Landscape and Urban Planning 217 (2022) 104285

Contents lists available at ScienceDirect

Landscape and Urban Planning

journal homepage: www.elsevier.com/locate/landurbplan

Local bird densities and habitats are poor predictors of bird collision with glass bus shelters

Ewa Zyśk-Gorczyńska [a], Hanna Sztwiertnia [a], Małgorzata Pietkiewicz [a], Aleksandra Kolanek [b], Katarzyna Bojarska [c], Michał Żmihorski [d,*]

[a] Glass Traps Foundation, Murarska 25/27/6, 54-135 Wrocław, Poland
[b] Department of Geoinformatics and Cartography, Institute of Geography and Regional Development, University of Wrocław, Poland
[c] Institute of Nature Conservation Polish Academy of Sciences, al. Adama Mickiewicza 33, 31-120 Kraków, Poland
[d] Mammal Research Institute Polish Academy of Sciences, Stoczek 1, 17-230 Białowieża, Poland

HIGHLIGHTS

- Glass bus shelters seem to pose an important fatal hazard to birds.
- Bird abundances recorded near bus shelters are poor predictors of bird-glass collisions.
- Habitat composition near bus shelters hardly predicted variation in bird-glass collision risk.
- Mechanisms driving bird-glass bus shelter collisions remains inadequate.

ARTICLE INFO

Keywords:
Glass structures
Bird mortality
Anthropogenic hazard
Bird-window collisions

ABSTRACT

Bird collisions with glass are a major source of avian mortality, killing billions of birds each year worldwide. Likely, the crucial step to prevent bird-glass collisions is understanding spatial and temporal bird-glass collision patterns. As more and more glass-made constructions appear in public spaces, it becomes essential to identify main drivers of bird collisions with these novel objects. In this study, we perform an attempt to identify local characteristics that may influence the risk of bird collisions with glass bus shelters. We monitored 58 bus shelters from March to July 2018 in urban and rural habitats of south-western Poland. We visited the shelters searching for bird carcasses and traces of collisions but also surveyed birds near shelters, considering the two scales (20 and 100 m of the shelter), and bird behavior (flying vs non-flying). We found 52 evidence of bird collisions and number of collisions per bus shelter ranged from 0 to 7 which substantially deviated from random distribution. Bird abundances recorded near bus shelters, recorded at both 20 m and 100 m scales, were poor predictors of bird-glass collisions and did not improve parsimony of models explaining collision risk. This refers to all recorded birds as well as to the subsets of flying individuals and species being collision victims. Similarly, habitat composition near bus shelters hardly predicted variation in bird-glass collision risk. As we did not manage to identify any important drivers explaining collision risk, we conclude that before we learn how to predict areas with high number of bird-glass collisions, we suggest that developers, urban planners and architects should be advised to design all public transportation shelters using nontransparent materials.

1. Introduction

Glass is dangerous for birds due to its specific properties, i.e., transparency and reflectiveness, which make glass an invisible barrier for birds as well as for other animals. Birds are often capable to see in the darkness or in UV light and recognize details from large distances, but their sight is not adapted to recognize transparent objects (Klem, 1990; Martin, 2011; Hastad & Ödeen, 2014; Loss et al., 2014). Reflection in glass may simulate a continuous habitat, which is especially dangerous when the reflected environments are attractive for birds (Gelb & Delacretaz, 2009; Klem, 1989). Also, artificial lights inside and outside buildings have been suggested to be a potential cause of bird-window

* Corresponding author.
E-mail address: zmihorski@ibs.bialowieza.pl (M. Żmihorski).

https://doi.org/10.1016/j.landurbplan.2021.104285
Received 2 June 2021; Received in revised form 30 September 2021; Accepted 9 October 2021

strikes, especially for nocturnal migrants (Keyes & Sexton, 2014; Lao et al., 2020; Parkins, Elbin, & Barnes, 2015). As a result, bird-glass collisions are an important and increasing source of bird mortality, as more and more glass buildings and other structures appear in urban and rural landscapes. For example, the annual bird mortality in North America is estimated to be 1 billion in USA and 42 million in Canada (Loss, Will, Loss, & Marra, 2014; Machtans & Thogmartin, 2014; Machtans, Wedeles, & Bayne, 2013) while 115 million of birds die due to collisions with glass in Germany every year (Wegworth, 2019).

