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Spatio-temporal hotspots of wildlife-vehicle collisions in Poland: How congruent are mammals, birds, reptiles and amphibians?

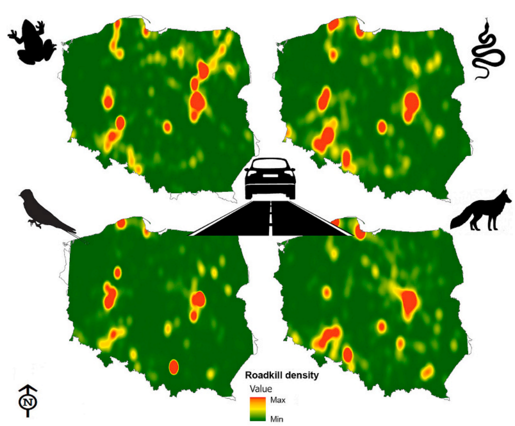
Federico Morelli [a,b,c,*], Yanina Benedetti [a], Karol Kustusch [d], Andrzej Wuczyński [e]

[a] *Czech University of Life Sciences Prague, Faculty of Environmental Sciences, Kamýcká 129, CZ-165 00 Prague 6, Czech Republic*
[b] *Institute of Biological Sciences, University of Zielona Góra, Prof. Szafrana St. 1, PL 65-16 Zielona Góra, Poland*
[c] *Department of Life and Environmental Sciences, Bournemouth University, Fern Barrow, Poole BH 12 5BB, UK*
[d] *Polish Roadkill Observation System, Waryńskiego 153, 86-300, Grudziądz, Poland*
[e] *Institute of Nature Conservation, Polish Academy of Sciences, Al. Mickiewicza 33, 31-120 Kraków, Poland*

HIGHLIGHTS

- Wildlife-vehicle collision (WVC) is recognized as a chief traffic threat to biodiversity
- We extracted WVC events from a dataset collected between 2000 and 2022 in Poland
- Spatio-temporal hotspots of wildlife-vehicle collisions in Poland were mapped
- A higher spatial congruence in WVC was found between birds and mammals
- Amphibians were the animal group less congruent with the other groups (approx. 13 %)

GRAPHICAL ABSTRACT



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ABSTRACT

The Polish Roadkill Observation System (PROS) database, a large dataset of roadkills collected between 2000 and 2022 in Poland, was used. We calculated the total length for each road type and the main type of environment around the wildlife-vehicle collision (WVC) event, in a grid of 10 × 10 km (e.g., spatial unit). We explored the spatial congruence in WVCs among amphibians, reptiles, birds and mammals across the country, using spatially explicit correlation based on the Mantel tests. We used a) Generalized Linear Mixed Models to investigate the association between WVC and the type of dominant environment and animal group, and b) Generalized Boosted Regression Models to investigate, separately for each animal group, the association between WVC and the length and type of road in each spatial unit. A total of 19,846 roadkills were recorded in Poland, involving 28,952 individuals from different animal species: 14 amphibians, 8 reptiles, 133 birds and 52 mammals. The spatial distribution of roadkill events in the country was mainly clustered around the biggest cities. Hotspots were concentrated near cities (Warsaw, Kraków, Rzeszów) and in areas known for high biodiversity. Coldspots -

* Corresponding author at: Czech University of Life Sciences Prague, Faculty of Environmental Sciences, Kamýcká 129, CZ-165 00 Prague 6, Czech Republic.
E-mail address: fmorellius@gmail.com (F. Morelli).

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relatively smaller than hotspots - were areas characterized by a high density of housing infrastructure, with lower naturality and a predominance of single roadkill casualties. A higher spatial congruence in WVC was found between birds and mammals (71 %) than between the other animal groups. Overall, the animal group less congruent with the other groups was amphibians (13 %), while birds were most congruent with all groups. We discussed some advantages and drawbacks when working with non-systematic survey datasets of roadkills. Finally, we recommended including roadkill clusters of multiple animal groups (hotspots) in strategies for mitigating wildlife-vehicle collisions but also considering more specific strategies, which can combine the type of environment and roads, concerning each animal group.

1. Introduction

Road networks are essential for human activities and development (Forman et al., 2003; Seiler, 2001), constituting a challenge to wildlife (Flory and Clay, 2009; Hetman et al., 2019; Spellerberg, 1998). The European continent is characterized by the world's highest road network density connecting human settlements, even higher than East Asia and the Pacific (IRF, 2023). Globally and especially in Europe, wildlife-vehicle collisions (WVC) represent a concern for the conservation of biodiversity (Andrews et al., 2015; Barrientos et al., 2021; Grilo et al., 2020; Medrano-Vizcaíno et al., 2022). Roads cause habitat reduction and fragmentation (Davenport and Davenport, 2006; Kociolek et al., 2011), noise or light pollution (De Molenaar et al., 2006; Dean et al., 2019; Johnson et al., 2017; Kaseloo and Tyson, 2005), potentially increasing the wild populations' isolation (Barbosa et al., 2020; Lodé, 2000; van der Ree et al., 2011). The most critical effect of the traffic associated with roads is the direct mortality caused by wildlife-vehicle collisions (Farias et al., 2022; Garriga et al., 2017; Loss et al., 2014; Mackinnon et al., 2005). WVCs are one of the most important causes of wildlife mortality globally (Hill et al., 2019). However, the number of animals killed by cars yearly is heavily underestimated (Schwartz et al., 2018). Even if millions of animals are killed by car collisions in Europe (Grilo et al., 2020), a comprehensive assessment of the persistent effect of roadkills on animal populations is still missing (Barrientos et al., 2021). A comparison of the negative effects of roads on different animal groups is also necessary to quantify effectively the relative impact on each taxon. It seems to be a particularly urgent task because road networks are growing in concomitance with human economic development (Laurance et al., 2014).

