbler-Finch (Pinzón cantor verde) *Certhidea olivacea*	E	VU				1
Common Gallinule (Gallinula) *Gallinula galeata*	N	NT				1
Common Cactus-Finch (Pinzón de Cactus Común) *Geospiza scandens*	E	LC				1
Galapagos Rail (Pachay) *Laterallus spilonota*	E	VU				1
Total per year			278	252	265	294
Number of sampled months			7	10	12	11

Endemism according to Jiménez–Uzcátegui et al. 2017: E = Endemic. N = Native. I = Introduced. M = Migrant. Red List ECU according to Freile et al. 2019: EN = Endangered. VU = Vulnerable. NT = Near Threatened. LC = Least concern. n/a = Not applicable.

More importantly, two species found dead on the roads of Santa Cruz are listed in the highest category in the Threatened Red List as endangered (Barn Owl *Tyto alba punctatissima*, Short-eared Owl *Asio flammeus galapagoensis*), and three species are listed as vulnerable (Yellow-crowned Night Heron *Nyctanassa violacea pauper,* Green Warbler-Finch *Certhidea olivacea*, Galapagos Rail *Laterallus spilonota*), three species as near-threatened (Galapagos Dove *Zenaida galapagoensis*, Woodpecker Finch *Camarhynchus pallidus*, Common Gallinule-Moorhen-*Gallinula galeata*), and 11 as of least concern) (Table 2).

The ranking for each predicting variable per year, according to the PRIDIT model, for all species merged is presented in Table 3. Predictors higher than ∣0.4∣ were considered to be strong predictors (in bold in Table 3). The ranking values go from −1 up to 1, with negative values showing a high tendency to be roadkilled and positive values showing low roadkill tendency. The associated categories (Table 1) were organized from –1 (first category up to 1 last category). For example, the value of –0.18 for age, in 2004, is a weak predictor across years because it is lower than the absolute value of 0.4, whereas for 2006 (−0.67) and 2018 (−0.85), it is strong (≥∣0.4∣), meaning that juveniles (negative value associated to the assigned first category) have a higher tendency to be roadkilled in the last 2 sampled years.

Table 3. Avian and environmental predictors (ranking values between −1 and 1) of bird road mortality in Santa Cruz for 2005, 2006, and 2018 (values in bold are stronger predictors: PRIDIT ≥ ∣0.4∣).

Variable Type	Indicators of Avian Road Mortality *	2005	2006	2018
Avian	Age	−0.18	**−0.67**	**−0.85**
	Sex	**−0.42**	0.12	**0.44**
	Endemism	**−0.77**	**−0.69**	**−0.40**
	Size	**−0.84**	**−0.70**	**−0.42**
Environmental	Ecosystem	**0.59**	0.36	−0.31
	Season	**−0.41**	**−0.47**	**−0.59**
	Slope	−0.10	−0.11	−0.25
	NDVI_1	−0.16	−0.13	0.35
	Precipitation	0.15	**0.50**	−0.33

* Interpretation: PRIDIT ≥ ∣0.4∣ shows the strength of the predictor across years and across indicators. Negative values are associated with the first assigned category (i.e., age = juveniles, sex = female, endemism = native/endemic, size = small, ecosystem = agricultural land, season = hot, slope = very strong, NDVI = few vegetation, precipitation = low).

Concerning avian indicators, bird size (weight in grams—g) and endemism status (endemic species) are the strongest predictors of bird-road mortality in Santa Cruz for the 3 studied years. In addition, seasonality is the stronger environmental predictor of avifauna roadkill death in all sampled years (see Table 3). Thus, small birds with low weight (~8–35 g) have a higher chance of dying compared to those with medium- (~36–100 g) or heavy-weight birds (~200–650 g). Consistently, endemic and native birds have a higher chance of dying compared to those of introduced status or migrant birds. This indicates that small endemic and native birds have a higher tendency to be roadkilled, particularly during days of hot temperatures.

For 2006 and 2018, age also determined the tendency to be roadkilled, with adults more susceptible than young birds. However, during the hot season, younger birds showed a higher tendency to be roadkilled compared to adults. Sex is another determinant that showed that females in 2005 had a higher tendency to be roadkilled compared to males, but in 2018, males tended to be roadkill compared to females. The surrounding ecosystem and NDVI are two particular environmental determinants with opposite symbols (+ or −) for each year, which points to a higher prevalence of roadkill birds in areas with deciduous forests.