To prevent bird-glass collisions, it is central to understand their spatial and temporal patterns and to identify their main drivers. Several factors can potentially play a role as collision drivers, including types of surrounding habitat, glass surface area and shape, time of day, seasonality and others (Borden, Lockhart, Jones, & Lyons, 2010; Cusa, Jackson, & Mesure, 2015; Hager et al. 2008, 2013; Ocampo-Peñuela, Winton, Wu, Zambello, Wittig, & Cagle, 2016). For example, some studies indicated that collisions are more frequent in rural than in urbanized areas, while presence of green areas surrounding glass surfaces may increase the risk of collision (Basilio, Moreno, & Piratelli, 2020; Bracey, Etterson, Niemi, & Green, 2016; Hager et al., 2013; Kummer, Bayne, & Machtans, 2016). A 10-percent increase in tree height and vegetation cover may cause 30% and 13% increase in the number of collisions during spring and autumn migration, respectively (Klem, 1989). Despite there is no clear research indicating that glass is particularly dangerous for specific age classes, sex or species of birds, some species may be especially prone to collisions, due to their behaviour (Dunn, 1993; Newton, Wyllie, & Dale, 1999; Nichols, Homayoun, Eckles, Blair, & Moreira, 2018) and migratory status (Hager, Trudell, McKay, Crandall, & Mayer, 2008; Horton et al., 2019; Loss et al., 2014; Sabo, Hagemayer, Lahey, & Walters, 2016). These include primarily small synanthropic species, such as passerines or migrant birds which are resting in the vicinity of glass surface (Borden et al., 2010; Parkins et al., 2015; Sabo et al., 2016). Importantly, Klem (1989) suggested that the rate of window strikes and the species involved are directly related to the numbers and species of birds present in the vicinity of windows.

Empirical analyses searching for predictors of collision risk are generally scarce, and were conducted mostly for collisions with buildings, road screens or glass fences (Bayne, Scobie, & Rawson-Clark, 2012; Borden et al., 2010; Gelb & Delacretaz, 2009; Johnson & Hudson, 1976; O'Connell, 2001). Currently, apart from buildings and other large glass structures, small objects made of glass, such as enclosures for pedestrian crossings and shelters for passengers of public transport (train stations, bus and tram stops), are becoming increasingly common worldwide. These structures provide additional bird collision risk and can significantly contribute to bird mortality (Barton, Riding, Loss, & Lepczyk, 2017; Zyśk-Gorczyńska, Skórka, & Żmihorski, 2020). In particular, bus shelters made of glass are becoming more and more popular. In Poland for example, most of wood, steel or concrete bus shelters are being replaced with ones made of glass. Glass shelters are constructed mostly because of passengers' and drivers' security and because they fit aesthetically with every surroundings (from historical city centres to rural landscape). These small objects seem to be partly overlooked in terms of bird-glass collision risk. Our recent study showed a distinct seasonal pattern of bird collisions with glass bus shelters, with substantially fewer collisions in winter and more in late spring and summer. We also found that collision risk is clearly higher in rural than urban landscape, and that dust or graffiti covering glass of bus shelters decreases collision risk (Zyśk-Gorczyńska et al., 2020). However, our previous research did not address a very important aspect that can affect the risk of collisions: the abundance of birds near glass bus shelters, as well as surrounding habitat, as potentially key factors explaining the number of bird collisions.

In this study, we attempt to investigate local characteristics that influence the risk of bird collisions with glass bus shelters. We monitored 58 bus shelters in spring-summer season in Poland, searching for traces of collisions, but also surveyed birds in vicinity of the shelters. First, we hypothesized non-random pattern of bird collisions with glass bus shelters, i.e., we expect some bus shelters have higher while some other lower frequency of collisions as compared to random pattern, and this might be partly linked with the presence of dust and graffiti on the glass of a shelter potentially reducing bird-glass collision risk (Zyśk-Gorczyńska et al., 2020). Second, we hypothesize that bird abundance near a glass bus shelter is a strong positive predictor of bird-glass collisions, as similar tendencies have been already reported for collisions with buildings (Basilio et al., 2020; Borden et al., 2010; Cusa et al., 2015; Hager et al., 2013; Nichols et al., 2018). We tested this hypothesis for all birds pooled but also for the subset of nine bird species that were registered during the study as collision victims, as we suspect these species may be more prone to collisions due to their life histories, e.g. flying speed, habitat preferences, and potentially many other features (Sabo et al., 2016). Also, we distinguished birds in flight, and we hypothesized that number of flying individuals is a better predictor of number of collisions than number of all birds pooled because some bus shelters may be placed at established bird's flyways and local trajectories of bird's movement (e.g. between foraging grounds and breeding sites) thus resulting in higher collision risk. Third, we predict that green and forested areas around glass shelters are associated with higher collision risk. This might be the case because migrating songbirds often stop to rest and forage in green areas (Bayne et al., 2012; Winton, Ocampo-Peñuela, & Cagle, 2018) and in such locations, window collision rates are often higher than in more urbanized regions (Bayne et al., 2012; Hager, Cosentino, & McKay, 2012; Klem, 1989).

