UNIVERSIDADE DE ÉVORA

ESCOLA DE CIÊNCIAS E TECNOLOGIAS

DEPARTAMENTO DE BIOLOGIA

Temporal patterns of bird roadkills in southern Portugal

Padrões temporais de mortalidade por atropelamento de aves no sul de Portugal

Pandora Francisca Costa Barão Pinto

Orientação: Dra. Sara Maria Lopes Santos

Dr. Rui Lourenço

Mestrado em Biologia da Conservação

Dissertação

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Resumo

Milhões de aves morrem atropeladas todos os anos mas pouca atenção foi dada às suas tendências populacionais ao longo do tempo. Nesta tese pretendo avaliar como as taxas de mortalidade por atropelamento de aves variam ao longo do tempo e quais as variáveis meteorológicas que contribuem para as tendências observadas. As minhas espécies-alvo são o pintassilgo *Carduelis carduelis*, o chapim azul *Parus caeruleus*, a toutinegra *Sylvia atricapilla*, o pardal comum *Passer domesticus*, o trigueirão *Emberiza calandra* e a coruja do mato *Strix aluco*. Quatro estradas foram monitorizadas no distrito de Évora de 2005 a 2013 e as estimativas de mortalidades foram corrigidas para ter em conta a persistência e detectabilidade das carcaças, tendo o número de atropelamentos aumentado consideravelmente. Modelos GAMM foram ajustados a todas as espécies como forma de incorporar a dependência temporal dos dados. Os resultados obtidos mostram que, em geral, a mortalidade diminuiu ao longo do tempo e foi geralmente maior durante os meses de primavera e verão. Os efeitos das variáveis meteorológicas nos padrões de mortalidade obtidos não foram óbvios, quando comparados com tempo e estação, e variaram entre as espécies, o que sugere a existência de factores adicionais para explicar as tendências observadas. Este estudo fornece dados concretos de que a mortalidade devido a colisões com veículos pode mudar ao longo do tempo, o que pode ter consequências demográficas e pôr em risco a eficácia de medidas de mitigação, destacando a necessidade de abordar maiores escalas temporais em investigação.

Temporal patterns of bird roadkills in southern Portugal

Abstract

Millions of birds are roadkilled every year but little attention has been given to its population trends overtime. In this thesis I intend to assess how the rates of bird mortality from vehicle collisions change overtime and which weather variables contribute to the observed trends and patterns. My target species are the goldfinch *Carduelis carduelis*, the blue tit *Parus caeruleus*, the blackcap *Sylvia atricapilla*, the house sparrow *Passer domesticus*, the corn bunting *Emberiza calandra* and the tawny owl *Strix aluco*. Four roads were monitored in the district of Évora between 2005 and 2013 and mortality estimations were corrected for carcass persistence and detectability, which significantly increased the number of roadkills. GAMM models were fit to all species as a way to incorporate the temporal dependence of the data. The results show that, overall, mortality decreased over time and was generally higher during spring and summer months. The effects of weather variables on the resulting mortality patterns were less obvious, when compared to time and season, and differed across the species, which may suggest the existence of additional factors important to explain the observed trends. This study provides concrete data that mortality due to car collisions may change overtime, which can have demographical consequences and risk the effectiveness of mitigation measures, highlighting the need to further address large temporal scales in research.

Introduction

Roads are important routes of transport and connectivity for people, and have become an increasingly common feature of our world as a result of human development and economic growth. However, roads also have numerous negative effects on adjacent habitats, wildlife and ecosystems and have become an issue of great concern in many countries worldwide (Coffin, 2007). They affect all kinds of living beings, from small invertebrates to large mammals, and both terrestrial and aquatic ecosystems (Trombulak & Frissel, 2000; Smith-Patten & Patten, 2008; Speziale et al. 2008). Being one of the main causes of fragmentation and loss of habitat; roads are also sources of pollution with chemicals, light and sound; and help the spread of invasive species (Trombulak & Frissell, 2000; Forman et al. 2003). Roads act as a barrier to animal movement in three ways: (i) physical, as it prevents individuals from crossing the road; (ii) behavioural, when animals avoid it; and (iii) by mortality due to collision with vehicles (i.e., roadkills). This way, they can alter the structure of populations in adjacent areas and may influence the genetic flow of species (Forman & Alexander, 1998; Trombulak & Frissell, 2000; Forman et al. 2003). The growing interest in quantifying and qualifying the ecological impacts of roads ultimately led to the emergence of Road Ecology, which in the end aims to avoid, minimize and compensate the damaging effects of roads on species and environment (Coffin, 2007; van der Ree et al. 2011).

Birds occupy a high diversity of ecological niches and play numerous vital roles in structuring and functioning of ecosystems, such as pollination and seed dispersal, therefore acting as bio-indicators of ecosystem health (Şekercioğlu et al. 2004). There are many reasons why birds use roads: (i) they provide foraging habitats for many species, such as scavenging raptors (capturing prey or taking advantage of roadkills) and insectivorous birds (the heat of the road attracts insects); (ii) they reduce predation pressure (e.g., offering hiding places, and enemy-free areas); (iii) the warm surface helps conserve metabolic energy; (iv) street lights prolong diurnal activity; (v) shrubs, trees, powerlines and other anthropogenic structures along roadsides are used as perching spots for birds of prey and songbirds, or nesting sites; and (vi) many birds use roads as ecological corridors or migration routes, etc. (Erritzoe et al. 2003;

Lambertucci et al. 2009; Morelli et al. 2014). But in spite of their attractiveness, roads pose a great risk of collision with vehicles for birds, with many millions of individuals dying every year in roads across the globe (Erritzoe et al. 2003).

Birds, common species in particular, are currently facing widespread declines in range and abundance due to human-driven changes (e.g., agriculture intensification; Donald et al. 2001; Fuller et al. 2005; IUCN, 2014; Loss et al. 2015; Inger et al. 2015), which is cause of growing concern. This could be exacerbated (or be an explanation) if local populations are suffering declines where the roadkill rate far exceeds recruitment rate, through reproduction and immigration. On the other hand, large numbers of casualties may not necessarily imply a threat to the survival of a species, but merely be a mirror of its abundance and distribution. There is however a clear lack of information in this respect, and also if mortality has changed for a species overtime (Erritzoe et al. 2003). Current research is mostly conducted at the spatial scale level and during short time periods (1-2 years; Garriga et al. 2017), targeting other road effects over roadkills (such as behaviour modifications, decrease in breeding success, etc.; Reijnen & Foppen, 2006) or the identification of factors affecting occurrence of roadkills (like habitat type, traffic disturbance, etc.; Reijnen & Foppen, 1994; Rosa & Bager, 2012). This situation, where we have many small scale independent studies, can't provide information necessary to quantify or mitigate the effect of roads on higher orders (e.g., populations, communities, ecosystems; Roedenbeck et al. 2007; van der Ree et al. 2011). To do so, road ecology studies need to address larger scales and, in the particular case of this thesis, a temporal one.

The question I intend to assess in this thesis is how birds' roadkill rates vary over time (annually and seasonally) and which weather variables contribute to the observed variations or trends. My target species are five passerines - goldfinch (*Carduelis carduelis*), blue tit (*Parus caeruleus*), blackcap (*Sylvia atricapilla*), house sparrow (*Passer domesticus*) and corn bunting (*Emberiza calandra*); and a strigiforme - tawny owl (*Strix aluco*). Data was obtained from a nine year survey of four road sections in the district of Évora, southern Portugal.

The goldfinch is a common passerine, mainly granivorous, that can be found in a wide variety of habitats, from parks and urban gardens, open or sparse forested areas, edges, streams and riverine areas, to orchards or cultivated lands. Breeding takes place between April and early August (Clement, 2016). This species is widely distributed across Europe and central Asia and the population seems to have undergone a moderate increase in Europe, thus being evaluated as least concern (LC) according to the global IUCN Red list category (EBCC, 2015; BirdLife International, 2017).

The blue tit is a forest bird, inhabiting a variety of woodland habitats, parks and gardens. The breeding season is from April to June. It feeds mainly on insects and spiders, plus fruits and seeds, nectar and pollen, although the diet can vary depending on food abundance (Gosler et al. 2013). This is a common European species, mostly resident, with populations showing a moderate increase across its range, and therefore considered to be of least concern by the IUCN (EBCC, 2015; BirdLife International, 2017).

The blackcap can be found in almost all kinds of forested areas and breeding mainly occurs from mid-April to August (Aymí et al. 2013). It is a typically insectivorous bird, but during autumn and winter, it feeds mostly on fruits, which can influence seasonal habitat occupation (Jordano & Herrera, 1981; De Los Santos et al. 1986). The blackcap has an extremely large range and can be found all over Europe and also in some areas of the north of Africa and sub-Saharan regions, where it migrates to (EBCC, 2015; BirdLife International, 2017). In the north and eastern parts of its range, this species is a long-distance migrant, while in the Mediterranean basin and some parts of Western Europe, it is partially migratory (Aymí et al. 2013). The population is suspected to be increasing globally; hence it's classified as least concern by the IUCN Red list (EBCC, 2015; BirdLife International, 2017).

The house sparrow is a species very closely associated with humans, easily found around man-made structures, from farms to urban centres. Breeding occurs from February to September, but timing may vary with altitude. It feeds mainly on seeds from grasses, cultivated cereals and low herbs, but also buds, berries and a variety of household scraps (Summers-Smith et al. 2015). Although this species is native to

Eurasia and North of Africa, it can now be found in most parts of the world, having been introduced to North and South America, South of Africa and Oceania (BirdLife International, 2017). In Portugal, house sparrow populations are considered stable, but in Europe, the population trend seems to be declining, which is mostly attributed to changes in agricultural practices. However, there has also been a significant decline in urban house sparrows but the causes are not properly understood (De Laet & Summers-Smith, 2007; Meirinho et al. 2013; EBCC, 2015). Nonetheless, due to its large range and general population size, house sparrow is classified as least concern acoording to the IUCN Red list (BirdLife International, 2017).

The corn bunting lives in open grasslands, both in natural steppe and agricultural lands. It feeds primarily on seeds but during the breeding season small invertebrates are a large part of its diet. On north-western populations, breeding starts from late May onward, but it probably starts sooner in the south of its range. North and western populations are mostly sedentary whilst the population from Central and Eastern Europe are partially migratory (Madge & de Juana, 2017). This species show a moderate decline across Europe, which is particularly accentuated in the northwest and is attributed to agricultural intensification (Donald & Forrest, 1995; EBCC, 2015; BirdLife International, 2017). In Portugal, on the other hand, the population is considered stable and because it has a large distribution across Europe and western and central Asia, corn bunting is classified as least concern by the IUCN (Meirinho et al. 2013, BirdLife International, 2017).