Accurate and spatially explicit information regarding roadkill events is crucial when assessing the impact of collisions with cars on wildlife (Ascensão and Desbiez, 2022). The identification of potential roadkill hotspots is a key tool for forecasting and mitigation planning at different spatial scales (Boyle et al., 2017; Carvalho-Roel et al., 2019; D'Amico et al., 2015; Garriga et al., 2017; Morelli et al., 2023; Santos et al., 2013). A multi-taxa approach is also required since most previous studies focus on a few groups (e.g., large mammals), with a consistent publication bias on taxa studied (Barrientos et al., 2021). In road ecology, addressing if the same problems are affecting different animal groups, and in which areas, would permit to development of suitable mitigation strategies (Gonçalves et al., 2018). Understanding how roads affect different animal groups helps to understand why some species are more affected by roadkill than others, and where. Amphibians and reptiles are among the most vulnerable species affected by roadkill (Farias et al., 2022; Sillero et al., 2019). The season, and surrounding environment where the roadkill events happen, play an important role (Arca-Rubio et al., 2023; Rosa and Bager, 2012). Roads across wetlands can be associated with higher rates of roadkills for amphibians because dividing suitable habitats for such species and crossing migration routes potentially reduces their population densities (Becker et al., 2010; Beebee, 2013). Roads across the forest or herbaceous-shrubby vegetation, on the other hand, can represent a threat to mammals and birds (Balčiauskas et al., 2023; Medrano-Vizcaíno et al., 2023; Orłowski, 2008). But also the type of road (e.g., high-traffic roads, primary, secondary or tertiary roads) can affect differently each animal group (Heigl et al., 2017; Machado et al., 2015). For example, in snakes, it was observed that the combination of the road type and the edge habitat contributed to road mortality (Wagner et al., 2021).

Although many studies address the problem of the impact of road traffic on nature and try to locate roadkill hotspots, the vast majority operate at the scale of selected roads or regions, and there are few studies conducted on the large spatial scale of countries or continents (Grilo et al., 2020; Loss et al., 2014; Medrano-Vizcaíno et al., 2023). We present these problems here on the scale of a large Central European country, Poland (312,696 km^2), with a diverse landscape and known for its high biodiversity. The road network in Poland is approximately 430,000 km long, of which approximately 80 % are local roads. The number of registered motor vehicles is almost 35 million (2022), placing Poland in 5th place in Europe (https://bdl.stat.gov.pl/). Nearly 500,000 road accidents are recorded annually in Poland, including almost 30,000 collisions involving animals (Krukowicz et al., 2022). The latter resulted in the death of several people and about 200 people injured every year (Tereszkiewicz and Choroszy, 2016). The costs of road collisions involving animals recorded in 2001–2010 were estimated at PLN 1.7 billion, i.e. over 400 million dollars (Tyburski and Czerniak, 2013). Despite the recognized problem of animal mortality on Polish roads and several relevant studies (for a review, see Wuczyński et al., 2023), there is almost no research identifying places and road sections where road accidents involving animals are particularly common (but see Jakubas et al., 2018; Skórka et al., 2015).

In this study, we combined a large dataset of wildlife-vehicle collisions collected in Poland during the period between January 2000 and December 2022, with the road network and environmental characteristics based on the composition of land use. We explored the spatial congruence on the distribution of WVC among amphibians, reptiles, birds and mammals, and the Polish areas characterized by hotspots or coldspots of overall WVC. Finally, we explored if the variation in WVC is associated with the types of environments and density of different types of roads.

2. Methods

2.1. Dataset of roadkill events for four animal groups in Poland

Data for this study were obtained from the Polish Roadkill Observation System (PROS) http://zwierzetanadrodze.pl, a nationwide volunteer-based programme for recording wildlife-vehicle collisions. Data is collected opportunistically and uploaded to the PROS database via a web application, where any individual user (citizen scientist) can enter observations of any land vertebrate species encountered as WVC or roadkill throughout Poland. Each observation is pin-located on a map giving geo-references, while further checkboxes allow for a wide range of information to be collected (Wuczyński et al., 2023). Each entry is reviewed by the biologists and portal administrators before acceptance, to minimise imperfections of citizen science. For this study, the full dataset was downloaded from PROS on April 1, 2023. It contained a total of 19,028 records involving 28,709 roadkilled individuals, spanning the years 2000–2022; with the bulk of the data (98 %) from 2015 onwards.

2.2. Spatial distribution and mismatch/congruence analysis of roadkill among four animal groups

The spatial distribution of WVC events for all animal groups in Poland was mapped using ArcGIS 10.8 (ESRI, 2020). Fig. 1 shows the road network in the country, by type of road (A), the spatial distribution of road casualties (B) and the roadkill density by merging all data of the four animal groups (C). The road network used in this study was extracted from the OpenStreetMap database. All road types were grouped into the following main categories: Service, residential, primary, secondary, tertiary, major and unclassified roads (Fig. 1A). A kernel density estimation technique was used to visualize and map the overall density of WVC events across the country (ESRI, 2020) (Fig. 1C and Fig. S1). The same strategy was applied for mapping and exploring temporal changes in the density of WVC during the period 2015 to 2022 (Fig. S2). For the temporal exploration, we chose the period 2015 to 2022 because it was more uniformly covered in terms of roadkill data collection.