2. Methods

2.1. Study area

We monitored 58 glass bus shelters along urban–rural gradient in south-western Poland (Fig. 1). The shelters were situated along a ca 160-km route stretching from the outskirts of Wrocław city in the north-east (coordinates: N51°06′36″, E17°01′20″) to Wałbrzych city, ca. 65 km to the south-west straight-line (N50°46′15″, E16°16′26″). Wrocław, located on the Silesian Lowland, is a city of ca 300 km^2, and population reaching 642,869 inhabitants (Central Statistical Office, 2020). The number of glass shelters in Wrocław is over 1000 and growing. Wałbrzych is a town located in the West Sudeten Foothills and Central Sudeten in the Wałbrzyskie Mountains. The town is inhabited by over 110,000 people (Central Statistical Office, 2020) and its area is ca 85 km^2. The number of glass bus shelters in Wałbrzych city is about 800. In contrast, the number of glass bus shelters in the monitored villages on the route between Wrocław and Wałbrzych is usually up to a few per village.

2.2. Bird collisions

From March to July 2018, we visited the 58 selected glass bus shelters every 12 days on average, each shelter being visited 16 times. During each visit, we first searched for bird carcasses within 3 m of the bus shelter (Fig. 2A). We determined species and when possible, sex and age of the carcasses. Next, all the shelter sides were carefully checked for traces of collisions, like feathers and bird contours (Fig. 2B, C) as this method is often used to estimate bird-glass collisions (e.g., Zyśk-Gorczyńska et al., 2021; Zyśk-Gorczyńska, Bojarska, & Żmihorski, 2021). All traces that could not be classified unequivocally as being a result of bird collisions were ignored. We removed the bird carcasses and all traces of collisions in order to prevent them from being counted again during subsequent visits. Also, for each monitored shelter during each visit we estimated presence of dust and graffiti on the glass of a shelter since in our earlier studies, the presence of both graffiti and dust were associated with a decrease of bird-glass collision risk (Zyśk-Gorczyńska et al., 2020).

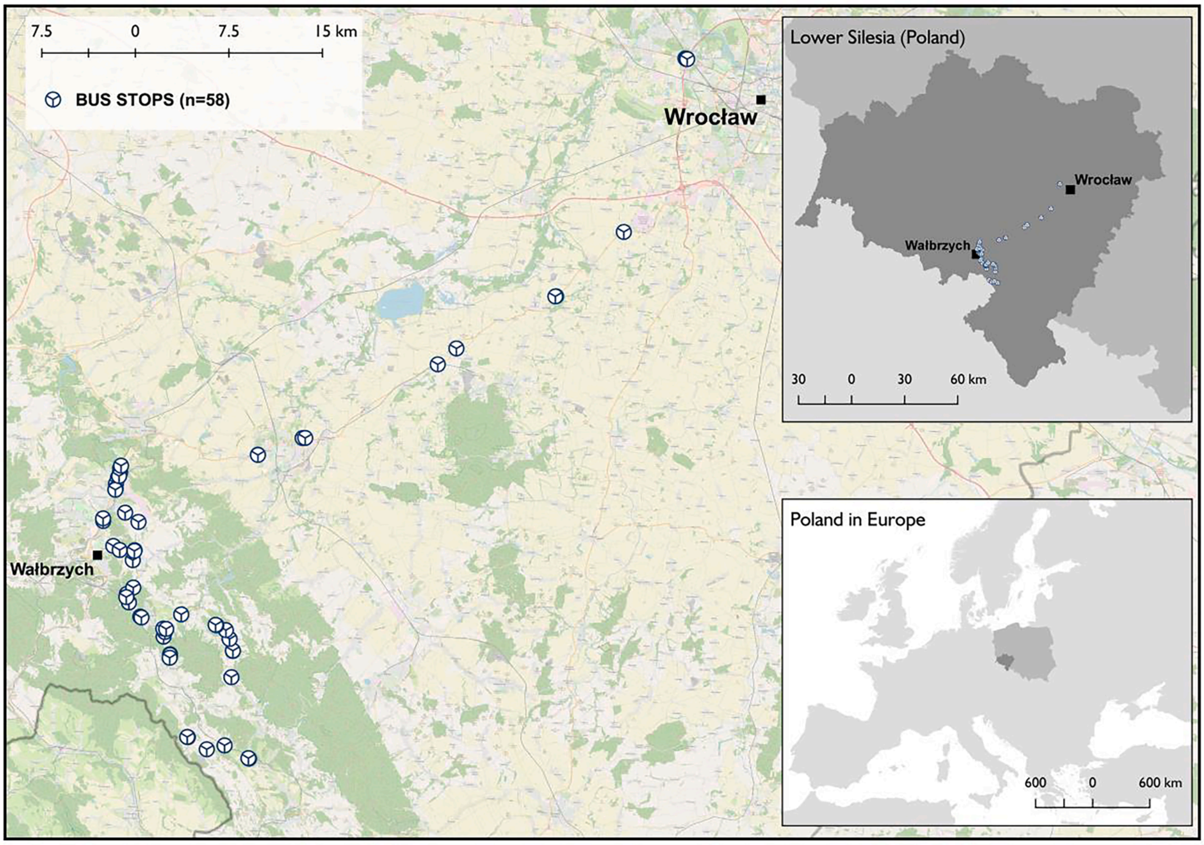

Fig. 1. Study area with monitored bus shelter locations. Inset maps: the administrative boundaries of Lower Silesia (upper map) and location of Poland against the background of Europe (lower map). Source: Open Street Map & own work.