Additionally, precipitation is a good determinant of avian roadkill mortality for 2006, showing that more birds died on days when precipitation was low. A very weak determinant is the slope of the road, which shows that more birds die at the extension of roads with higher slopes, which is consistent for all studied years.

Table 4 shows the prevalence of roadkill birds (species merged) per year according to the stronger predictors computed by PRIDIT, which have been consistent over the three years.

Table 4. Summary table of roadkill prevalence by year according to the PRIDIT scoring.

Variable Type	Indicator	2004, N = 278 *n* (%)	2005, N = 252 *n* (%)	2006, N = 265 *n* (%)	2018, N = 294 *n* (%)
Avian	**Age group**				
	Juvenile	95 (34)	82 (33)	80 (30)	129 (44)
	Indeterminate	0 (0)	1 (0.4)	0 (0)	5 (1.7)
	Adult	183 (66)	169 (67)	185 (70)	160 (54)
	Sex				
	Female	123 (44)	81 (32)	71 (27)	60 (20)
	Male	67 (24)	41 (16)	58 (22)	85 (29)
	Indeterminate	88 (32)	130 (52)	136 (51)	149 (51)
	Endemism				
	Endemic/Native	270 (97)	235 (93)	250 (94)	270 (92)
	Introduced	8 (2.9)	17 (6.7)	15 (5.7)	6 (2.0)
	Migrant	0 (0)	0 (0)	0 (0)	18 (6.1)
	Size				
	Small bird (8–35 g)	258 (93)	214 (85)	226 (85)	261 (89)
	Medium bird (36–100 g)	19 (6.8)	36 (14)	34 (13)	28 (9.5)
	Heavy bird (200–650 g)	1 (0.4)	2 (0.8)	5 (1.9)	5 (1.7)
Environmental	**Ecosystem**				
	Agricultural Land	168 (60)	57 (23)	37 (14)	119 (40)
	Deciduous Forest	55 (20)	172 (68)	168 (63)	142 (48)
	Forest and Shrubland and Evergreen Forest	5 (1.8)	12 (4.8)	29 (11)	18 (6.1)
	Evergreen Seasonal Forest	45 (16)	4 (1.6)	9 (3.4)	12 (4.1)
	Deciduous Shrubland	5 (1.8)	7 (2.8)	22 (8.3)	3 (1.0)
	Season				
	Hot	230 (83)	145 (58)	208 (78)	255 (87)
	Transition	26 (9.4)	68 (27)	28 (11)	5 (1.7)
	Cold	22 (7.9)	39 (15)	29 (11)	34 (12)
	Month				
	January	16 (5.8)	9 (3.6)	16 (6.0)	18 (6.1)
	February	n.a	n.a	7 (2.6)	11 (3.7)
	March	91 (33)	n.a	23 (8.7)	24 (8.2)
	April	82 (29)	69 (27)	53 (20)	41 (14)
	May	n.a	25 (9.9)	60 (23)	95 (32)
	June	41 (15)	31 (12)	40 (15)	63 (21)
	July	16 (5.8)	45 (18)	24 (9.1)	n.a
	August	22 (7.9)	23 (9.1)	18 (6.8)	16 (5.4)
	September	n.a	13 (5.2)	5 (1.9)	7 (2.4)
	October	n.a	3 (1.2)	6 (2.3)	11 (3.7)
	November	10 (3.6)	23 (9.1)	4 (1.5)	5 (1.7)
	December	n.a	11 (4.4)	9 (3.4)	3 (1.0)

n.a: not applicable.

The analysis results of only Yellow Warbler are listed in Table 5 because it was the most prevalent species in all sampled years. Age and sex are strong determinants (PRIDIT $\geq |0.4|$) for all years, and seasonality is a consistent determinant of roadkill mortality for the Yellow Warbler.

Regarding conservation status, two endemic species of owls (Barn Owl and Short-eared Owl) are classified as endangered, but only one owl roadkill per year appeared in our sample (See Table 2). These are bigger birds (~200 to 600 g) compared to the Yellow

Warbler but also endemic. Adult owls were shown to die on roads situated in agricultural areas and with high NDVI (See Table 6).

Table 5. Determinants of avian roadkill mortality for Yellow Warbler *Setophaga petechia aureola* (N = 569) for 2005, 2006, and 2018.