We estimated the dominant environment around the geographic coordinates of each WVC event. We used such estimation to classify each record based on the surrounding land use types. The land use types were extracted from the CORINE land-cover (CLC) vector data derived from 25-m resolution (Bossard et al., 2000). Land-use categories level 2 taken from CLC were grouped to obtain the six main land-use types (i.e. arable land, industrial and transportation, urban, non-agricultural vegetated, permanent crops, mines and dumps). To classify the dominant environment, we calculated the percentage of each land-use type through the "intersect operator" of ArcGIS 10.8.1 software (ESRI, 2020) in a circle with a radius of 100 m around each record. The dominant environment was the land use type with a cover of >60 %, while the remaining areas were classified as "mixed" environments (Benedetti and Morelli, 2017).

Additionally, we calculated the total length (in km) for each road type in a fixed spatial unit of 10 × 10 km squares in a grid covering the whole of Poland (Fig. S1). The grid was created with ArcGIS software (ESRI, 2020). Total road length was calculated using the command "line density" from Spatial Analyst in ArcGIS 10.8 (ESRI, 2020). For each spatial unit (10 × 10 km squares) the number of individuals killed in each animal group was extracted.

To map the hotspots of WVC in Poland, we used all data, merging the four animal groups. We used the ArcGIS "Hot Spot Analysis" tool, identifying statistically significant spatial clusters of high values (hotspots) and low values (coldspots) of animal WVC. The Hot Spot Analysis calculate the Getis-Ord Gi* statistic for each feature in a dataset, obtaining z-scores and *p*-values (ESRI, 2020) through the evaluation of each feature (e.g., geographic coordinates of each WVC event) within the context of neighbouring features. We considered the number of individuals of each species involved in each WVC event. To be a statistically significant hotspot, a feature has to be characterized by a high value and simultaneously be surrounded by other features with high values (Ord and Getis, 1995).

2.3. Statistical analysis

To test the spatial congruence of WVC among the four animal groups in Poland (Fig. 3), we used a spatially explicit correlation test based on the Mantel statistic (Mantel, 1967). The Mantel statistic (r_M) ranges between −1 and +1, similar to a correlation coefficient (Fortin and Payette, 2002). The r_M evaluates the similarity between two matrices measuring a variable, calculated as a geometric distance matrix (Legendre and Legendre, 2012). Mantel test calculations were performed running the package 'ade4' for R (Dray and Dufour, 2007) and the statistical significance was obtained through Monte Carlo permutations with 999 randomizations, with the 'vegan' package for R (Oksanen et al., 2016).

Two models were run: first, a generalized linear mixed model (GLMM) to test whether variation in WVC (e.g., individuals involved in each road casualty modelled as the response variable, following a Poisson distribution) is associated with the combination between the type of dominant environment surrounding the road casualty spatial position and the respective animal group (modelled as predictors). The identity of 10 × 10 km squares covering Poland was added as a random factor (Bates et al., 2015) to account for potential spatial associations (e.g., an association tend to be stronger in a given area). GLMM was run with the package 'lme4' (Bates et al., 2015; McCullagh and Nelder, 1989). The model's overall fit or performance was evaluated using the pseudo r square values (Burnham and Anderson, 2002; Hu et al., 2006). Second, a series of machine-learning models based on hierarchical predictive tools focused on roadkill risk in each animal group (e.g., the number of individuals involved in the WVC event modelled as the response variable), by considering road attributes (length and type of road within each 10 × 10 km square) as predictors. Generalized Boosted Regression Models were used, with the R package 'bgm' (Ridgeway et al., 2024). These models combine two techniques: decision tree algorithms and boosting methods (Elith et al., 2008). Generalized Boosted Regression Models repeatedly fit many decision trees to improve the accuracy of the model. In such a model the best fit is automatically detected by the algorithm (Ridgeway et al., 2024).

All statistical tests were performed with R software version 3.5.1 (R Development Core Team, 2023).

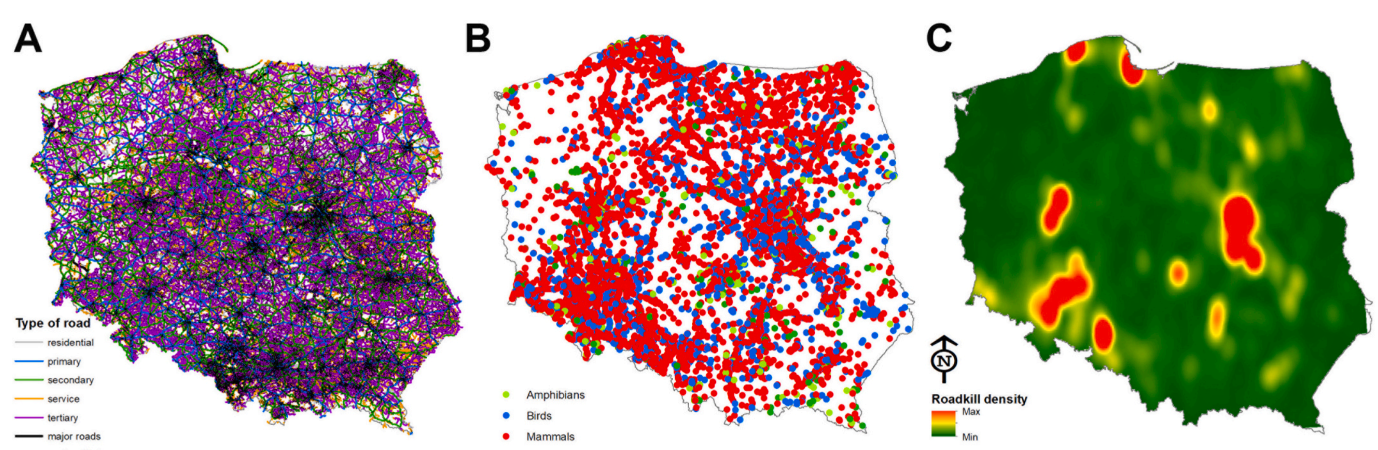

Fig. 1. Spatial distribution of each type of total roads (A), occurrence of wildlife-vehicle collisions (roadkills) in each animal group (amphibians, reptiles, birds and mammals) (B), and kernel density map of overall WVC considering the number of individuals involved (C), in Poland. The values of kernel density are presented in a coloured gradient from lower (dark green), moderate (yellow) to higher (dark red).