A highly sedentary and territorial species, the tawny owl is a forest bird, although it can be found in urban and clear-felled areas and intensive agricultural areas. The breeding season of this species goes from February to July. It feeds on small mammals and birds but will also consume amphibians, reptiles, occasionally fish and a variety of invertebrates (Hagemeijer & Blair, 1997; Holt et al. 1999). The tawny owl can be found all over Europe and some parts of the west and central Asia and is considered to be of least concern by the IUCN Red list (BirdLife International, 2017).

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Research article

Temporal patterns of bird roadkills in southern Portugal

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Abstract

Despite mortality by collision with vehicles being a big source of mortality for many bird species worldwide, very little attention has been given to its temporal trends. We assessed how the roadkill mortality patterns of common bird species changed over a period of nine years in southern Portugal and which weather factors influence the observed patterns. We corrected mortality estimations and fitted GAMM models to all species. Roadkills' numbers increased substantially after correcting for survey frequency, and carcass persistence and detectability. Our results show that, overall, mortality decreased over time and was generally higher during spring and summer months. The lack of a clear relationship between the weather variables and the observed mortality patterns suggests the existence of additional factors important to explain the observed trends. Our study provides concrete data that mortality due to car collisions may change overtime, which can have demographical consequences and risk the effectiveness of mitigation measures, highlighting the need to further address large temporal scales in research.

Key words: Temporal trends, passerines, tawny owl, common species, mortality, annual patterns.

1. Introduction

Biodiversity worldwide is currently facing unprecedented declines due to human activity. For the past 500 years, there has been an increase in extinction rates that far exceeds the expected rate based on geological record (Dirzo & Raven, 2003; Hoffmann et al. 2010; Dirzo et al. 2014; Ceballos et al. 2015). Such trends are linked to the major causes of biodiversity loss: habitat change, climate change, spread of invasive alien species, over-exploitation and pollution (Butchart et al. 2010). Much of the conservation efforts are focused on rare species, since theoretically they are the ones facing greater risk of extinction, but common species on the other hand have received far less attention (Inger et al. 2015; Gaston, 2010; 2011). Their sheer numbers make them significant ecosystem shapers – creating, maintaining and modifying habitats; they are involved in many biotic interactions and act as the support of many ecosystem services. But despite playing key roles in terrestrial and marine ecosystems, common species are greatly affected by habitat loss and degradation, over-exploitation and invasive species, often suffering big population and distribution losses (Gaston, 2010; 2011). Birds in particular, are experiencing widespread declines in range and abundance as a result of human-driven changes (Donald et al. 2001; Fuller et al. 2005; Loss et al. 2015; IUCN, 2014). The decline of common birds is of growing concern, as more studies suggest that they play vital roles in structuring and functioning of ecosystems. A drop in their numbers will have negative consequences in many ecosystem processes and services, such as decomposition, pollination, pest control and seed dispersal (Şekercioğlu et al. 2004; Inger et al. 2015). According to the 2015 report of the British Trust for Ornithology (BTO), 29 bird species show a population decline of more than 50% in recent years (Robinson et al. 2015), among which are species considered common such as house sparrow (*Passer domesticus*), common starling (*Sturnus vulgaris*), common house martin (*Delichon urbicum*) or corn bunting (*Emberiza calandra*). Among the most reported ecological causes to explain some of these declines are agricultural intensification and habitat changes (Robinson et al. 2015; Donald et al. 2001). But there are additional anthropogenic factors that negatively affect hundreds of millions of individuals every year.

Roads have numerous direct and indirect impacts on birds and have become an issue of great concern in many countries worldwide. The most visible impact of roads on birds is mortality by collision with vehicles (Forman et al. 2003). It is estimated that between 89 to 340 million birds are road-killed each year in the United States (Loss et al. 2014) and in some European countries estimates vary from 653 000 in the

Netherlands, 1.1 million in Denmark, more than 7 million in Bulgaria, 8.5 million in Sweden, 9.4 million in Germany and 27 million in England (Erritzoe et al. 2003). These are impressive numbers and yet, very little attention has been given to the temporal trends of these numbers. Most studies focus on documenting spatial patterns of roadkills, concentrating on mortality 'hotspots', which are useful for defining location of mitigation measures. On the other hand, they are normally conducted over fairly short time periods (1-2 years) and only report on seasonal variations in roadkills. Therefore, it is fundamental to assess if this source of mortality has been changing over the years so we can understand its influence and possible impact on the persistence and viability of populations.

Passerines (Passeriformes) and owls (Strigiformes) are among the taxonomic groups more often referred to in studies documenting roadkills (Erritzoe et al. 2003; Benitez-Lopez et al. 2010; Grilo et al. 2014). Some studies show that species with the highest mortality rates are the more common ones, although some behavioural and ecological characteristics contribute to a higher vulnerability of some of these species to roadkills (Moller et al. 2011; D'Amico et al. 2015). In southern Portugal, a recent research was conducted to see if mortality of passeriformes is associated with abundance near roads and morphological, ecological and behavioural traits (Santos et al. 2016). Results showed a strong relation between vulnerability to roadkills and foraging behaviour and habitat type, with the most vulnerable birds being the small woodland species that feed in shrubs and trees. It was also shown that there was a higher than expected mortality for goldfinch (*Carduelis carduelis*), blue tit (*Parus caeruleus*) and blackcap (*Sylvia atricapilla*), considering their abundance near roads. Besides passerines, owls are also subject of high roadkill rates, particularly tawny owl (*Strix aluco;* Silva et al. 2008; Silva et al. 2012; Santos et al. 2013). There has been evidence that road mortality contributed to reduce barn owl populations in the UK (Ramsden, 2003) and in view of that, a high mortality in tawny owl, especially if it leads to a population decline, could be a cause for worrying since this species is a top predator. Thus, if reproduction and immigration are unable to offset the number of roadkills, this could lead to a decline in local abundances and compromise the long-term survival of populations. On the other hand, it is well known that there are warmer years and more humid and cold years. It is possible that the variation in annual mortality patterns may be partially explained by changes in weather conditions. For example, weather variations may explain differences in food availability for wildlife, which in turn limit animal populations (White, 2008). Less rainfall translates into lower vegetation growth and consequently lower reproductive success of primary consumers (herbivorous). With lesser availability of prey, predators have to move more and may face larger risk of mortality, such as roadkills. Also, long-term shifts in average weather, i.e. climate change, are already having effects on animals, such as earlier breeding, changes in timing of migration and breeding performance, changes in population sizes, etc. (Crick, 2004), which could potentially influence mortality over time.

In this study we intend to assess how the roadkill rates of six bird species vary over time (annually and seasonally) and which weather variables contribute to the observed variations or trends. Besides the three species with a higher than expected mortality – goldfinch (*Carduelis carduelis*), blue tit (*Parus caeruleus*) and blackcap (*Sylvia atricapilla*), and the tawny owl which is the strigiforme with highest casualties in roads near woodlands (Santos et al. 2013) – we will also consider the house sparrow (*Passer domesticus*) and corn bunting (*Emberiza calandra*), which are subject to high mortality rates, but in proportion to their local abundance (Santos et al. 2016). Thus, we intend to verify if there are different patterns between the species that die more than expected and the species that die as expected according to their abundances. For the tawny owl, it is not known whether mortality is higher or lower than expected. It is hypothesized that, should a decline of roadkills occur through the years, it is more likely in goldfinch, blue tit or blackcap (due to their greater vulnerability; Santos et al. 2016) when compared with remaining studied species.

2. Methods

2.1. Study area

The study area is located in southern Portugal, in the district of Évora (38°32'24'' to 38°47'33''N; -08°13'33'' to -07°55'45''W). The landscape is characterized by woodlands of cork and holm oaks (*Quercus suber* and *Q. rotundifolia*) and agricultural areas (arable land, olive groves, and vineyards), with a smooth and undulating relief (under 400 m above sea level). The climate is typically Mediterranean with hot, dry summers and mild winters with annual rainfall averaging 609.4 mm. During summer (in July), mean temperature varies from 16.3^{o}C to 30.2^{o}C and in winter (January) it fluctuates between 5.8^{o}C and 12.8 C (Évora 1981-2000; IPMA, 2017).

The roadkill surveys were performed on four road sections (N4 and N114, M529 and M370), totalling 37 km between Évora and Montemor-o-Novo (Fig. 1).

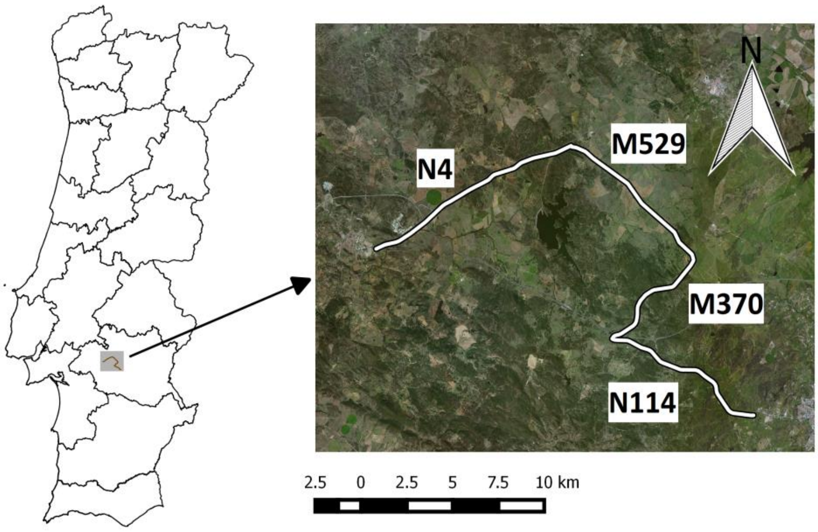

Fig. 1 Location of the four studied roads (N114, N4, M529 and M370) in southern Portugal.

2.2. Roadkill dataset

A dataset of 2 533 road-killed birds, recorded between 1st January 2005 to 31th December 2013 (nine years) was obtained from the UBC database (Conservation Biology Unit, Department of Biology, University of Évora). Considering the above value, 26.6% of these birds were blue tit (n=674), 19.5% blackcap (n=494), 15.7% goldfinch (n=398), 14.5% tawny owl (n=368), 12.2% house sparrow (n=308), and 11.5% corn bunting (n=291).