Type	Determinants	2005	2006	2018
Avian	Age *	Juvenile		Adults
	Sex *	Male		Female
Environmental	Ecosystem area	Deciduous Forest	Agricultural Land	Evergreen Forest
	Season		Hot	
	Slope	High	Low	High
	NDVI_1	High	Low	High
	Precipitation	Low	High	High

* PRIDIT ≥ |0.4|).

Table 6. Determinants of avian roadkill mortality of Owls (Barn Owl and Short-eared Owl) for 2005, 2006, and 2018 based on qualitative analysis (no PRIDIT) (N = 7).

Type	Determinants	2005	2006	2018
Avian	Age		Adults	
	Sex		Indeterminate	
Environmental	Precipitation	High	Low	Low
	Ecosystem area	Agricultural		Deciduous Forest
	Season	Cold	Hot	Cold
	Slope	Mid	High	Slightly
	NDVI_1 (Vegetation)	High	Low	High

Additional Findings

Table 7 shows the local names, endemism status, and Red List ECU category of six additional vertebrate species (organized by taxa-alphabetical order) that were found dead on the road. Two birds were found during the first phase of the data collection, and two reptiles and two introduced mammals were found roadkilled during the second phase (see Table 7).

Table 7. Vertebrate species list that were found roadkilled in Santa Cruz, in 2004, 2005, 2006, and 2018.

Vertebrate (Local Name) ***Scientific Name***	**Endemism**	**Red List ECU**
Birds		
Galapagos Vermilion Flycatcher (Pájaro Brujo) *Pyrocephalus nanus*	E	VU
Vegetarian Finch (Pinzón Vegetariano) *Platyspiza crassirostris*	E	NT
Reptile		
Indefatigable Lava Lizard (Lagartija Indefatigable) *Microlophus indefatigabilis*	E	NT
Steindacher Racer (Culebra de Steindachner o rayada) *Pseudalsophis steindachneri*	E	EN
Mammals		
Black rat (Rata Negra) *Rattus rattus*	I	n.a
Feral cat (Gato feral) *Felis catus*	I	n.a

n.a: not applicable

4. Discussion

The intrinsic traits of bird species and some environmental elements seem to influence avifauna roadkill mortality. This study reports bird mortality resulting from vehicles that impact birds while using the main road of Santa Cruz Island. Here, we report the number of roadkilled birds found during the study years and identify which Threatened Red List species are the most affected. Our study identified strong predictors of avifauna roadkill mortality: bird size and endemism status (avian factors) and seasonality (an environmental factor). We also propose a statistical methodology for future research in this field. Additionally, we report the factors associated with avian roadkill mortality that are weaker predictors or only affect bird road mortality in particular years. The predictors and determinants reported by us have been previously reported by numerous studies in the field of roadkill avian mortality [3,9,18], highlighting their importance to be considered in conservation strategies.

The results reported for 2004 served as the baseline data that guided the 3-year data-collection period, which was done in 2005, 2004, and 2006, showing similar trends. In 2018, we decided to repeat the protocol to evaluate the variability of the data within and between the sampled years. Initially, 16 bird species were reported in the initial 3-year period (2004–2006), and five species were added in 2018 to reach a total of 21 bird species for the 4 sampled years. Furthermore, other vertebrates that were found dead on the roads during data collection were reported as additional findings because they may serve as insight for other conservation studies (i.e., Galapagos Snake-dorsalis *Pseudalsophis steindachneri*, Indefatigable Lava Lizard *Microlophus albemarlensis*, Vegetarian Finch *Platyspiza crassirostris*, Galapagos Vermilion Flycatcher *Pyrocephalus nanus* (endemic species), and feral cats *Felis catus* and black rats *Rattus rattus* (introduced species). As a result, we can say that 27 species (including birds and other vertebrates) were found roadkilled on the Santa Cruz Island main road. When merging our results with previously reported dead or injured animals found sporadically during other studies (11 species) [26], the total number of affected species in the archipelago increases to 38 species (San Cristóbal Mockingbird *M. melanotis*, Large Tree Finch *C. psittacula*, Brown Pelican *Pelecanus occidentalis urinator*, San Cristóbal Lava Lizard *Microlophus bivittatus*, Albemarle Lava Lizard *M. albemarlensis*, Santa Cruz Marine Iguana *Amblyrhynchus cristatus hassi*, Isabela–Fernandina Marine Iguana *A. c. cristatus*, Galapagos Land Iguana *Conolophus subcristatus*, Central Galapagos *Racer P. dorsalis*, Eastern Santa Cruz Giant Tortoise *Chelonoidis donfaustoi*, Santa Cruz Galapagos Giant Tortoise *C. porteri*).