Fig. 2. Examples of bird fatalities and signs of bird collision with glass bus shelters: a) dead greenfinch Chloris chloris found near the glass shelter, b) feathers left on a glass, c) a body outline.

2.3. Bird counts

We conducted bird inventory near bus shelters during six controls from March to July 2018 (dates of controls: 27.03., 20.04., 27.04, 31.05, 27.06, 26.07). Controls started early in the morning and lasted till the evening. In order to diversify the time of day during which birds were counted near a specific bus shelter, controls each time started from a different bus shelter. Only days with appropriate weather conditions were chosen for controls (no heavy rain, mist or strong wind). At each bus shelter, the observer recorded seen and heard birds for 10 min, and noted the number of individuals of each species. The observer remained at the bus shelter throughout the observation time and assigned each individual to one of the two distance bands: 0–20 or 20–100 m from the shelter, and to one of the two behavior categories: on the ground and plants (standing/not in flight) or in flight. Based on the bird inventory, for each bus shelter we calculated number of individuals of all bird species, as well as number of individuals of nine species registered as collision victims. Here we assumed that bird species that were recorded previously as collision victims in the study area (Zyśk-Gorczyńska et al., 2020; Zyśk-Gorczyńska, Mikusek & Sztwiertnia, 2021) might be especially prone to collisions due to their life histories, thus it is worth to consider local abundance of these species as a separate explanatory variable. We calculated eight bird abundance indices: number of all bird species and nine species being collision victims including all individuals or flying individuals only (hereafter: All.Birds, Victim.Birds, All.Flying.Birds, Victim.Flying.Birds), separately within the radius of 20 m or 100 m (i.e. 0–20 m and 20–100 m pooled) of the bus shelter.

2.4. Spatial data processing

The spatial data were obtained from the national Database of Topographic Objects shared by the Head Office of Geodesy and Cartography (BDOT10k 2020) The following land-use variables were selected for further analyses: wooden area (Forest), grassy vegetation and agricultural crops (Open) and buildings (Buildings), as potentially important for diversity and abundance of birds. Two buffers (0–20 m and 20–100 m, corresponding to distance bands used for bird counts) were generated around each bus shelter. Land-use data were trimmed to the buffers and areas of objects belonging to each class inside buffers were calculated (hereafter referred to as Forest20, Forest100, Open20, Open100, Buildings20, Builings100). All spatial analyses were performed on the EPSG:2180 ("PUWG1992") projection using ArcMap (ESRI 2020) and QGIS software (QGIS 2020).

2.5. Statistical analyses

First, we checked if the distribution of collisions across 58 studied bus shelters deviates from random. For this purpose, we simulated 10,000 times random distribution of 52 collisions registered across 58 shelters and compared the simulated distribution with empirical data. Specifically, we compared empirical and simulated proportion of bus shelters without any collision as well as proportion of bus shelters with number of collisions exceeding 4, 5 and 6.

We performed a set of 51 generalized linear models implemented in "mgcv" package (Wood, 2017) in R (R Core Team, 2020). In all the models each bus shelter ($n = 58$) was treated as a single data record, and number of bird-glass collision in each shelter, ranging from 0 to 7, was a response variable. The response variable was over-dispersed, as its variance was over 3 times greater than the mean (2.8 vs 0.9, respectively). We thus used negative-binomial family (and logarithmic link) for all 51 models, with theta shape parameter automatically estimated from data. Specifically, we performed eight models using bird abundance near bus shelters as predictors, eight models using land-use types near bus shelters as predictors, and 32 models using both birds and land-use types as predictors (in case of all predictors, the two spatial scales were included: 20 and 100 m). In all these 48 models, we also included glass transparency as predictor ("Dust" variable), as in our previous studies (Zyśk-Gorczyńska et al., 2020) we showed that presence of dust and graffiti reduces bird-glass collision risk. Finally, three null models were performed for comparisons. First, model with longitude and latitude was considered to check if number of bird-glass collisions can effectively be explained just by geographical location of a given bus shelter. For this purpose, we added nonparametric part into the model and fitted longitude and latitude with interaction of nonparametric thin plate regression splines with upper limit of the fit wiggliness parameter "k" set to 10 (Wood, 2017). Second, model without any explanatory variables except "Dust" variable, and third, model without any explanatory variable (i.e., intercept-only model), were fitted.