3. Results

Using the PROS database covering the whole area of Poland, considering the years from 2000 to 2022, after excluding the cases without identification of animals at the level of generic name, were extracted a total of records of 19,846 WVC events involving 28,952 individuals from at least 207 different animal species (14 amphibians, 8 reptiles, 133 birds and 52 mammals) (Table S1). From the included records, 580 (approx. 2.8 % of the total) were represented by pets (e.g., dogs or cats) (Table S1). The highest rate individuals by record were calculated within amphibians (10.7, the Common Spadefoot *Pelobates fuscus*; 9.6, the Common frog *Rana temporaria*) and within birds (9, the Brambling *Fringilla montifringilla*) (Table S1). Overall, the mean values of rate individuals by record were higher in amphibians and birds, than in reptiles and mammals (Table S1). The species with the higher WVC incidence in Poland for each animal group, when considering the whole period analyzed (2000 to 2022), were the Common toad *Bufo bufo* (amphibians), the Grass snake *Natrix natrix* (reptiles), the Common pigeon *Columba livia* (birds) and the *Erinaceus species* followed by the Red fox *Vulpes vulpes* (mammals) (Table S1).

Overall, the spatial distribution of WVC events in the country was clustered, mainly around the cities of Warsaw, Wrocław, Opole, Poznań and Gdańsk (Fig. 1C). A graphical exploration of the temporal variation in WVC distribution suggests relative stability in the spatial patterns of WVCs between 2015 and 2022, with similar areas showing the higher density of WVC events (Fig. S2).

The spatially explicit comparison of the WVC spatial distribution among animal groups (Fig. 3) showed that WVC distribution density was highest and significantly correlated between birds and mammals (r_M = 0.709, p = 0.001, Fig. 3C and D). The lowest spatial congruence was found for amphibians and reptiles (r_M = 0.077, p = 0.01, Fig. 3A and B). The spatial association between reptiles and birds was positive and significant (r_M = 0.198, p = 0.002, Fig. 3B and C), while between amphibians and mammals was a little bit lower but significant (r_M = 0.157, p = 0.003, Fig. 3A and D). Finally, the values of the spatially explicit correlation test were r_M = 0.138 between amphibians and birds (p = 0.006, Fig. 3A and C) and r_M = 0.130 between reptiles and mammals (p = 0.006, Fig. 3B and D). After merging all data from the four animal groups during the whole period (years 2000–2022) in Poland, and based on a pool of 19,846 records, we identified five main clusters of hotspots (e.g., points with a high density of WVCs surrounded by other points with high density) and three main clusters of coldspots (Fig. 4). Such areas were spatially associated with more densely populated areas of the country, characterized by dense road networks (big cities and their outskirts), and areas known of high biodiversity (protected areas, river valleys, uplands) (Fig. 1A).

The result of the generalized linear mixed model indicated that overall, considering the number of individuals involved in the WVC events, most of the events were recorded in anthropized or mixed environments (urban, industrial areas or mines) with fewer events associated with non-agricultural vegetated areas (Table 1). Overall, mammals were characterized by a higher number of individuals involved in WVC events, especially if compared with reptiles and birds, both groups characterized by a lower number of individuals involved in each WVC (Table 1). The number of individuals of birds involved in WVC was relatively higher in permanent crops when compared to the other types of environments (Table 1). Mammal and reptile individuals involved in WVC were most negatively associated with the following environment types: industrial areas and mines or dump areas (Table 1).

Finally, when accounting for variation in the number of individuals involved in WVCs concerning the length and type of road, separately by animal groups, we found that amphibian roadkills were relatively higher in areas characterized by residential, tertiary and unclassified roads (relative importance above 30 % for the firsts two types of roads, while above 20 % for unclassified roads, Fig. 3). Reptiles roadkills were higher mainly in areas with residential and primary roads (relative importance above 57 % for the first, and 26 % for the second one, Fig. 3). The number of birds involved in WVC increased mainly in areas with primary roads (relative importance above 46 %) followed by areas with residential roads (relative importance above 19 %) (Fig. 3). Finally, mammals roadkill increased mainly in areas characterized by residential roads (relative importance above 62 %), followed by areas with primary roads (relative importance above 12 %) (Fig. 3).

Table 1
Result of the generalized linear mixed model, accounting for variation in wildlife-vehicle collisions (individual casualties), regarding the combination between the type of dominant environment and animal group. The modelling procedure added the identity of 10 × 10 km squares covering Poland as a random factor (groups = 1983). Only significant variables are shown in the table. Model fit: Pseudo-R^2 (fixed effects) = 0.175, Pseudo-R^2 (total) = 0.676.