The novelty of this study relies on providing a predictor of avifauna roadkill mortality, which includes both avian and environmental variables, combined with qualitative and quantitative data that could serve as a criterion for policymakers when planning avifauna conservation. Moreover, the construction of the predictor used a methodology that combines PCA and RIDIT to rank the assigned numerical scores provided to the categories used in data collection. This approach is ideal because it saves the cost of new surveys and allows us to analyze collected data that combine continuous and non-continuous variables. The applied methodology is often functional in epidemiology and fraud studies [10], and it is by all means suitable for avifauna road-mortality studies. Additionally, the technique helps us to validate the hypothesis used during the a priori creation of categories. In that line, we found that when the weight of the variable is strong (PRIDIT $\geq |0.4|$), the indicator is insensitive to the category assigned. The latter was analyzed for age and sex (assigning the indeterminate category to the second group instead of the last one), showing no changes in the sign or value ([17]).

Until recently, the gap in reporting bird-road mortality has been a barrier to developing strategies that control vehicle collisions. Reporting only descriptive statistics on roadkill prevalence per year is necessary but insufficient to inform conservation or local management decisions. A previous study on a highway road transect in Santa Cruz, which is a paved road similar to the one we sampled, reported 125 birds belonging to seven species [27], with the Yellow Warbler being the most roadkilled species (92 carcasses).

In summary, the consistency of the predictor for all years showed that small birds with low weight (~8–35 g) and of endemic and native status have a higher chance of being roadkilled, and, notably, this occurs on high-temperature days (hot season). Bird size is a crucial factor influencing the tendency to be roadkilled, which is highly related to the species' features [28]. A high roadkill mortality of small bird species was also reported in a study conducted on the same island but on a different transect road, where 168 bird carcasses of low weight (between 7 and 40 g) were found. Also, they found that most of these birds were native to the island. The behavior of small native birds can be associated with their low flight maneuverability compared to large birds, which constrains them from avoiding cars, and more severely because they are not used to car noise. Moreover, the endemic species are relatively slow and clumsy flyers (particularly young birds) compared with the related mainland species, resulting in a slow reaction to escape. The endemism status, (i.e., being endemic, native or not) reflects the adaptation capacity of the bird to anthropogenic influences such as vehicle noise. Endemic and native species are not familiar with the sound of motor vehicles. Not surprisingly, the effect could increase with the integration of electric vehicles into the traffic because low-carbon strategies are not in line with wild-bird conservation ones.

Beyond the association of bird size with roadkill mortality is the influence of the season [9]. Our results show that only one environmental predictor, which is seasonality, seems to be persistent for all the studied years, with birds more likely to be killed during periods with hot temperatures. Also, younger birds have a high prevalence of roadkill during the hot season, probably because adults are breeding. In the literature, seasonality is reported as a factor associated with roadkill avian mortality, with increased roadkill during migration periods and breeding seasons. In the hot season, birds become aggressive and territorial because they want to reproduce; this behavioral change makes them fly in open areas and follow other birds to fight. During the rainy season, less roadkill prevalence was reported, which could be attributed to the reduced flying behavior, low speed of vehicles on a wet road, or the washing effect of the carcasses by the heavy rains (despite data collection being avoided during heavy rainy days). However, these assumptions require an in-depth analysis of avian and human (vehicle's driver) behavior.

Our study may suggest that the possible reasons for bird mortality might depend on the intrinsic traits of the bird (i.e, size and endemism status) and seasonality. Unfortunately, conservation interventions cannot control for the latter, but we have to use the analytical power of the analysis to observe that the birds tend to learn avoidance behaviors. The literature on PRIDIT has mentioned that humans tend to learn behaviors, specifically referring to a learning curve, that can be observed over time, and which is unworkable for other classical statistical analyses [10]. This means that for some determinant variables that change over time, there could be a tendency to learn avoidance behavior [29,30]. For example, female birds showed a learning behavior that can be observed from 2005 to 2006, and, finally, in 2018, males have a higher tendency to be roadkilled. A similar tendency could be observed for age, with a predictor that increases over time showing that juveniles somehow learn to avoid vehicles.