Collinearity among explanatory variables (for both 20- and 100-m scales) was checked with variance inflation factor and we did not record any VIF scores exceeding 2.0. Also, spatial autocorrelation of residuals of all 51 models was checked with spline correlogram implemented in "ncf" R package (Bjornstad, 2020). The set of competing 51 GLMs were compared using information-theoretic approach. Specifically, we calculated Akaike information criterion for small samples (i.e., second-order AIC; AICc) for all the models and calculated AIC difference, i.e., differences in AIC scores between a given model and best model (ΔAICc). Following Burnham and Anderson (2002) we assumed that models with ΔAICc between 0 and 2 are equally good and have similar support in empirical data.

3. Results

We found 52 evidence of bird collisions at 21 out of 58 glass shelters (i.e., 37 shelters without any collision) and number of collisions per bus stop ranged from 0 to 7 (mean = 0.90; SD = 1.67). In 40 cases we recorded traces of a collision with a shelter, while in 12 cases we recorded both traces and carcasses of nine bird species: three Common blackbirds *Turdus merula*, two Song thrushes *Turdus philomelos*, Common starling *Sturnus vulgaris*, Great tit *Parus major*, Eurasian nuthatch *Sitta europaea*, Blue tit *Cyanistes caerulesu*, Yellowhammer *Emberiza citrinella*, European Greenfinch *Chloris chloris* and Eurasian siskin *Spinus spinus*. The traces left on the glass included feather remains ($n = 38$) and whole bird contours ($n = 14$). All of the 12 carcasses were passerines, with Common blackbird being the most common. Adults predominated ($n = 11$) among the dead birds.

We recorded 2883 observations of 61 bird species in the vicinity of the studied 58 glass bus shelters. Among the recorded species Common starling, House sparrow *Passer domesticus*, Rock dove *Columba livia*, Common swift *Apus apus*, Common blackbird, Great tit and Eurasian collared dove *Streptopelia decaocto* were the most common (all seven exceeded 100 recorded individuals, see Appendix A for abundances of all species).

Distribution of collisions across bus shelters was significantly deviated from random. For simulated random data, the share of bus stops without any collision ranged between 18 and 29 (interquartile range covering 99% of cases) and never exceeded 33 (for 10,000 simulations) while the empirical number of such bus shelters was much higher (37). The probability that four or more collisions happen at one bus shelter under random model (i.e. simulated data) was low ($p = 0.02$), and lower for five or more collisions ($p = 0.003$), six or more ($p = 0.0005$) and seven or more ($p = 0.00008$), as found in simulations. However, in empirical data we observed two bus shelters with seven collisions, which points at highly non-random distribution of collisions across monitored bus shelters.

Among all 51 competing models explaining number of collisions per bus shelter, the model including all flying birds within 20 m and glass transparency had the lowest AICc score. However, eight other models, including the null model, were equally good (ΔAICc 0–2), thus indicating that local bird abundance and dominating local land use (at both 20 and 100 m scales) seem rather weak predictors of number of bird collisions with glass bus shelters. The model containing geographical location of the studied bus shelters was, however, markedly less parsimonious than the best model (ΔAICc = 3.08), which suggests no clear spatial pattern exists in collisions. Also, no clear differences were observed between sets of models using smaller (r = 20 m) and larger (100 m) spatial scales (Table 1).

4. Discussion

Following our predictions, we found a non-random pattern of bird-glass collisions, with some bus shelters having substantially higher collision risk than expected by chance. However, no correlation between bird density near bus shelters and number of bird-glass collisions was observed. The abundance of flying individuals and abundance of bird species being collision victims also remained largely uncorrelated with the number of collisions recorded. Similarly, habitat structure in the surrounding of bus shelters did not explain variation in number of collisions. We thus failed to confirm our two hypotheses posed in the introduction. Our results suggest that in case of bird-glass shelter strikes, the mechanisms might be different than the ones recorded for bird collisions with buildings, where local avian abundance and main land-use type surrounding glass shelters seem to have an impact on bird collision risk. Below we discuss potential study limitations and possible explanations for the observed patterns.

We did not confirm important link between bird abundance and collisions despite relatively high sampling effort (6 visits per shelter, 10 min per visit) ensuring relatively reliable local bird density estimations. In most studies aiming to estimate local terrestrial bird densities with the help of point-counts maximum 4 visits are recommended (5 to 10 min each) and assumed to be sufficient (Gregory et al., 2004). Given substantially higher sampling effort in our studies, it is rather unlikely that undersampling is a problem. Also, distance bands used by us (20 and 100 m) seem reasonable (see also Gregory et al., 2004), although we cannot exclude that different bands (e.g. looking at nearest 10 m instead of 20 m) might produce slightly different patterns. Finally, the studied bus shelters slightly differed in term of construction, size, etc., but these differences are not large as we selected relatively similar shelters for the study and cannot explain such large variation in observed number of collisions among shelters. In our opinion, therefore, methodological limitations are not responsible for the lack of association between bird densities and collision risk.