Road surveys were performed by an experienced observer driving a car at low speed (20-40 km/h) and starting at sunrise. The frequency of surveys varied between daily (2005; 16th March 2009 to 31th October 2009; 16th March 2010 to 22nd March 2013) and weekly (2006-2008; November 2009 to 15th March 2010). No surveys were done during the month of April 2013. Every carcass found was identified to the lowest taxonomic level and taken its GPS position. For more survey details see Santos et al. (2011, 2013, 2016). Due to the temporal extension of these surveys, it was not always possible to guarantee the same observer, however, there was always care to standardize procedures and minimize the error caused by different observer skills.

2.3. Explanatory Variables

In order to assess the influence of weather conditions on roadkill temporal patterns, we selected the following variables: year, month, mean monthly maximum temperature (^{o}C) (mtmax), mean monthly minimum temperature (^{o}C) (mtmin), total monthly rainfall (rainfall), the sum of rainfall for the first 4 months of the year (January - April) and the difference in monthly rainfall in relation to mean annual value. Values for all weather variables were obtained from Instituto Português do Mar e da Atmosfera (IPMA, 2017).

2.4. Data Analyses

2.4.1 Data organization

The roadkill dataset was first organized as a time series data, being each observation a unique month count of observed roadkills and starting in January 2005. Thus, we built six datasets, each one belonging to a different species. When assessing mortality rates there are a number of factors that affect the probability of finding a carcass and, ultimately, can lead to an underestimation of mortality numbers (Santos et al. 2011; Teixeira et al. 2013). Considering that the surveying periodicity varied over the years and smaller birds quickly disappear from roads (Santos et al. 2011; Teixeira et al. 2013), it was necessary to correct the roadkill counts. Carcass detection probability was obtained with Huso estimator that combines the carcass persistence probability, the searcher efficiency and the survey interval (Korner-Nievergelt et al. 2015). Then it is possible to estimate the number of animals that have died from the number of carcasses counted and the estimate for carcass detection probability. We defined daily persistence probability of 0.366 for passerine and 0.745 for owl carcasses (Santos et al. 2011). There was no experimental data for searcher efficiency, but we considered 0.8 for passerines and 1.0 for owls, meaning that, being present on the road, passerines are harder to find than owls due to its smaller size. We used two functions within Huso estimator to estimate the number of carcasses: the median of posterior distribution of number of carcasses (posteriorN) and the Horvitz-Thompson estimator (HT; equals the number of carcasses found divided by the detection probability) (Korner-Nievergelt et al. 2015). To choose the best approach, a Wilcoxon rank test was calculated to verify if different survey frequencies (daily vs. weekly) had different estimates. The HT equation was considered more adequate because no differences between survey frequencies were found ($W = 8$, $p = 0.730$), while the posteriorN equation yielded significant differences between survey frequencies ($W = 20$, $p = 0.016$) giving higher estimates of mortality for months with weekly surveys. In further analyses, the HT approach was used (see Appendix figures).

2.4.2. General roadkill trends

To characterize mortality patterns of species, temporal trend graphics were done for each species and generalized linear models (with Poisson link) were adjusted to visualize the significance of the tendencies.

2.4.3. The influence of variables on roadkills

A preliminary selection of explanatory variables was done with exploratory plots and Pearson correlations that were calculated to check for collinearity problems (Zuur et al. 2007, 2010). “Minimum mean temperature” was discarded due to high correlation with “maximum mean temperature” ($r > 0.70$). Concerning rainfall-related variables, only total rainfall was kept (due to high correlation) and a logarithmic transformation was applied to remove outliers and improve normality.

Exploratory analysis of the data showed that the response variable (mortality numbers) did not have a normal distribution nor a linear relationship with all predictor variables and, being count data, we would have to model it with a Poisson distribution. Furthermore, we had a temporal data series and a probable lack of statistical independence between observations. This led us to use Generalized Additive Mixed Models (GAMM) as a way to incorporate the temporal correlation component of the data and also include a Poisson link and non-linear effects (Zuur et al. 2007, 2009). We used auto-regressive (AR) and auto-regressive moving average (ARMA) models with a residual correlation structure (using alternatively, year or month) to determine the influence of year, season, and weather conditions on mortality trends (Zuur et al. 2009). The correlation structure that yielded a model with the lowest Akaike's Information Criteria (AIC) was selected. All explanatory variables were initially entered as smoothing terms and only remained in the model as such if significant ($P < 0.05$) and non-linear (edf > 2). The significant explanatory variables with linear effects (edf < 2) were maintained in the model but defined as linear terms (without the smoothing term). Models with lower AIC were considered to be superior to the remaining (Zuur et al. 2009). The final model for each species was selected using AIC and an assessment of goodness of fit was done with residual plots and amount of explained deviation.

Estimates and calculations of carcass detection probability were conducted with 'carcass' R package (Korner-Nievergelt et al. 2014, Korner-Nievergelt et al. 2015). Mixed models were applied using 'mgcv' package (Wood, 2017). All analyses and graphical outputs were performed with R version 3.3.0 (R Development Core Team 2011).

3. Results

From 2005 to 2013 a total of 2 533 road-killed birds belonging to the six target species were recorded. This number increased substantially to 7 438 carcasses after applying the Huso estimator that accounts with survey frequency, mean carcass persistence time and observer detectability (Korner-Nievergelt et al. 2014). After correcting for roadkill estimates, blue tit and blackcap were the species with highest mortality numbers, accounting for 27.7% (n = 2060) and 25.8% (n = 1918) of the total number of roadkills, respectively. The goldfinch, corn bunting, and the house sparrow had intermediate levels of mortality with 14.9% (n = 1106), 12.7% (n = 942) and 12.6% (n = 935) of total mortality, respectively. Among the species considered for this study, the tawny owl had the lowest mortality rates, but still accounting with 6.4% (n = 477) of roadkills.

3.1. General Roadkill Trends

There is a general decreasing trend of the number of roadkills for all species studied from 2005 to 2013 (Fig. 2). This decreasing trend seems highest in the blackcap (GLM coefficient = -0.016) and lowest in the blue tit and goldfinch (GLM coefficient = -0.008), although the difference between the two coefficients is small.

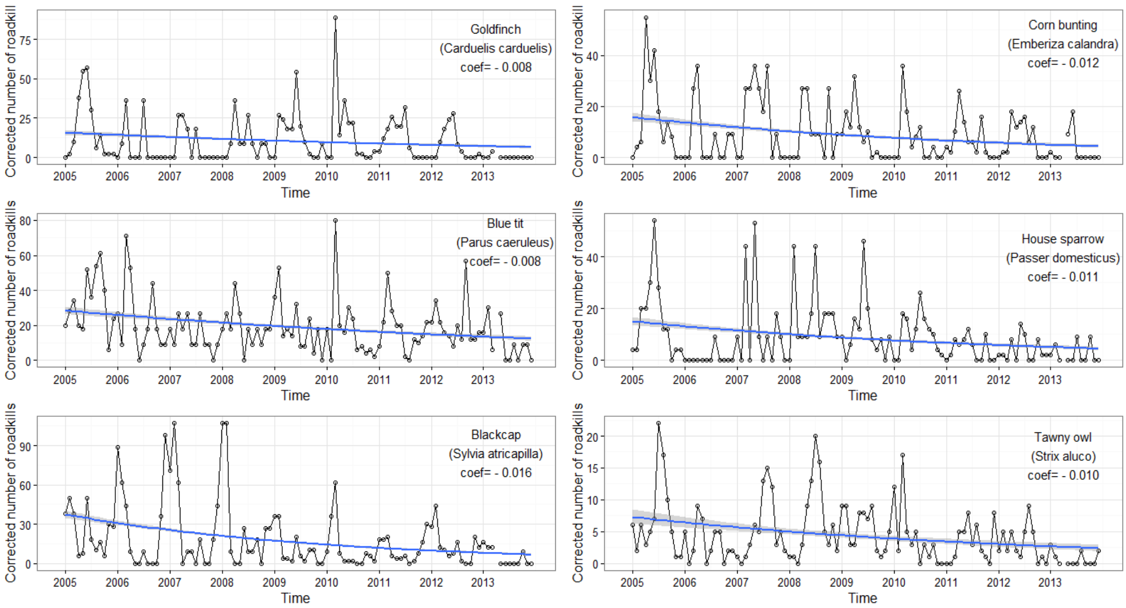

Fig. 2 Annual trends of the estimated mortality caused by roadkills for goldfinch, corn bunting, blue tit, house sparrow, blackcap and tawny owl for nine years (2005-13). A GLM model was fitted for each species and the respective coefficient is presented.

The roadkill patterns were not regular within years and there was some seasonality in roadkills for all species (some months with very high roadkill rates and other months with minimum roadkill rates). Figure 3 shows how mortality varied along the year for each species. In general, roadkills increase during spring and summer months, except for the blackcap. The mortality pattern of this species peaks in winter months, reaching its highest value in our study in January. The goldfinch, corn bunting and house sparrow show similar patterns, dying more between March and July, with much lower numbers of roadkills during the remaining months. Comparatively to the other species, the mortality in the blue tit was rather constant throughout the year, slightly increasing in spring and summer. Roadkills of tawny owls were higher during summer, peaking in July and August, though there was also a slight increase in January.