Variables	Estimate	SE	z value	p
Intercept	0.377	0.047	8.089	<0.001
Environment (industrial and transport)	1.484	0.087	16.981	<0.001
Environment (mines and dumps)	1.125	0.387	2.904	0.004
Environment (mixed)	1.489	0.043	34.683	<0.001
Environment (non-agricultural vegetated)	−0.211	0.091	−2.317	0.021
Environment (urban)	1.113	0.045	24.534	<0.001
Group (birds)	−0.383	0.051	−7.502	<0.001
Group (mammals)	0.4	0.045	8.981	<0.001
Group (reptiles)	−0.772	0.097	−7.971	<0.001
Industrial and transport: birds	−1.64	0.107	−15.294	<0.001
Mines and dumps: birds	−0.893	0.415	−2.155	0.031
Mixed: birds	−1.268	0.058	−21.855	<0.001
Permanent crops: birds	2.653	1.009	2.628	0.009
Urban: birds	−0.357	0.058	−6.167	<0.001
Industrial and transport: mammals	−2.236	0.099	−22.642	<0.001
Mines and dumps: mammals	−1.28	0.396	−3.231	0.001
Mixed: mammals	−1.471	0.049	−30.173	<0.001
Non-agricultural vegetated: mammals	−0.658	0.114	−5.794	<0.001
Urban: mammals	−0.978	0.051	−19.148	<0.001
Mines and dumps: reptiles	−2.611	1.067	−2.447	0.014
Mixed: reptiles	−0.599	0.103	−5.814	<0.001
Non-agricultural vegetated: reptiles	−0.771	0.373	−2.068	0.039
Urban: reptiles	−1.256	0.131	−9.597	<0.001

4. Discussion

In Poland, we found 207 different animal species involved in WVC events. When considering the proportion of species by animal group, birds and mammals were the most frequently killed on roads (133 birds and 52 mammals) with 14 amphibians and 8 reptiles. The most frequently recorded species were the Common toad *Bufo bufo* (amphibians), the Grass snake *Natrix natrix* (reptiles), the Common pigeon *Columba livia* (birds) and *Erinaceus species* (e.g., *europaeus* or *roumanicus*) followed by the Red fox *Vulpes vulpes* (mammals). All these species are currently classified as least concern by the Red List of Threatened Species in Europe (IUCN, 2021). However, when considering the number of individuals involved in each road casualty, the relative effect of WVC on wildlife mortality changes. The highest number of individuals killed on roads belongs to mammals (13,264), amphibians (8500), birds (5915), and reptiles (1273) (Table S1). It is important to note that amphibians are the group most affected by road networks, with a higher rate of individuals involved in accidents concerning the total number of events than other groups. This information is significant, given that amphibians are already among our planet's most drastically impacted species (Farias et al., 2022; Mestre et al., 2019; Puky, 2006). The collisions with cars represent a threat to amphibians because of their lower ability to recognize traffic risks (Gibbs and Shriver, 2005), creating large concentrations in suitable habitats, as well as their relatively slow mobility when traversing the roads (Marsh et al., 2005).

The spatial distribution of WVCs for all four animal groups was mainly associated with big cities, showing just small variations over the years. The spatial distribution of wildlife-vehicle collisions was more congruent between birds and mammals (approx. 71 %) than between the other animal groups. The animal group less congruent with the other groups was amphibians (mean $r_M = 0.13$ or 13 %). In comparison, the animal group characterized by the higher overall spatial congruence with all groups was birds (mean $r_M = 0.35$ or 35 %) (Fig. 3). This is a partial indication that different mitigation strategies could be developed for each animal group.

When considering the overall hotspots and coldspots of WVC at the country level, we can notice that they only partially coincide with the density maps of roadkill incidents. Hotspots correspond to collision clusters of amphibians (Fig. 2A), and coldspots rather to the collision of birds and mammals (Fig. 2C and D). The distribution of hotspots also corresponds to the distribution of cases of mass mortality: records describing 100–500 casualties were located in the centre of the revealed hotspots and concerned amphibians. At the same time, the hotspots show areas of high biodiversity, such as the valleys of the Bug, Biebrza and Noteć rivers in central Poland and diverse foothill areas in the south, along the Carpathians belt, between Kraków and Rzeszów. These findings confirm that in such places, road traffic has a particularly strong impact on wildlife (Coelho et al., 2008; Garrah et al., 2015; Healey et al., 2020). Significantly, the modelling revealed the isolated northernmost point marking one of the most valuable natural places in Poland, the Biebrza National Park, where there has been a long-known problem of very high road mortality of animals (Gryz and Krauze, 2008; Hermaniuk and Ołdakowski, 2016). Both designated groups of coldspots are located on the outskirts of large agglomerations of Warsaw and Wrocław. They are characterized by a high density of roads and the development of housing infrastructure, resulting in a relative poverty of nature and a predominance of records with single casualties.

Here, we found that most wildlife-vehicle collisions were observed in mixed environments, industrial and urban areas. Relatively fewer individuals were roadkilled in vegetated areas not devoted to agricultural activities. However, when combining the type of environment with the animal group, we found that reptiles killed by car collisions are less frequent in some environmental types (e.g., mainly in mines or urban areas). On the contrary, birds seem to be more frequently found as road casualties in agricultural permanent crops. Finally, mammals are more frequently found killed in the more urbanized environments. We can highlight some points when comparing our findings with the existing evidence. The literature shows that most of the road mortality of amphibians and reptiles is associated with agricultural environments (Heigl