Table 1
Set of 51 competing generalised linear models explaining number of bird-glass collisions across 58 bus shelters at two spatial scales (20 and 100 m of bus shelters). For each model explanatory variables are given and difference between a certain model and best model (ΔAICc). Nine models with ΔAICc within 0–2 are bolded.

Explanatory variables	ΔAICc 20-m buffer	ΔAICc 100-m buffer
Bird abundance models		
All.Birds + Dust	**0.76**	2.70
All.Flying.Birds + Dust	**0.00**	**1.48**
Victim.Birds + Dust	3.52	3.52
Victim.Flying.Birds + Dust	2.89	2.59
Habitat models		
Buildings + Dust	2.91	**0.33**
Forest + Dust	3.80	**1.61**
Open + Dust	3.56	3.77
Buildings + Forest + Open + Dust	7.92	4.65
Bird abundance and habitat models		
All.Birds + Buildings + Dust	2.57	2.33
All.Birds + Forest + Dust	3.33	3.86
All.Birds + Open + Dust	3.41	5.07
All.Birds + Buildings + Forest + Open + Dust	8.13	7.37
All.Flying.Birds + Buildings + Dust	**1.77**	**1.48**
All.Flying.Birds + Forest + Dust	2.61	3.18
All.Flying.Birds + Open + Dust	2.60	3.68
All.Flying.Birds + Buildings + Forest + Open + Dust	7.44	6.81
Victim.Birds + Buildings + Dust	5.06	2.38
Victim.Birds + Forest + Dust	6.16	4.12
Victim.Birds + Open + Dust	6.01	5.94
Victim.Birds + Buildings + Forest + Open + Dust	10.53	7.27
Victim.Flying.Birds + Buildings + Dust	4.24	**1.17**
Victim.Flying.Birds + Forest + Dust	5.51	3.59
Victim.Flying.Birds + Open + Dust	5.51	4.53
Victim.Flying.Birds + Buildings + Forest + Open + Dust	9.90	6.33
Null models		
(intercept only)	4.32	
Dust	**1.34**	
Longitude + Latitude + Dust	3.41	

Environmental factors and attractiveness of local habitats to birds affect local bird abundance, thus often increasing probability of collisions (Cusa et al., 2015; Gelb & Delacretaz, 2009; Gómez-Martínez et al., 2019). In contrary to these expectations, predictive power of local bird abundance and local land-use types were generally low in our study and they did not increase model parsimony as compared to null models, thus indicating that these variables are rather useless for explaining spatial patterns in bird-glass collisions. suggest that collision risk is not simply a function of bird abundance (Kahle, Flannery, Dumbacher, & Longcore, 2016; Sabo et al., 2016). We propose here several hypothetical explanations.

In theory location of a bus stop in relation to flying routes of local birds may partly explain the variation in collisions among shelters. Spatial configuration of patches of habitats preferred by birds and their nesting or foraging sites (including bird feeders) may cause that some locations or routes are more often used by birds, and glass shelters placed in such locations will have elevated collision rates (Klem et al., 2004; Kummer & Bayne, 2015). If this is the case, however, we would expect correlation between collisions and number of flying individuals. Shelter-specific reflections in the glass may also contribute to the collision risk which might be related to placement of glass panes in relation to sun or green areas in the vicinity, so combination of such characteristics can potentially affect collision risk with certain shelters. These, however, are only speculations as we did not measure the reflections. We thus strongly recommend to estimate the reflections and measure presence of trees and shrubs nearby in future studies explaining bird-glass collisions.

Third, the age of a glass object may also be important – resident birds may become habituated to long-standing glass structures, but installing new glass objects may increase collision rates as the local birds have no time to get used to their presence (Klem, 1989). It cannot be excluded that shelters with more collisions were newer, unfortunately we do not have data on the shelter age, although most of the glass bus shelters in this study were relatively new (up to a few years old). Finally, predicted collision patterns can also be disrupted by timing and frequency of human presence at a bus stop (and its surroundings, e.g., sidewalk, bike path). Birds may avoid bus shelters very often used by people, but can also hit the glass when frightened by the sudden approach of people. Thus, the human factor may also be an important variable affecting the number of bird collisions with a particular glass shelter and needs further investigations.

4.1. Conservation implications

The construction of glass small architecture objects seems to be a dominant trend in many countries. Most wooden, concrete or timber structures such as fences, zoo viewing panels, bus shelters, winter gardens, balconies, orangeries and others have been or are being replaced by glass structures. The impact of such seemingly small glass objects on birds is meanwhile rather poorly studied and despite their relatively small size, glass bus shelters seem to pose an important, yet underestimated, fatal hazard to birds. Unfortunately, however, our understanding of mechanisms driving bird-glass bus shelter collisions remains inadequate. In the present study we did not manage to identify any important drivers explaining spatial variation in collision risk. Given highly non-random collision pattern we conclude that further studies of these issues are urgently needed. However, before we learn how to identify glass bus shelters with exceptionally high collision risk, developers, urban planners and architects should be advised to either generally design public transportation shelters using nontransparent materials or to apply by default already known solutions (e.g. plastic markings on the glass) that improve glass visibility for birds.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.landurbplan.2021.104285.