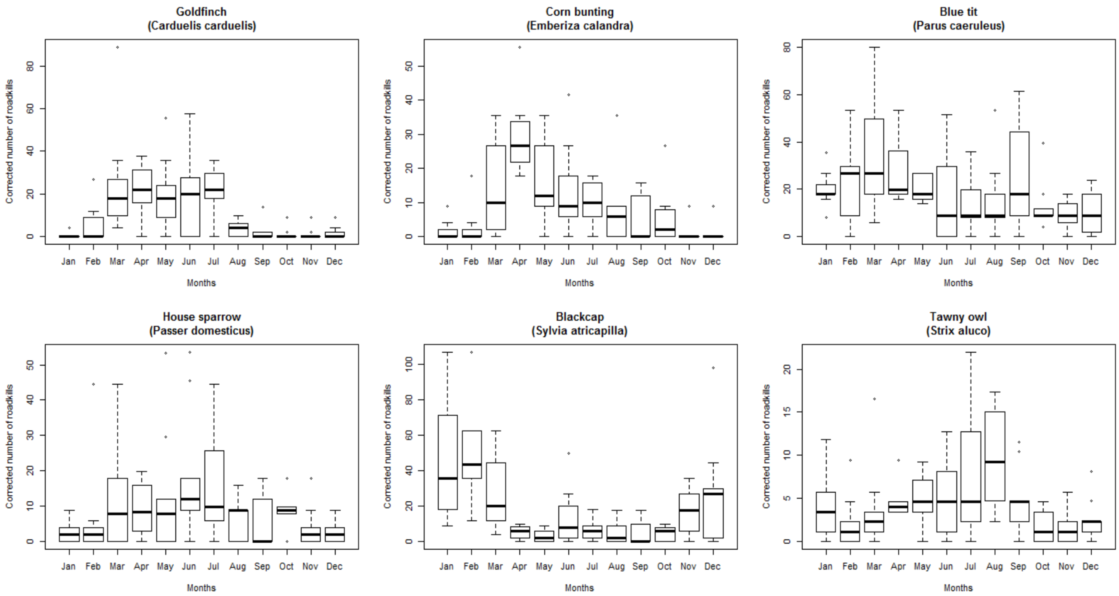

Fig. 3 Seasonal trends of the estimated mortality caused by roadkills for goldfinch, corn bunting, blue tit, house sparrow, blackcap and tawny owl.

3.2. The influence of weather variables on roadkill trends

The best GAMM model for the blue tit, corn bunting, and house sparrow was an auto-regressive model incorporating dependence between consecutive months (phi=-0.05 for the blue tit; phi=-0.04 for the corn bunting; and phi=-0.07 for the house sparrow).

The best model for the tawny owl incorporated a temporal dependence between years (phi=0.16), while the best model for the goldfinch and blackcap was an auto-regressive moving average (ARIMA) model (phi1=0.06, phi2=-0.06 for the goldfinch; phi1=-0.08, phi2=0.86 for the blackcap) (Table 1).

The models built showed good fit to the roadkill time series data after inspection of residual plots. The amount of variance explained was quite good for the blackcap, corn bunting and goldfinch (between 53.2% and 68.7%) but lower for the blue tit, house sparrow and tawny owl (between 23.8% and 33.6%; Table 1).

Table 1 Summary of GAMM results with parameters of explanatory variables included in final models for each species (EDF: estimated degrees of freedom of non-linear terms, F: F test of non-linear terms, p-value: significance of F test of non-linear terms; Coef.: regression coefficient of linear terms, t: t test for significance of coefficient, p-value: significance of t test of linear terms; Phi: parameters referring to the residual correlation structure, R^2 adj.: proportion of explained deviation of model).

	Variables	Smooth terms			Linear Terms			Phi
		Edf	F	p-value	Coef.	T	p-value	
	Year	3.930	56.013	<0.001				0.06; -0.06 (a)
	Month	3.868	105.267	<0.001				
	Rainfall	3.277	8.571	<0.001				
Goldfinch	Mtmax	3.895	26.630	<0.001				
	Year	3.718	28.660	<0.001				-0.05 (c)
	Month	3.851	67.080	<0.001				
	Rainfall	3.826	8.724	<0.001				
Blue tit	Mtmax	3.531	3.262	0.00989				
	Year	3.847	95.990	<0.001				-0.08; 0.86 (b)
	Month	3.686	43.115	<0.001				
	Rainfall	3.730	9.662	<0.001				
Blackcap	Mtmax	3.975	47.416	<0.001				
	Year	3.933	66.541	<0.001				-0.07 (c)
House sparrow	Month	3.636	51.747	<0.001				
	Rainfall	2.896	9.805	<0.001				
	Year				-0.12	-6.340	<0.001	-0.04 (c)
	Month	3.937	164.62	<0.001				
	Rainfall	3.886	11.87	<0.001				
Corn bunting	Mtmax				-0.06	-3.085	0.00266	
	Year	3.060	13.076	<0.001				0.16 (c)
	Month	3.745	6.757	<0.001				
	Rainfall				-0.08	-1.703	0.0917	
Tawny owl	Mtmax				-0.05	-2.013	0.0469	

*Correlation structures: (a) ARMA (2,0); (b) ARMA(1,0); (c) AR(1).

Mortality rates of the goldfinch through time were best explained by year, month, temperature and rainfall. From 2005 to 2007 there was a steep decrease in mortality, although reaching high values in 2010, and decreasing again from 2011 onward. There was also a seasonal effect within the year, with mortality peaking in March- June. Months with temperatures around 15-20°C and higher than 30°C had higher probability of increased mortality. The effect of rainfall was less clear but indicates that mortality was higher for more than 50 mm of monthly rainfall (Fig. 4).

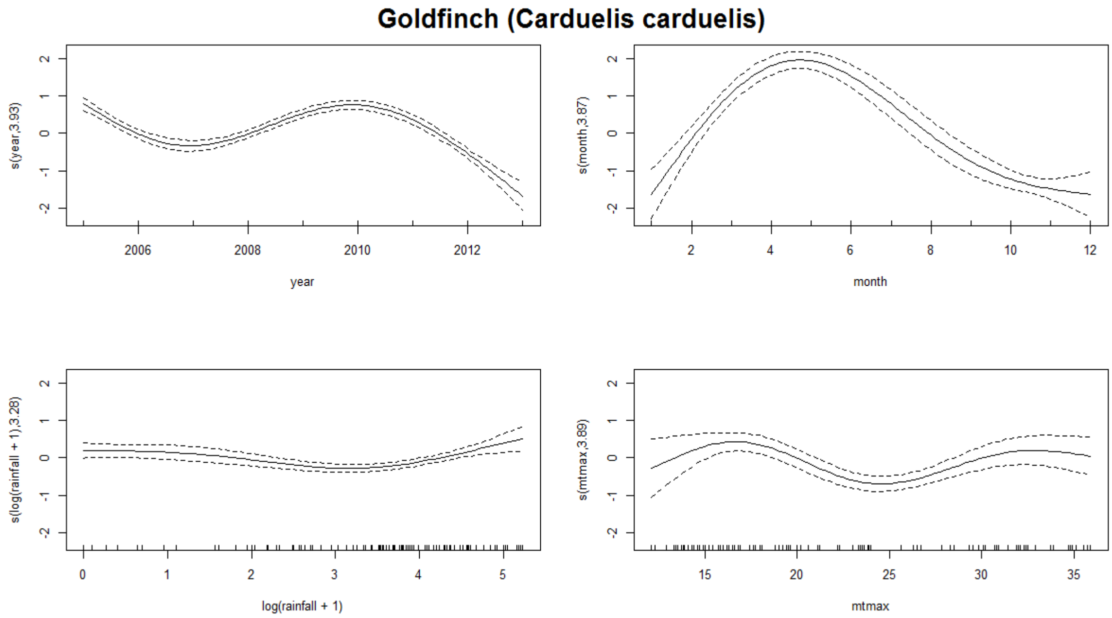

Fig. 4 Non-linear factors affecting the temporal distribution of roadkills for goldfinch. Fitted smooth terms (written as s(name of variable, number of degrees of freedom)) for goldfinch's mortality (solid lines) and confidence intervals (dashed lines); top left panel: year, top right panel: month, bottom left panel: rainfall, bottom right panel: maximum temperature.

The trend in mortality rates of the blue tit were best explained by year, month, temperature and rainfall. Mortality for this species was highest in 2005 and decreased afterwards up till 2008. From here on, it slightly increased until 2011, which was followed by another decrease. There is also a seasonal effect within the year, with higher levels of mortality in March-April and again in September-October. The effects of temperature and rainfall are more subtle, but results indicate that mortality is higher at temperatures lower than 17°C and higher than 30°C, while rainfall has the same effect at monthly values around 2-7 mm and 50-90 mm (Fig. 5).

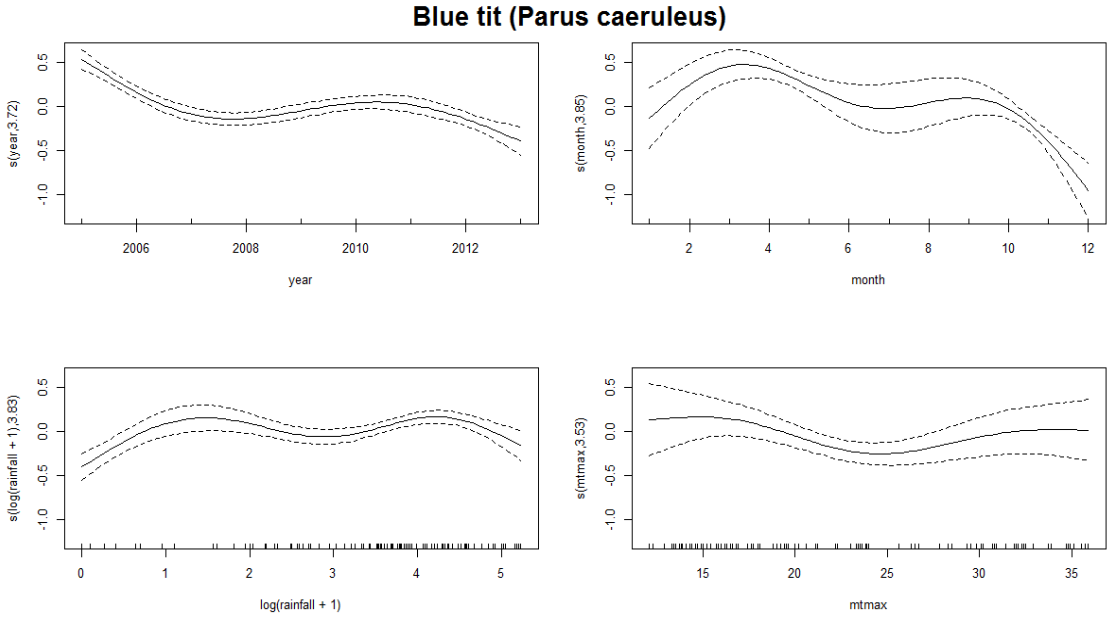

Fig. 5 Non-linear factors affecting the temporal distribution of roadkills for blue tit. Fitted smooth terms (written as s(name of variable, number of degrees of freedom)) for blue tit's mortality (solid lines) and confidence intervals (dashed lines); top left panel: year, top right panel: month, bottom left panel: rainfall, bottom right panel: maximum temperature.