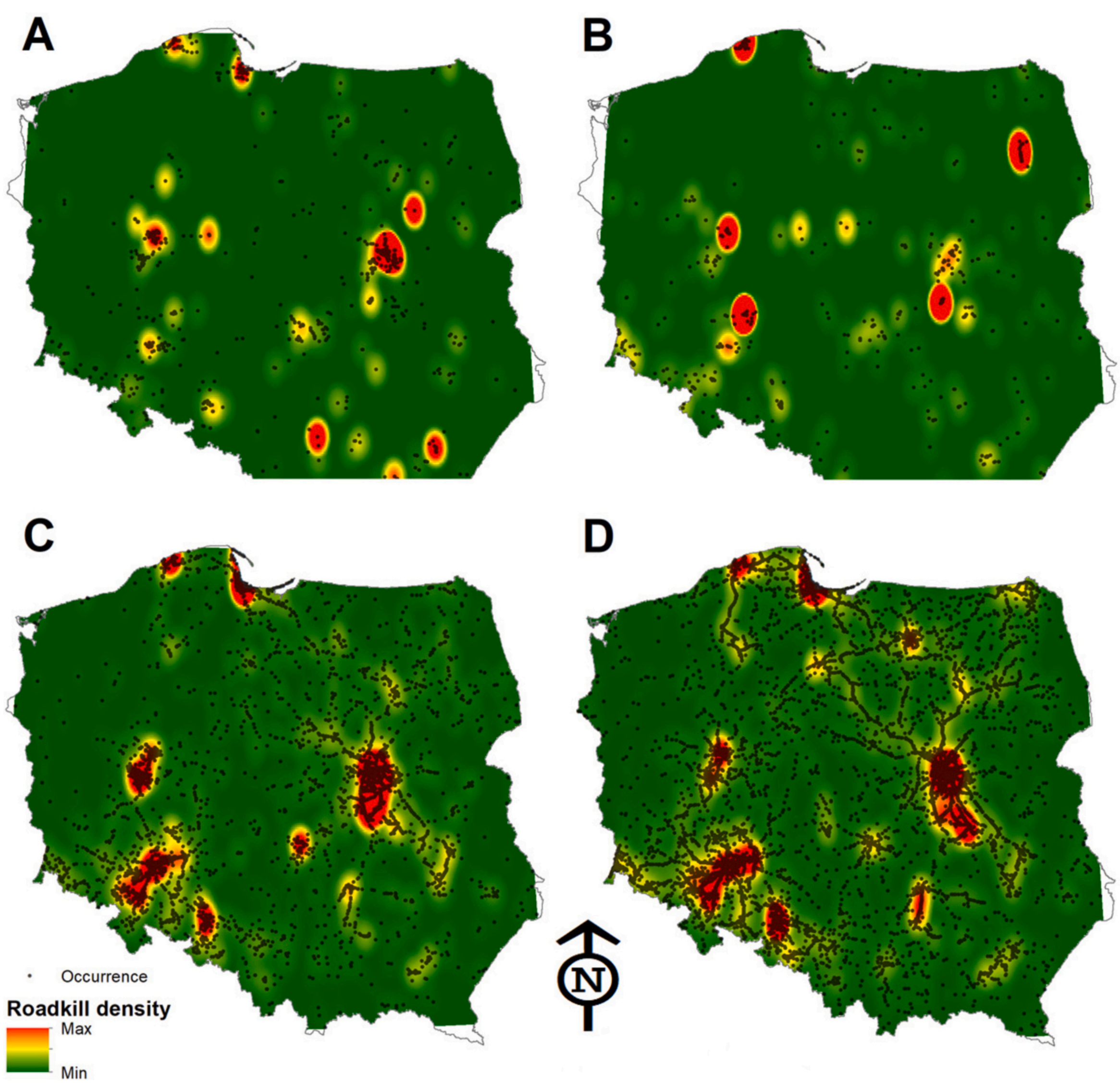

Fig. 2. Spatial distribution of wildlife-vehicle collisions (roadkills) in Poland for amphibians (A), reptiles (B), birds (C) and mammals (D). The kernel density maps are considering the number of individuals involved. The values of kernel density are presented in a coloured gradient from lower (dark green), moderate (yellow) to higher (dark red).