References

Barton, C. M., Riding, C. S., Loss, S. R., & Lepczyk, C. A. (2017). Magnitude and correlates of bird collisions at glass bus shelters in an urban landscape. *PLos One, 12*(6).

Basilio, L. G., Moreno, D. J., & Piratelli, A. J. (2020). Main causes of bird-window collisions: A review. *Annals of the Brazilian Academy of Sciences, 92*, Article e20180745.

Bayne, E. M., Scobie, C. A., & Rawson-Clark, M. (2012). Factors influencing the annual risk of bird-window collisions at residential structures in Alberta, Canada. *Wildlife Research, 39*(7), 583–592.

BDOT10k (2020). National Database of Topographic Objects. Polish Head Office of Geodesy and Cartography. Available online: http://www.gugik.gov.pl/ (accessed on 15 August 2020).

Bjornstad, O.N. (2020). ncf: Spatial Covariance Functions. R package version 1.2-9. https://CRAN.R-project.org/package=ncf.

Borden, W. C., Lockhart, O. M., Jones, A. W., & Lyons, J. S. (2010). Seasonal, taxonomic, and local habitat components of bird-window collisions on an urban university campus in Cleveland, OH. *Ohio Journal of Science, 110*(3), 44–52.

Bracey, A. M., Etterson, M. A., Niemi, G. J., & Green, R. F. (2016). Variation in bird-window collision mortality and scavenging rates within an urban landscape. *The Wilson Journal of Ornithology, 128*(2), 355–367.

Burnham, K. P., & Anderson, D. R. (2002). *Model selection and multimodel inference: A practical information-theoretic approach* (2nd edn.). New York: Springer.

Central Statistical Office (2020). https://stat.gov.pl/en/.

Cusa, M., Jackson, D. A., & Mesure, M. (2015). Window collisions by migratory bird species: Urban geographical patterns and habitat associations. *Urban Ecosystems, 18*(4), 1427–1446.

Dunn, E. H. (1993). Bird mortality from striking residential windows in winter. *Journal of Field Ornithology, 64*(3), 302–309.

ESRI, (2020). Environmental Systems Research Institute. ArcGIS Desktop: Release 10.7; Environmental Systems Research Institute: Redlands, CA, USA, 2013.

Gelb, Y., & Delacretaz, N. (2009). Windows and vegetation: Primary factors in Manhattan bird collisions. *Northeastern Naturalist, 16*(3), 455–470.

Gómez-Martínez, M. A., Klem, D., Rojas-Soto, O., González-García, F., & MacGregor-Fors, I. (2019). Window strikes: Bird collisions in a Neotropical green city. *Urban Ecosystem, 22*(4), 699–708.

Gregory, R. D., Gibbons, D. W., & Donald, P. F. (2004). Bird census and survey techniques. In W. J. Sutherland, I. Newton, & R. E. Green (Eds.), *Bird ecology and conservation; a handbook of techniques* (pp. 17–56). Oxford: Oxford University Press.

Hager, S. B., Cosentino, B. J., & McKay, K. J. (2012). Scavenging affects persistence of avian carcasses resulting from window collisions in an urban landscape. *Journal of Field Ornithology, 83*(2), 203–211.

Hager, S. B., Cosentino, B. J., McKay, K. J., Monson, C., Zuurdeeg, W., Blevins, B., & Fenton, B. (2013). Window area and development drive spatial variation in bird-window collisions in an urban landscape. *PLoS One, 8*(1), e53371.

Hager, S. B., Trudell, H., McKay, K. J., Crandall, S. M., & Mayer, L. (2008). Bird density and mortality at windows. *Wilson Journal of Ornithology, 120*(3), 550–564.

Hastad, O., Ödeen, A. (2014). A vision physiological estimation of ultraviolet window marking visibility to birds. PeerJ, (2), e621.

Horton, K. G., Nilsson, C., Van Doren, B. M., La Sorte, F. A., Dokter, A. M., & Farnsworth, A. (2019). Bright lights in the big cities: Migratory birds'exposure to artificial light. *Frontiers in Ecology and the Environment, 17*(4), 209–214.

Johnson, R. E., & Hudson, G. E. (1976). Bird mortality at a glassed-in walkway in Washington State. *Western Birds, 7*, 99–107.

Kahle, L. Q., Flannery, M. E., Dumbacher, J. P., & Longcore, T. (2016). Bird-window collisions at a west-coast urban park museum: Analyses of bird biology and window attributes from Golden Gate Park, San Francisco. *PLoS One, 11*(1).