Roadkills of the blackcap were best explained by year, month, temperature and rainfall. Mortality decreased along the years, being highest between 2005 and 2007. There is evident seasonality in the mortality pattern of blackcaps, with individuals dying more in winter months. In respect to the weather variables, mortality increases between 2-7 mm and for more than 55 mm of rainfall/per month; and when temperatures are between 10-17^{o}C and 27-34^{o}C (Fig. 6).

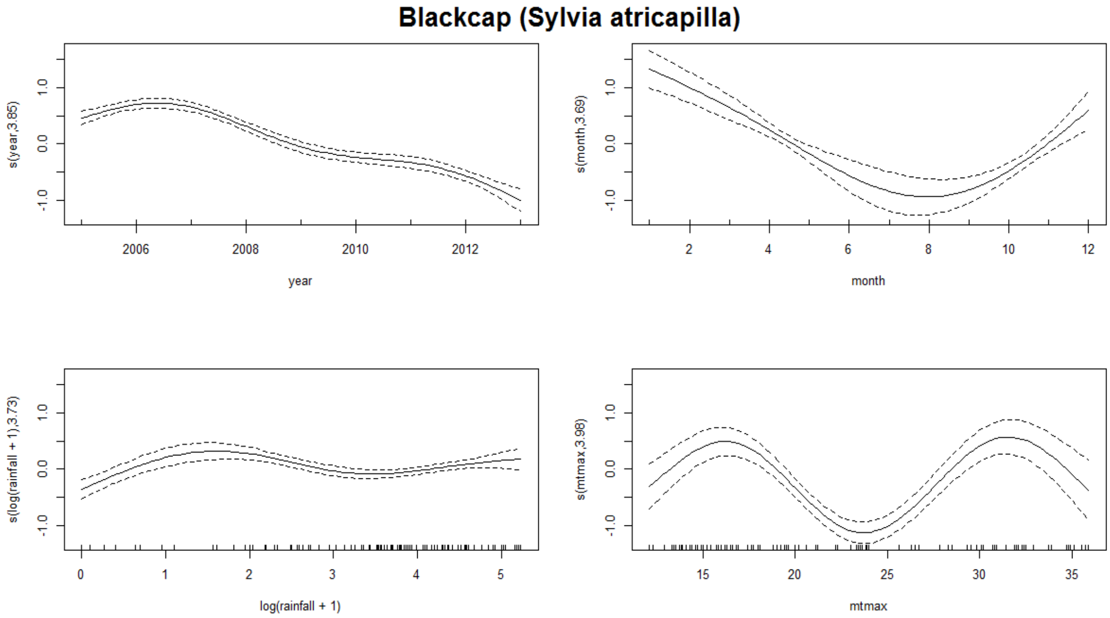

Fig. 6 Non-linear factors affecting the temporal distribution of roadkills for blackcap. Fitted smooth terms (written as s(name of variable, number of degrees of freedom)) for blackcap's mortality (solid lines) and confidence intervals (dashed lines); top left panel: year, top right panel: month, bottom left panel: rainfall, bottom right panel: maximum temperature.

Mortality of the house sparrow was best explained by year, month and rainfall. There was a decrease in mortality from 2005 to 2006, followed by a peak between 2008 and 2010, after which it decreases again. Mortality was also highest from March to August. The effect of rainfall on the number of roadkills of house sparrows was not very obvious, but for values lower than 55 mm, mortality seemed to decrease (Fig. 7).

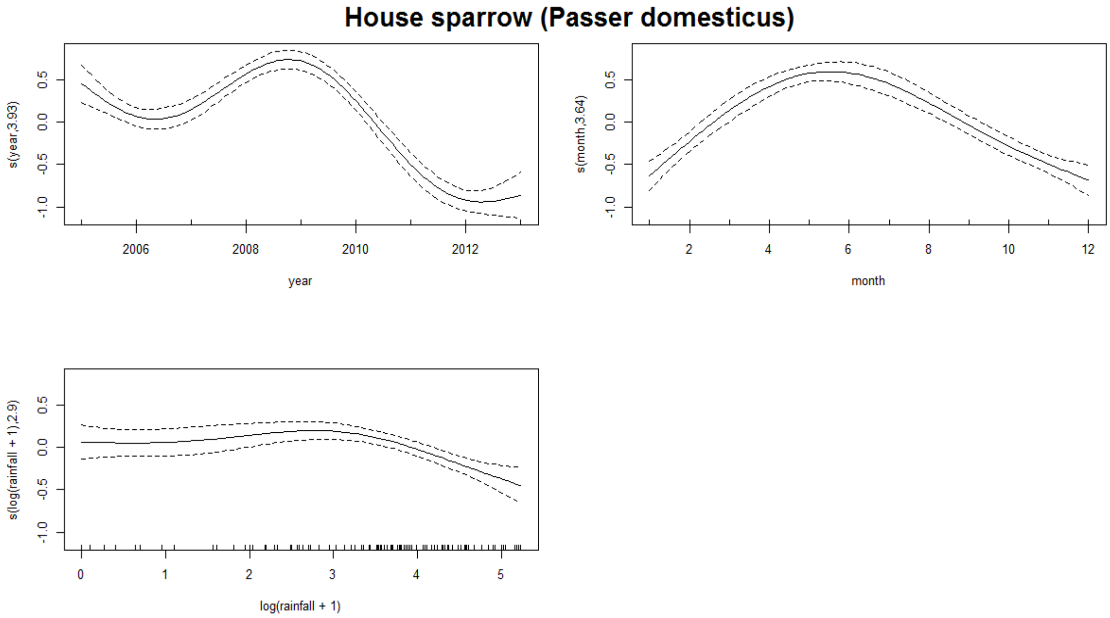

Fig. 7 Non-linear factors affecting the temporal distribution of roadkills for house sparrow. Fitted smooth terms (written as s(name of variable, number of degrees of freedom)) for house sparrow's mortality (solid lines) and confidence intervals (dashed lines); top left panel: year, top right panel: month, bottom left panel: rainfall.

The mortality of the corn bunting was best explained by year, month, temperature and rainfall. Mortality decreased linearly through the time period considered (negative coefficient), the same occurring with higher temperatures (Table 1). Within the year, mortality started to increase in the beginning of the year, peaking from April to June and decreasing afterwards. For monthly values of rainfall between 2-7 mm and 55-148 mm, the number of roadkills of corn buntings increased (Fig. 8).

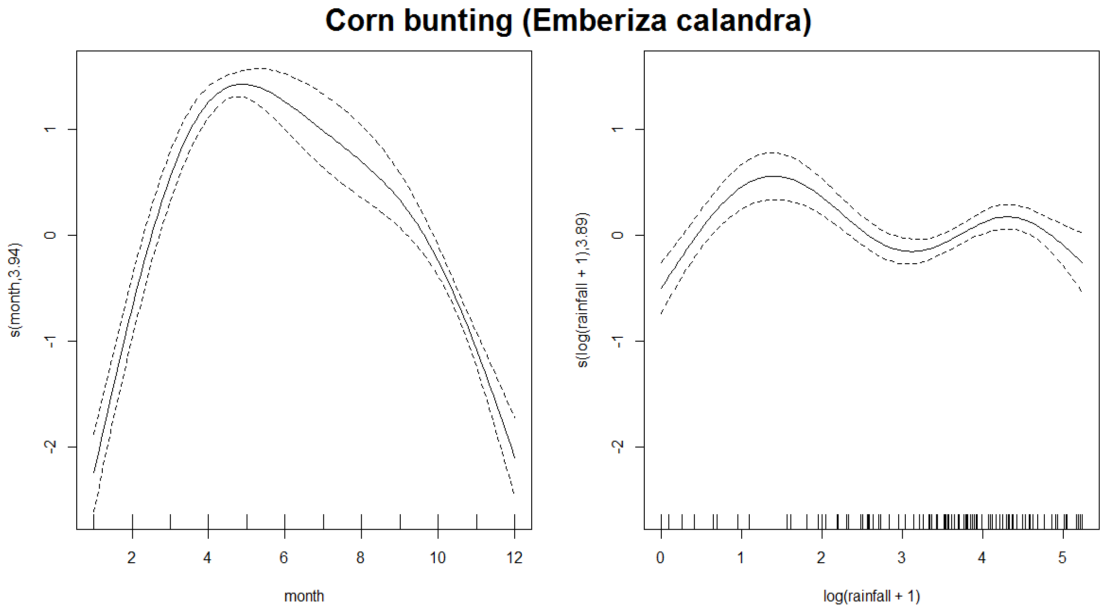

Fig. 8 Non-linear factors affecting the temporal distribution of roadkills for corn bunting. Fitted smooth terms (written as s(name of variable, number of degrees of freedom)) for corn bunting's mortality (solid lines) and confidence intervals (dashed lines); left panel: month, right panel: rainfall.

Mortality of the tawny owl through the study period was best explained by year, month, temperature and rainfall, the last two with linear effects. Mortality lightly decreased from 2005 to 2007, remaining stable until 2010, when a steep decrease occurred. There is a seasonal effect within the year with mortality increasing in March and peaking between June and August, followed by a decline (Fig. 9). Rainfall and maximum temperature are negatively correlated with mortality (-0.08 and -0.05 respectively; Table 1), so roadkills are increased during cold and dry months.