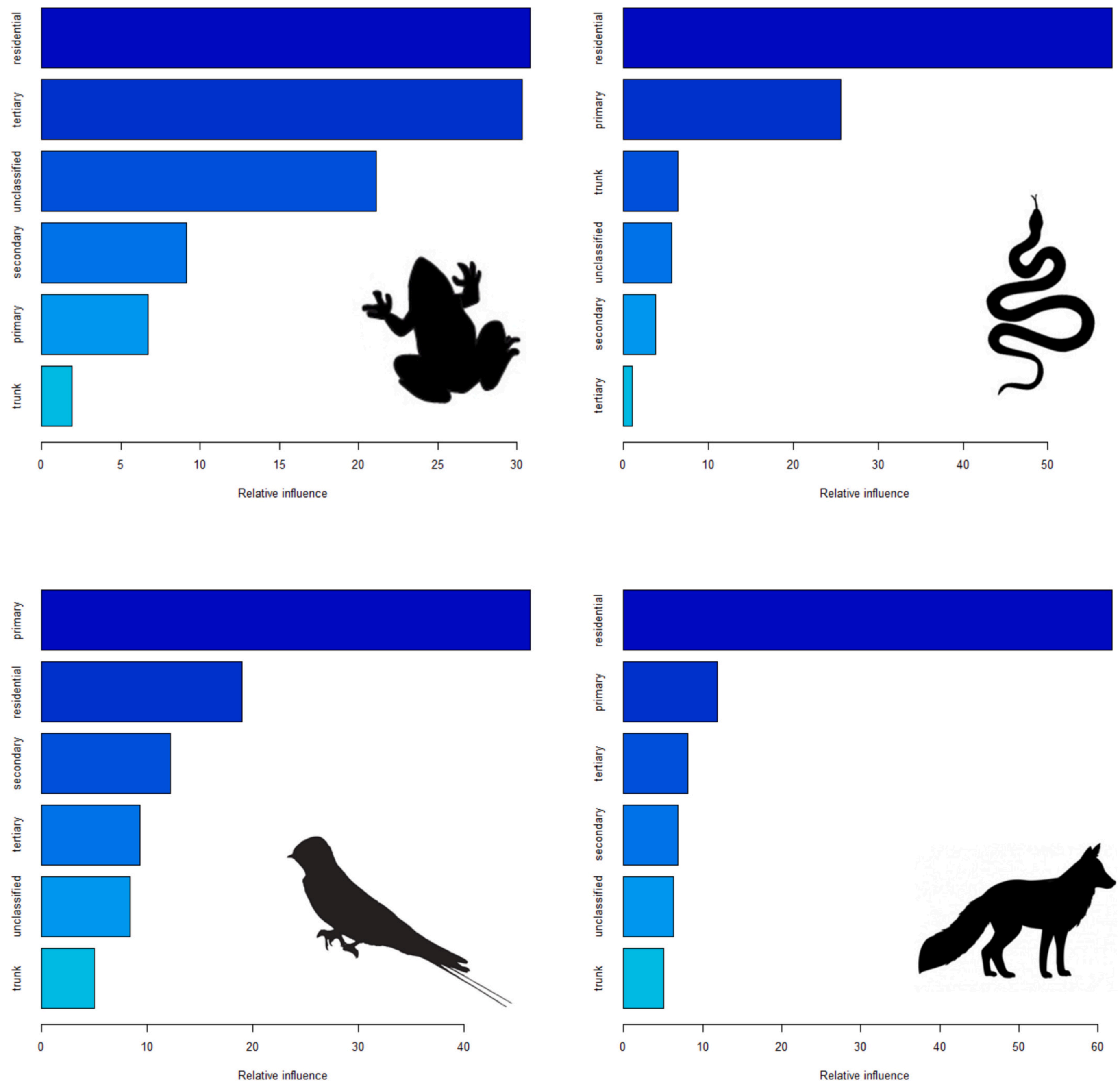

Fig. 3. Overview of the Generalized Boosted Regression Models accounting for variation in wildlife-vehicle collisions (individual casualties), regarding length and type of road within each 10 × 10 km square, modelled separately for each animal group (e.g., amphibians, reptiles, birds and mammals). The plot shows the variables included in the model and their relative influence on the response variable.

et al., 2017). According to the study mentioned above, there is a significant similarity in the occurrence of roadkill between amphibians and reptiles in Austria, with both groups mainly concentrated in arable land, vineyards, and urban or suburban areas (Heigl et al., 2017). However, our results only partially support this finding (see Table 1, Fig. S3). A potential source of heterogeneity could be linked to the different approaches used in each study. While Heigl et al. (2017) examined a relatively short (97 km) section of tertiary road, our study was based on a nationwide programme covering thousands of kilometres of various types of roads.

When considering the WVC events and the potential effect of the length of different types of roads, it emerged that, overall, the type of roads largely characterizing areas at higher roadkill risk for wildlife are primary and residential roads. However, a more accurate assessment for each animal group separately showed that amphibians were more affected by the density of residential, tertiary and unclassified roads, while reptiles were mostly affected by residential roads. At the same time, bird roadkill was more consistently recorded in areas with high density of primary and residential roads, while mammals were mostly affected by the density of residential roads. These differences can also be related to other variables, not enough evaluated in this study (e.g., environmental characteristics or the presence of different human-related structures typical of each type of road), so it is necessary to consider it with a principle of caution.

We consider it important to highlight the advantages and potential weaknesses associated with using non-systematic or opportunistic