Keyes, T., & Sexton, L. (2014). Characteristics of bird strikes at Atlanta's commercial buildings during late summer and fall migration, 2005. The Oriole, 79.

Klem, D., Jr. (1989). Bird-window collisions. *Wilson Bulletin, 101*, 606–620.

Klem, D., Jr. (1990). Collisions between birds and windows: Mortality and prevention. *Journal of Field Ornithology, 61*, 120–128.

Klem, D., Jr., Keck, D. C., Marty, K. L., Ball, A. J. M., Niciu, E. E., & Platt, C. T. (2004). Effects of window angling, feeder placement, and scavengers on avian mortality at plate glass. *Wilson Bulletin, 116*, 69–73.

Kummer, J. A., & Bayne, E. M. (2015). Bird feeders and their effects on bird-window collisions at residential houses. *Avian Conservation and Ecology, 10*(2), 6.

Kummer, J. A., Bayne, E. M., & Machtans, C. S. (2016). Use of citizen science to identify factors affecting bird-window collision risk at houses. *Condor, 118*(3), 624–639.

Lao, S., Robertson, B. A., Anderson, A. W., Blair, R. B., Eckles, J. W., Turner, R. J., & Loss, S. R. (2020). The influence of artificial light at night and polarized light on bird-building collisions. *Biological Conservation, 241*, 108358.

Loss, S. R., Will, T., Loss, S. S., & Marra, P. P. (2014). Bird-building collisions in the United States: Estimates of annual mortality and species vulnerability. The Condor, 116, 8–23.

Machtans, C. S., & Thogmartin, W. E. (2014). Understanding the value of imperfect science from national estimates of bird mortality from window collisions. *The Condor, 116*(1), 3–7.

Machtans, C. S., Wedeles, C. H. R., & Bayne, E. M. (2013). A first estimate for Canada of the number of birds killed by colliding with building windows. *Avian Conservation and Ecology, 8*(2), 6.

Martin, G. R. (2011). Understanding bird collisions with man-made objects: A sensory ecology approach. *Ibis, 153*, 239–254.

Newton, I., Wyllie, I., & Dale, L. (1999). Trends in the numbers and mortality patterns of Sparrowhawks (*Accipiter nisus*) and Kestrels (*Falco tinnunculus*) in Britain, as revealed by carcass analyses. *Journal of Zoology, 248*(2), 139–147.

Nichols, K. S., Homayoun, T., Eckles, J., Blair, R. B., & Moreira, F. (2018). Bird-building collision risk: An assessment of the collision risk of birds with buildings by phylogeny and behavior using two citizen-science datasets. *PLoS One, 13*(8), e0201558.

Ocampo-Peñuela, N., Winton, R.S, Wu C.J., Zambello, E, Wittig, T.W. & Cagle, N.L. (2016). Patterns of bird-window collisions inform mitigation on a university campus. Peerj, 4, e1652.

O'Connell, T. J. (2001). Avian window strike mortality at a suburban office park. *The Raven, 72*(2), 141–149.

Parkins, K. L., Elbin, S. B., & Barnes, E. (2015). Light, glass, and bird-building collisions in an urban park. *Northeastern Naturalist, 22*(1), 84–94.

QGIS (2020). Geographic Information System: Release 3.0. Open Source Geospatial Foundation Project. Technical documentation. www.qgis.org/en/docs/index.html.

R Core Team (2020). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. https://www.R-project.org/.

Sabo, A. M., Hagemayer, N. D. G., Lahey, A. S., & Walters, E. L. (2016). Local avian density influences risk of mortality from window strikes. Peer Journal, 4, e2170.

Wegworth, C. (2019). Vogelschutz und Glasarchitektur im Stadtraum Berlin. Eine aktuelle Bestandsaufnahme und Ermittlung von Erfordernissen für eine verantwortungsvolle Stadtplanun. Berlin. Bund.

Winton, R.S., Ocampo-Peñuela N., & Cagle, N. (2018). Georeferencing bird-window collisions for targeted mitigation. PeerJ, 6, e4215.

Wood, S. N. (2017). *Generalized Additive Models: An Introduction with R* (2nd ed.). Chapman and Hall/CRC.

Zyśk-Gorczyńska, E., Bojarska, K., & Żmihorski, M. (2021). Nonrandom bird-glass collision pattern: Fewer strikes near glass edge. *Acta Ornithologica, 56*, 133–137.

Zyśk-Gorczyńska, E., Mikusek, R., Sztwiertnia, H. (Ed). (2021). Kolizje ptaków z transparentnymi powierzchniami – kompendium wiedzy. Wrocław.

Zyśk-Gorczyńska, E., Skórka, P., & Żmihorski, M. (2020). Graffiti saves birds: A year-round pattern of bird collisions with glass bus shelters. *Landscape and Urban Planning, 193*, Article 103680.