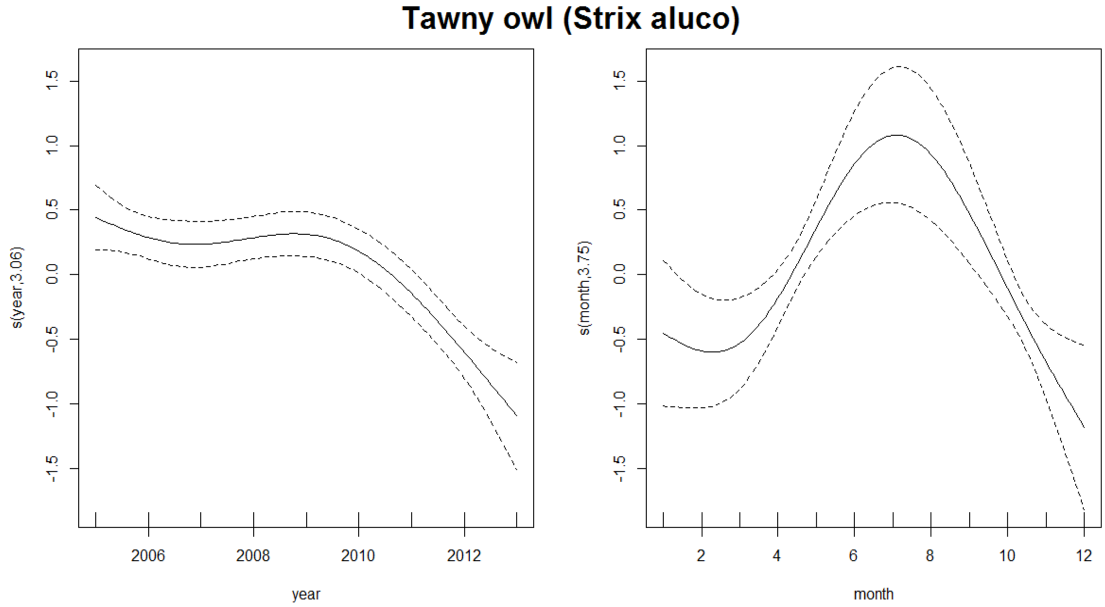

Fig. 9 Non-linear factors affecting the temporal distribution of roadkills for tawny owl. Fitted smooth terms (written as s(name of variable, number of degrees of freedom)) for tawny owl's mortality (solid lines) and confidence intervals (dashed lines); left panel: year, right panel: month.

4. Discussion

Our study revealed an overall decreasing trend in the number of roadkills from 2005 to 2013 for all studied species, although slightly more evident in some of them. However, the differences detected did not support our proposed hypothesis: the three most vulnerable species to roadkills (i.e., higher than expected mortality: goldfinch, blue tit, and blackcap) did not show a stronger decline when compared to species that die in proportion to their abundance (house sparrow and corn bunting). Although the decreasing trend was stronger for blackcap, the same was not observed for goldfinch or blue tit, and all species presented a decreasing trend.

While the mortality pattern was not the same throughout the years, all species showed marked seasonality in the number of roadkills. The effects of weather variables were less obvious, when compared to time and season, and differed across the species, which may suggest the existence of additional factors important to explain the observed trends.

4.1. The declining trend of roadkills

In the specific case of the blackcap, a potential explanation for the observed reduction in mortality throughout the years could be differences in migration flows, which may be related to worldwide species trends and climate change. Many studies report an association between bird migratory phenology and weather variables, with the recent shifts in migration periods being a response to climate change (Gordo, 2007; Jonzén et al. 2007).

However, the number of road-killed individuals should be mainly a consequence of bird abundances near roads (Moller et al. 2011). Thus, the decrease in mortality from collision with vehicles that we witnessed in this study, could be a consequence of a local or regional decline in the populations of the resident species, probably influenced to some degree by years of cumulative roadkills. The house sparrow is one of the most frequently reported road-killed species, both in neotropical and temperate zones (Erritzoe et al. 2003; Rosa & Bager, 2012). Despite its large range, in Europe, house sparrows have been declining since 1980, with this trend explained by the intensification of agricultural practices (De Laet & Summers-Smith, 2007; BirdLife International, 2017). Reports from Spain indicate the same decline for this species, while in Portugal, the house sparrow is considered to have a stable population trend. The european trend of the corn bunting also shows a population decline, attributed as well to changes in agriculture, but all other target-species are either stable or show moderate increases in their numbers across Europe and Portugal (Meirinho et al. 2013; SEO/BirdLife, 2014; GTAN-SPEA, 2016; BirdLife International, 2017). Thus, a decreasing trend in roadkills seems unexpected, unless the regional trend of populations is somewhat different than the national trend. Still, one should consider the possibility that population trends near and far from main roads may have opposite directions – despite a general population increase, abundance near main roads might be declining from continuous and accumulated effect of mortality and disturbance.

Bird abundance near roads could also be affected by the surrounding habitats and their quality (Orlowski, 2008; Erritzoe et al. 2008; Rosa & Bager, 2012; Santos et al. 2016). There are contradictory approaches to the value of roadside vegetation and hedgerows for birds. Some studies show their positive role in transforming roadsides into suitable habitats (Morelli et al. 2014; Morelli et al. 2015), while others highlight the higher mortality in such areas (Orlowski, 2008). Roadside vegetation is used by many bird species as a breeding, foraging and resting area, but its presence could potentially act as an ecological trap. This is of particular importance when certain habitat types (e.g. woody vegetation in cropland borders) are only present along the communication routes, attracting birds to the area and potentially making them more vulnerable to roadkills (Orlowski, 2005, 2008). Orlowski (2005) found that, in an agricultural landscape, barn swallows (*Hirundo rustica*) were attracted to treebelts and hedgerows along roads due to a higher density of insects and especially during severe weather conditions (as a way to reduce the energetic cost of flight), thus being at risk of colliding with oncoming vehicles. However, this seems to be an unlikely explanation in our case as habitat quality is overall high and did not change significantly over the last nine years. In the last years, especially since the forest fires of 2005, the management of road verges has increased in Portugal. This implies a more regular and intensive cut of the vegetation along road verges. This fact may have contributed to reduce the attractiveness of roads to most birds, because of a decrease of food availability, which in turn reduced the number of road casualties.

Many studies mention road characteristics (e.g. traffic density, speed and road width) playing a key role in shaping road casualties and populations' density near roads (Erritzoe et al. 2003; Clevenger et al. 2003). Tawny owl was reported to be less abundant or more absent in the proximity of roads with high traffic density due to such factors as traffic disturbance, loss of habitat quality and fragmentation (Silva et al. 2012). Holm & Laursen (2011) found that the number of fledglings per breeding attempt of great tit (*Parus major*) was much lower in areas adjacent with fast and frequent traffic and attributed it to the death of the parent birds due to collision with vehicles. The probability of collision between a bird and a vehicle is likely to increase with traffic volume (Clevenger et al. 2003), and thereby reducing the survival rate of birds in roadside habitats. In Portugal no estimate is available for the evolution of traffic volume (ITF, Road Safety Annual Report 2016), so we cannot accurately assess its influence on shaping mortality throughout the years in our study area. However, between 1990 and 2014, the number of motorized vehicles more than doubled, rising from about 2.2 million vehicles in 1990 to 5.7 million in 2014 (+161%) (ITF, Road Safety Annual Report 2016), potentially increasing general traffic volume. From 2008-2010 almost all species showed a decline in mortality (figures 4, 5, 6, 7 and 9) which could be related to a decrease in traffic volume due to the recent economic crisis. In Spain, there was a decrease by 14% of the traffic volume between 2007 and 2013, which until then had been increasing, and the number of registered vehicles and vehicle fleet also slightly decreased as a result of the economic downturn (ITF, Road Safety Annual Report 2016). Portugal was also affected by this crisis so it's possible the same traffic drop occurred at the time, which in turn may have led to a decrease in roadkills. Nonetheless, an increase in traffic numbers may also translate into a depletion of individuals, not just because of an increasing number of roadkills, but also due to a disturbance factor (e.g., pollution, traffic noise, visual disturbance, etc.; Kociolek & Clevenger, 2009). Disturbance caused by roads has been reported to lead Andean condors (*Vultur gryphus*) to avoid the area, choosing to feed far from roads (Speziale et al. 2008; Lambertucci et al. 2009). Pinto and collaborators (2005) reported that great bustard (*Otis tarda*) populations in Portugal are concentrating themselves geographically, and one of the reasons for the local population declines was road building. Traffic volume and traffic noise have been reported to lead birds to avoid roads, with many species of woodland and open habitat showing strong declines in density, by reducing habitat quality and affecting the breeding ability of many species (Reijnen & Foppen, 1994, 1997, 2006; Brotons & Herrando, 2001; Parris & Schneider, 2008; Kociolek et al. 2011; Arévalo & Newhard, 2011; Polak et al. 2013). Traffic noise and traffic volume are highly correlated, and may act in synergy to exclude birds from habitats next to noisy, busy roads (Parris & Schneider, 2008). Because birds heavily rely on sound to attract mates, defend territories or avoid predation, traffic noise has been identified as the most critical disturbance factor (Reijnen & Foppen, 1997, 2006). In an experimental study in the United States, traffic noise was applied to a roadless area, creating a "phantom road" in a stopover site for autumn migratory birds (McClure et al. 2013). The observed decline of bird densities by over one-quarter and almost complete avoidance of some species of a high-quality site, showed that traffic noise alone was enough to lead birds away from an area (McClure et al. 2013). Species with low frequency calls that nest near the ground are especially sensitive to this type of disturbance (Polak et al. 2013), so ultimately the impact of traffic noise may depend on species-specific traits. Studies have shown that bird population densities decline as we get closer to roads and this effect could extend over distances up to 1 Km (Benítez-Lopez et al. 2010), therefore, it's possible that the decline in mortality observed may have come as a result of birds avoiding the area due to road disturbance.

The role mortality itself plays in reducing bird densities near roads is sometimes dismissed (Reijnen & Foppen, 2006), probably because it's correlated with traffic volume, which in turn is correlated with traffic noise (Summers et al. 2011), and this effects are often difficult to disentangle. But some studies have shown that traffic mortality is the main factor contributing to the decline in bird abundances (Summers et al. 2011; Jack, 2013). Nonetheless, considering that mortality rates can be quite high for some species, it is possible that after a while, roadkills may exert selection, favouring individuals that either learn to avoid roads or exhibit characteristics that allow them to do so, and thus reduce the number of casualties. During a 30 year survey of the cliff swallow (*Petrochelidon pyrrhonota*) in southwestern Nebraska, Brown and Brown (2013) reported a significant decline in the frequency of road-killed individuals and at the same time observed that the wing-length of the animals found on roads was longer than in the population more distant from the road. They hypothesized that the observed decline in mortality could not be explained by factors such as decreases in abundance or traffic volume, and was therefore the result of selective mortality favouring individuals whose wing morphology allows for a better escape from vehicles. Mumme et al. (2000) also reported a decline in roadkills for the Florida scrub-jay (*Aphelocoma caerulescens*) after nine years, with mortality being higher for 30-90 days old juveniles and in the first two years of immigrant jays without previous experience living in road territories. Thus, the decline in roadkills was experience-dependent, being the result of surviving jays learning to avoid cars or selective mortality (Mumme et al. 2000). However, this experience with roads and ability to avoid cars did not seem to pass from the parents to their offspring, which may mean that roadside habitats could be potentially acting as a population sink for this species (Mumme et al. 2000). Legagneux & Ducatez (2013) found that birds standing on the road or on road edges initiated flight sooner or later depending on the speed limit (although the actual speed of the vehicles had no effect on escape response) and thus, attributing it to learned behaviour. However, it seems that not all species are be able to properly assess the risk of high-speed vehicles and consequently are unable to adjust their escape response and avoid collision (DeVault et al. 2015). Furthermore, on a study with rock pigeons (*Columba livia*), DeVault and collaborators (2017) argue that continual exposure to vehicles triggers a habituation-like effect which could lead to an ineffective avoidance response to car collisions. In that case, we would expect to observe an increase in mortality over time, which does not correspond to our results. So, the ability of a bird to avoid collision with oncoming vehicles might be dependent of species sensitivity to collision risk and ability to adapt their avoidance behaviour, and thus we can't assume that all species are able to safely recognize and avoid the dangers that roadside habitats pose.