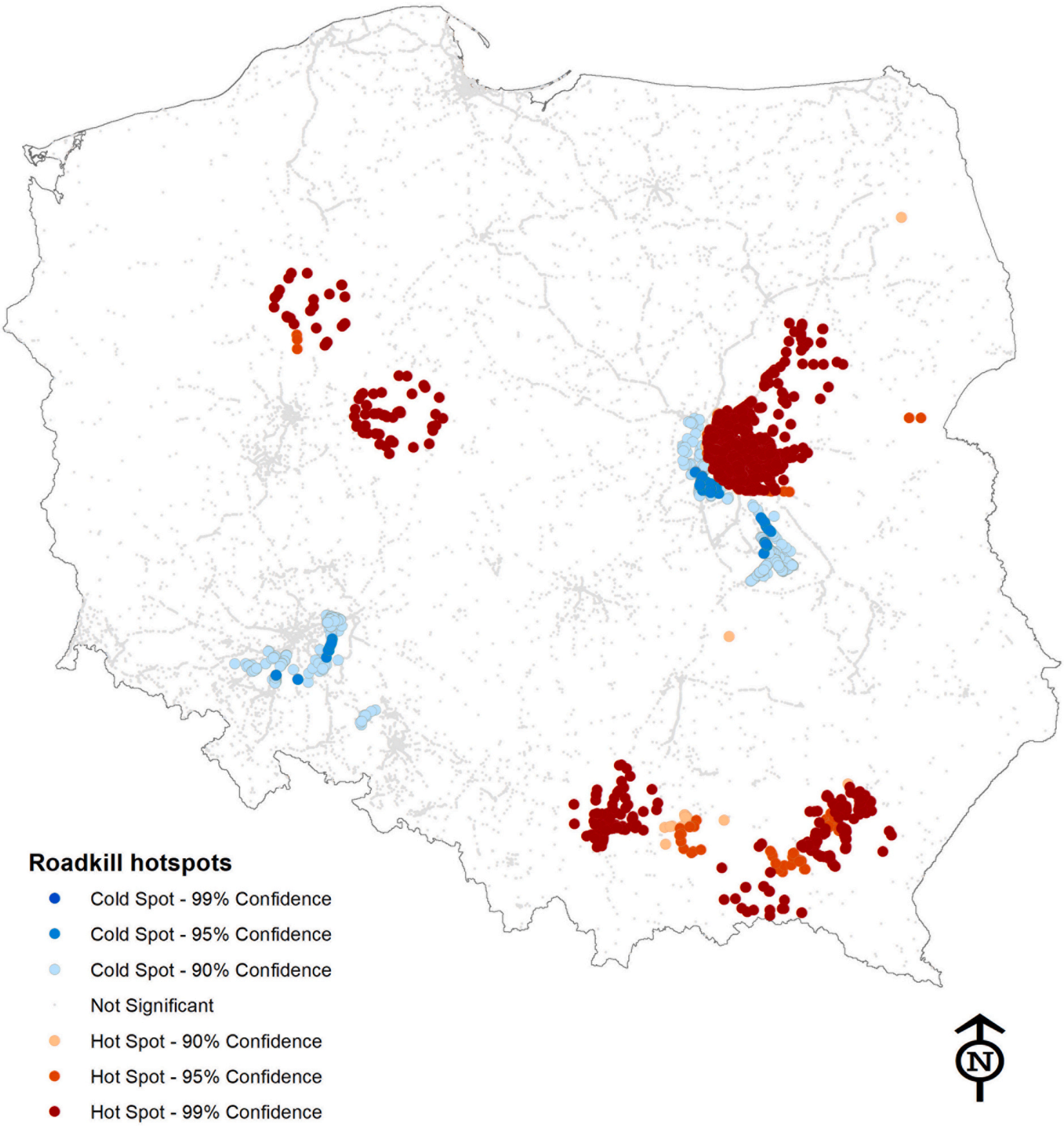

Fig. 4. Spatial distribution of hotspots and coldspots of overall wildlife-vehicle collisions merging the data from the four animal groups in Poland. ArcGIS Hot Spot Analysis was applied by using the Getis-Ord Gi* statistic to classify points in hotspots (red gradient), coldspots (blue gradient) and moderate or no significance (grey), taking into account each feature within the context of neighbouring features.

datasets or data collected by citizen science. The main advantages are related to the possibility of engaging common people in scientific activities and simultaneously increasing the availability and size of large datasets, useful for urban assessment and ecological planning (Aceves-Bueno et al., 2015; Callaghan et al., 2023). However, there are some concerns about such a type of source of information. Typically, citizen science data tend to be biased in space, with more records collected close to urban areas, but this bias is expected to be systematic across taxa (Tang et al., 2021), reducing any misunderstanding in the interpretation of congruence analysis among animal groups. Non-systematic datasets collected by voluntaries can suffer potential sampling biases associated with observer skills and heterogeneous fieldwork effort (Backstrom et al., 2024). However, recent studies comparing the overall roadkill trends from non-standardized data with standardized survey-based data, demonstrated that both sources of information about roadkill can be reliable and relatively congruent (Chyn et al., 2019; Shin et al., 2022). In our study, to reduce the potential bias related to the different skills of observers each entry in the PROS database covering the whole area of Poland was assessed by the biologists and portal administrators to mitigate as much as possible the concerns about citizen programs above mentioned. Additionally, to reduce the bias due to a heterogeneous fieldwork effort made by different volunteers, we modelled the spatial units of 10 × 10 km as random factors. Roughly, we assumed that volunteers were more active in specific spatial units, so mostly associated with a group of them. Anyway, we think that further studies must pay more attention to the impact of sampling biases of non-standardized survey strategies on the overall dataset.

5. Conclusions and perspectives

Considering that road networks are the main tool for transportation that guarantees the success of human development through social and economic activities (Forman et al., 2003; Verrelli et al., 2022), we know the difficulty and necessity of developing strategies to mitigate their negative impact on overall biodiversity (Farias et al., 2022; Medrano-Vizcaíno et al., 2022). Therefore, we recommend increasing the study of WVC clusters of multiple animal groups (multi-taxa hotspots), improving strategies for mitigating wildlife-vehicle collisions. Such areas should also be subject to future mortality surveys, better if combining citizen science approaches with standardised data collection strategies. Finally, some differences related to different associations between animal groups and the type of road or surrounding environment can justify the use of animal group-specific or species-specific strategies (single-taxa approach). Amphibians are the animal group which deserves particular attention regarding roadkill mitigation policies, since are the group less congruent with WVC hotspots of multiple taxa. Moreover, several factors still not fully understood can play different roles, depending on the animal group focused (seasonality associated with migratory movements, weather characteristics, moon phases, etc.) (Garriga et al., 2017; Mestre et al., 2019). A comprehensive approach based on a multi-taxa focus, with a local or regional focus on single animal groups or species, could be the more effective combination to fill the gap in animal mortality related to collisions with vehicles, providing a better understanding of the magnitude of roadkill in wildlife and insights for conservation planning.

CRediT authorship contribution statement

Federico Morelli: Writing – review & editing, Writing – original draft, Visualization, Supervision, Methodology, Formal analysis, Data curation, Conceptualization. **Yanina Benedetti:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Conceptualization. **Karol Kustusch:** Writing – review & editing, Investigation, Funding acquisition, Data curation. **Andrzej Wuczyński:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Investigation, Funding acquisition, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2024.177485.

Data availability

Data will be made available on request.

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