Furthermore, environmental determinants of avian-road mortality should be considered for conservation strategies. In that line, we can see that only seasonality is a strong predictor, and the rest are just determinant variables that change over time and, therefore, are weaker predictors for overall mortality. In that line, seasonality can change the behavior of birds because birds tend to reproduce during the hot season [31]. Additionally, many studies have reported that roadkill bird mortality is associated with landscape and road features [32]. While our results show that the surrounding ecosystem, vegetation zone, and slope of the road are weaker predictors, they can be recognized as determinants of roadkill bird mortality and can inform conservation strategies such as road signaling. Hereafter, the use of warning signs on roads that are surrounded by vegetation (i.e., decidous forest zones), agricultural areas, and with high slopes (25–55%) is suggested since these showed to have a higher chance in bird fatalities.

By observing only the most affected species (i.e., Yellow Warbler), the indicator revealed that these birds have a higher chance of being roadkilled in the hot season and on roads with gentle slopes (3–7%). Thus, seasonality and road section are good predictors to implement local strategies for the conservation of the Yellow Warbler despite being a species of least concern. For larger birds weighing over 35 g, such as owls, we found that age, NDVI (Normalized Difference Vegetation Index), and ecosystem type are key determinants of roadkill mortality. This is particularly important to consider since some of these larger species are endangered. We emphasize the importance of studying species with low roadkill prevalence due to their ecological significance and role in biodiversity. Notably, our results indicate that roadkill prevalence is not necessarily correlated with species abundance. For instance, while Finches have been reported as the most abundant species on Santa Cruz Island [33], our study shows they have a lower roadkill prevalence compared to Yellow Warbler. It is worth noting that the previous study estimated abundance based on singing animals, whereas our research provides tangible roadkill data.

These novel results show the need to implement actions to mitigate avian mortality caused by vehicle collisions in Santa Cruz, especially since some threatened and unidentified species were found dead during data collection. Some limitations of this study may be related to underreporting because there were months that were not sampled for the period from 2004–2006, which may increase the total number per species and per month. Some observation bias probably resulted from the collection of carcasses, although assistants were highly trained to recognize dead birds. Also, some underreporting might result from the overnight disappearance rate and the vehicle's speeds, which were not assessed in this study. Furthermore, the reported predictors use the total number of roadkilled species, which limits the prediction for each species, mainly because of the low prevalence of other species (except Yellow Warbler). However, the construction of the variable discriminatory power allowed us to be confident in the construction of the predictor, which may also cover the fact that some dead birds were missed during the collection of carcasses because some may have been thrown far from the road due to the vehicle impact or because predators ate the carcasses before we were on the road.

Future studies should focus on using indicators that measure some of the vehicle elements that may influence roadkill predictors, such as engine power, speed, and traffic rate, and include human indicators that might influence driving behaviours. Also, future studies should include a sampling quality analysis, using the observations of the principal investigator and comparing these with the assistant's observations to control for mistakes and bias. Additionally, qualitative studies should document drivers' perceptions of the effect of vehicle use on roadkill mortality. The latter studies this can better inform local authorities during policy planning.

Based on our results, we can suggest that strategies to reduce the prevalence of roadkilled birds on the roads of Santa Cruz could include educational strategies for drivers and the community (i.e., community awareness using long-term campaigns, driving-skills training, and promotion of safe speed limits using social media), and this should involve all institutional actors for policy engagement (i.e., traffic surveillance, speed control, and traffic signs in hot spots) [16,34].

5. Conclusions

Avifauna in the Galapagos Islands are confronted with fatal vehicle impacts on roads, and we found three strong predictors of avian road mortality, which are bird size, endemic status, and seasonality. Not surprisingly, the most affected species is the Yellow Warbler because of its small size and endemic status, and according to our results, they die more during the hot season. Drastic temperature increases caused by climate change can be detrimental for this species, which, despite its abundance in the islands and being a non-threatened species, is an important element of biodiversity, and, therefore, essential to consider in conservation strategies. In this study, other determinants of avifauna road mortality are explored, which should be controlled in developing conservation strategies.

More importantly, the methodology used is recommended to be applied to other contexts with similar problems.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/birds5030031/s1. Data that serves as supporting information is available at: DOI 10.6084/m9.figshare.26377654. The geographic location of all roadkilled species in a heatmap per year can be found in Supplementary maps.

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