4.2. Seasonality of roadkills

The seasonal patterns of roadkills observed for the six species are similar to those reported in previous studies and are mainly associated with ecological needs and the life cycle of the species – phenology (Rosa & Bager, 2012; Carvalho & Mira, 2011; Garriga et al. 2017), which may make them more vulnerable to vehicle collisions. For the five species that are resident in the study area, mortality generally peaked in spring-summer, generally between April and September. This corresponds to the periods of breeding activity (incubation and fledging) and juvenile dispersion (Erritzoe et al. 2003; del Hoyo et al. 2015). This last period results in an increase in abundance of individuals (especially inexperienced ones), which may explain increased mortality for these species (Erritzoe et al. 2003; Grilo et al. 2014). Particularly in the case of the tawny owl, the number of roadkills seems greater during the post-natal dispersal, suggesting that the juvenile individuals are more vulnerable to collision with vehicles than adults. Santos and collaborators (2013) found that juveniles represented 56% of the casualties along the year. During the fledging period, adults make many and longer movements to be able to feed the young, which may cause birds to cross roads more frequently, or use road verges to search for food, that would explain an increase in roadkills (Kuitunen et al. 2003; Holm & Laursen, 2011).

Another possible explanation for higher mortality on roads during spring-summer is the intensification of traffic volume during the holidays or the increase of food availability near roads for seed-eating birds due to agricultural crops and harvest during summer months (Erritzoe et al. 2003; Rosa & Bager, 2012). During winter, on the other hand, there is a shorter length of daylight and generally less traffic (Erritzoe et al. 2003). When considering the whole bird species, from November to January there may be fewer individuals killed as the migratory species head south. However, when the majority of trans-Saharan migrants are already in Africa, a large number of birds of common species coming from higher altitudes arrive (Elphick, 2007). In many cases, this wintering contingent increases the ranks of the resident population. Such is the case for the blackcap which our results show to die more during the winter months, a period when the population registers a large increase by the arrival of birds breeding in central and northern Europe and wintering in southern Europe (Cramp & Brooks, 1992). Lastly, when comparing roadkills from different countries for specific species, it is important to take into account that seasonal patterns of avian mortality may vary from place to place as a result of geographical variations in their ecology and phenology (Erritzoe et al. 2003).

4.3. Relationship between roadkills and weather variables

Despite the role weather plays in many aspects of the life traits and activity patterns of birds, very few studies considered its influence in road fatalities. One would expect that more extreme weather conditions, such as the severe drought verified in Portugal in 2005 (Climatic characterization of the year 2005, IPMA, 2017), would have a considerable impact on population density and space use due to limited resources and, thus, enhance road casualties (Erritzoe et al. 2003). Weather conditions affect the metabolic rate of birds (e.g. cold weather requires more energy to maintain body functions) and can influence foraging conditions (Crick, 2004). Therefore, roads could be attractive to animals during more extreme weather conditions, increasing their likelihood of being hit, by offering cover and food as a result of moister conditions and more abundant vegetation on verges, in contrast to the surrounding areas (Erritzoe et al. 2003; Orlowski, 2005; Morelli et al. 2014).

Our results suggest a correlation between roadkills, and rainfall and temperature for most species, particularly for high or low values of these predictors. Garriga et al. (2017) reported similar results in northeastern Iberia, with bird roadkills being positively associated with temperature and negatively related to humidity and irradiation. However, the lack of a clear relationship with rainfall and temperature in our study may suggest that there are other factors with greater influence in the number of roadkills for this taxonomic group.

4.4 Study limitations

The weather variables we used to describe temporal trends in bird roadkills did not explain a high amount of variability in data. Additional variables would have been helpful, such as yearly traffic volume for the studied roads or for the region. However, there is no information on traffic trends in Portugal (ITF, Road Safety Annual Report 2016). On the other hand, yearly data on bird local abundances should also help to explain the patterns observed. Also, the patterns may result from a complex interaction of variables which is difficult to disentangle using simple mathematical models. Information to overcome this limitation, however, may be difficult to acquire, particularly at large temporal scales, if continuous accurate measures and monitoring programs are not in place.

4.5. Conclusions and conservation implications

The decline in roadkills over nine years we observed for our six common species, provides concrete data that mortality due to car collisions may change over time. Although, we do not have enough information to claim with certainty the cause of our results, these may be a consequence of a cumulative effect of different factors over time and learning ability of our target species.

Although road mortality is a significant source of mortality for birds and a serious conservation issue, the lack of information on its demographic consequences poses a severe threat to the long-term survival of animals in road habitats and can jeopardize the effectiveness of mitigation measures, especially if we do not fully understand the driving forces behind it and their actual impact. This requires continuous monitoring of roadside populations and road features. The overall impact of roadkills in the long-term survival of a population may depend of particular circumstances, species and other road factors, which can act in synergy with each other, and therefore future research should take that into account.

In conclusion, there is a need to assess the possible impact that roadkills have on abundance, dynamics and even viability of wildlife populations. Future research should focus on addressing large temporal scales to increase inferential strength in its results to properly assess population changes.

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Final Considerations

The present study evaluated the temporal pattern in the roadkills of common bird species and the effect of weather predictors. Considering the impact roads have on birds, particularly in the amount of direct mortality caused through collisions with vehicles, and the current decline of common species, it is important to understand how mortality varies over the years and seasons, know which factors influence it, and its importance on the long-term persistence of species. Some studies have already shown that direct mortality due to collision with vehicles, over time, has major effects on bird populations (Mumme et al. 2000; Ramsden, 2003; Brown & Brown, 2013). Thus, bearing in mind the vast network of roads worldwide in combination with other anthropogenic factors (e.g., habitat loss and fragmentation, invasive species, climate change), the potential impact of road mortality on the long-term persistence and viability of bird populations should be assessed (Erritzoe et al. 2003; Kociolek & Clevenger, 2009). However, such issues can only be tackled with long-term studies which require systematic compilation of data on population sizes, vital rates, etc., which are often not compatible with most MSc or PhD theses or short-term research contracts (Roedenbeck et al. 2007; van der Ree et al. 2011). The results obtained in this thesis should address partially this question (i.e., long-term viability), because a decreasing trend in roadkill numbers may be perceived as a first sign of local population depletions (Lesbarrères & Fahrig, 2012).

A novelty which our study introduced is the use of carcass persistence time and survey frequency to provide a correction of roadkill numbers. Many studies underestimate the actual amount of mortality, because carcasses quickly disappear from roads, which can have important implications to road mitigation programs and the design of mitigation measures (Santos et al. 2011).

Although we failed to find a clear association between weather variables and temporal patterns of roadkills, it does not imply that weather has a negligent effect on mortality, only that other road-related factors may have a stronger influence. Therefore future research should focus in exploring how all these elements come into play and their significance on the number of bird roadkills. We hope that the present study may help to shed some light on how roadkills can impact and shape wildlife populations over time and alert to the need of more knowledge about this phenomenon.

If clear relationships are established in the future between regional trends in population density and regional trends in roadkill frequency, then monitoring programs of road-killed fauna may be used also to inform about population status. This can represent a useful conservation tool, as very often monitoring wildlife populations has larger costs than monitoring road casualties.

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Appendix

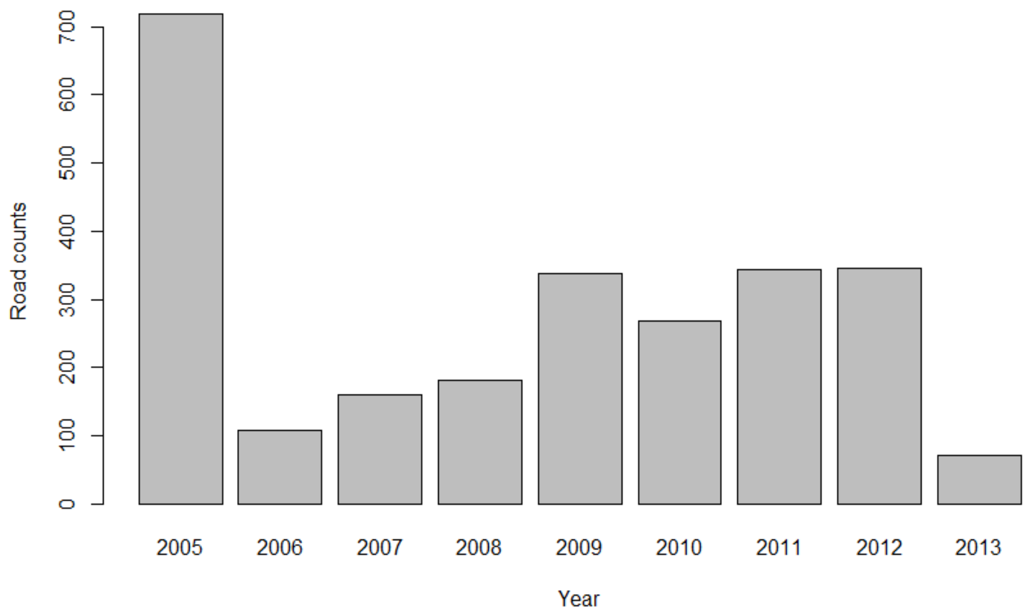

Fig. 10 Sum of the mortality of the six species in annual totals, with no correction for roadkill counts.

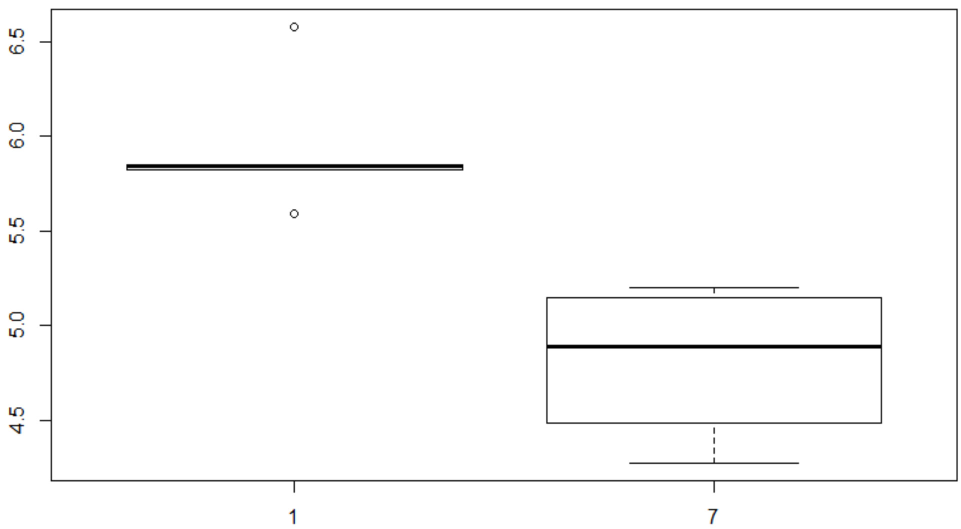

Fig. 11 Boxplot of roadkill counts (with no correction) for daily and weekly surveys. Mortality counts are higher in the years where surveys were performed daily, which means that survey frequency may be influencing the results and thus, must be corrected.

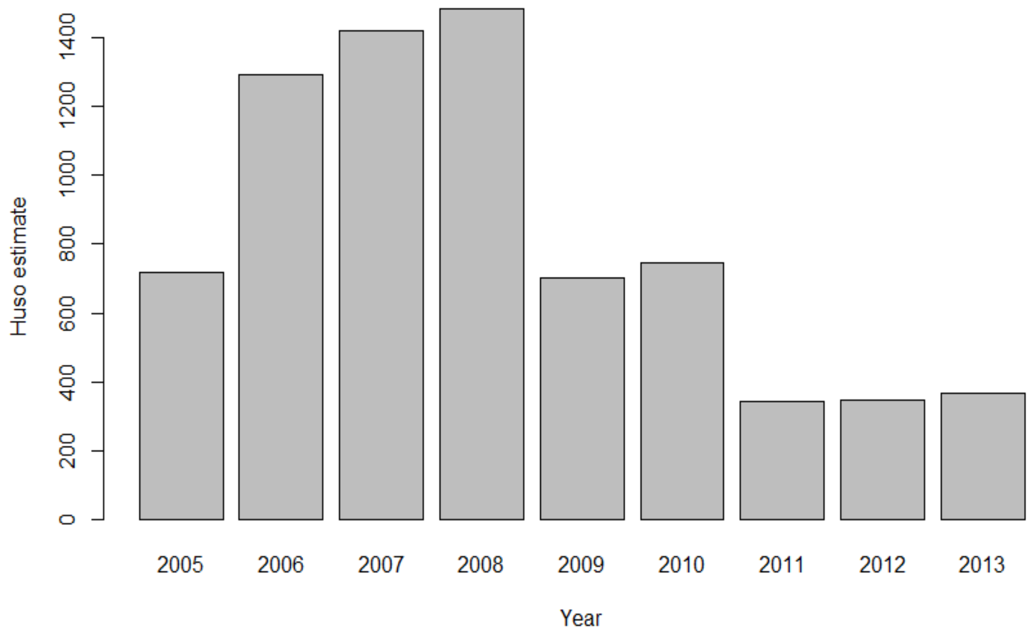

Fig. 12 Sum of the mortality of the six species in annual totals, correcting the roadkill counts with the Huso estimator and posteriorN function.

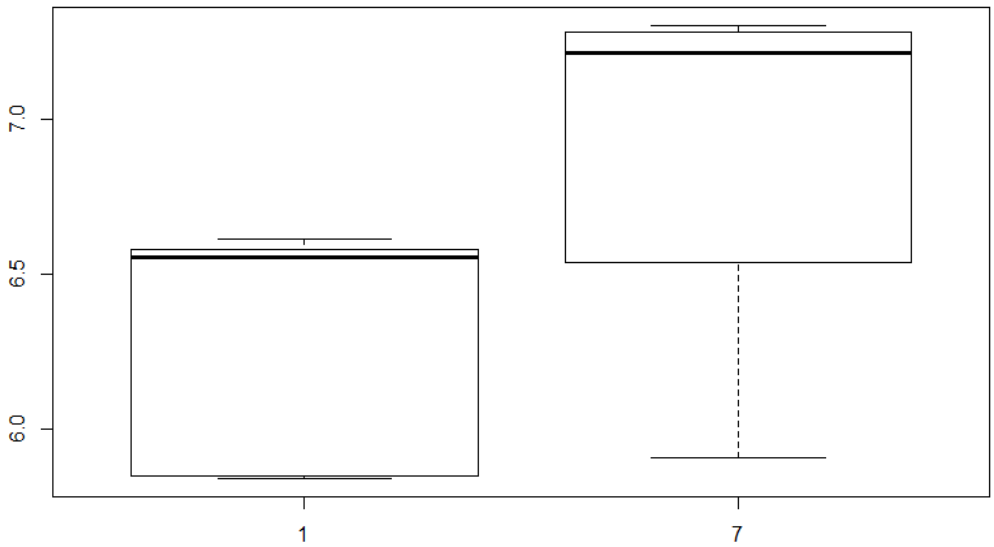

Fig. 13 Boxplot of corrected roadkill counts for daily and weekly surveys, using the Huso estimator and posteriorN function. The plot suggests that in the years where surveys were performed weekly, the roadkill estimations were higher. This suggests that the posteriorN function may be overestimating the calculated values.

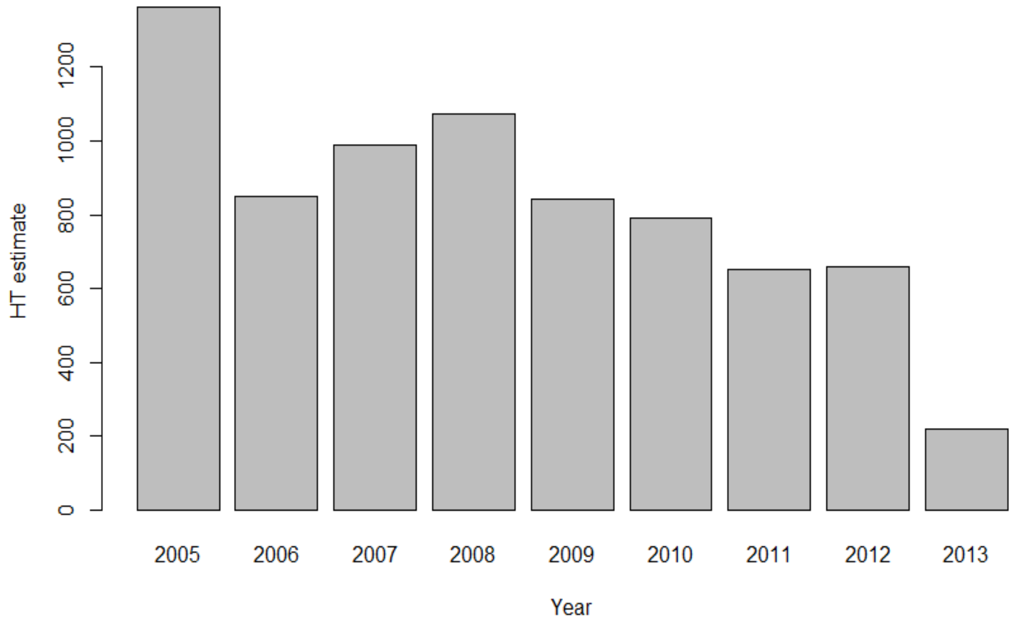

Fig. 14 Sum of the mortality of the six species in annual totals, correcting the roadkill counts with the Huso estimator and Horvitz-Thompson function.

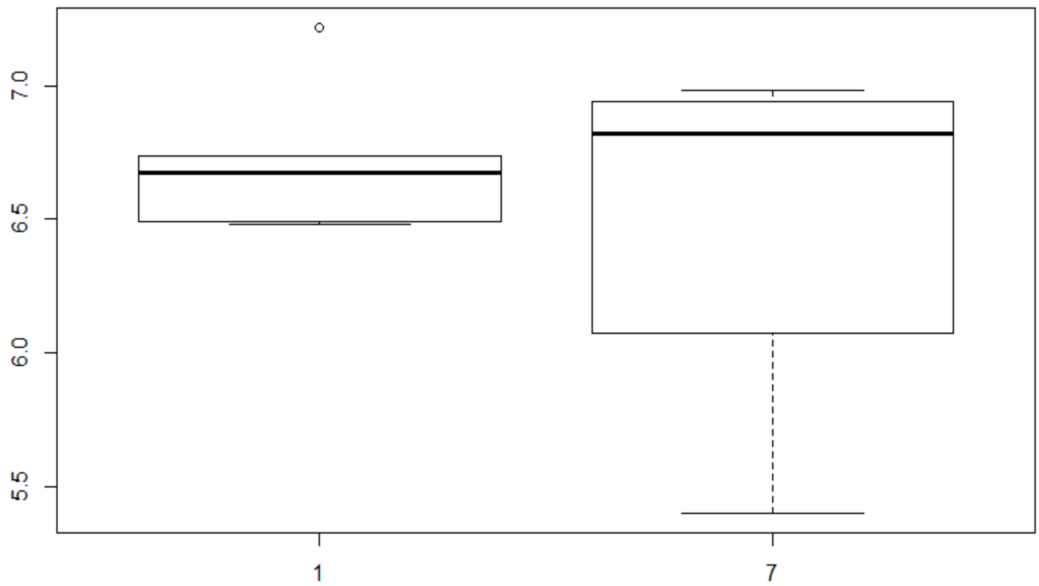

Fig. 15 Boxplot of corrected roadkill counts for daily and weekly surveys, using the Huso estimator and Horvitz-Thompson function. In this case there are no significant differences in the mortality estimations between the frequencies of surveys. Considering these results we may assume that the Horvitz-Thompson function gives more accurate roadkill estimates.