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Research Paper

Graffiti saves birds: A year-round pattern of bird collisions with glass bus shelters

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ABSTRACT

The increase in the human population is bringing with it a concomitant rise in the number of novel man-made structures appearing in different environments, which may affect wildlife. Glass shelters at bus stops create surfaces invisible to many animals like birds and may increase their mortality; evidence for this is rare, however. The main aim of the study was to analyse the temporal variation and frequency of the risk of birds colliding with small, man-made, glass structures. A year-round survey investigating the frequency of bird collisions with 81 glass bus shelters was performed in south-western Poland. A total of 2467 visits to these bus stops yielded evidence of 155 collisions at 40 of them (mean: 1.9 per shelter, range 0–18). The bird carcasses most often found were of passerines, principally blackbirds *Turdus merula*. The traces left on the glass included feather remains (70%) and whole bird contours (30%). The probability of finding, during a single visit to a bus stop, that a bird had collided with the glass shelter tended to be higher in rural than in urban areas. Both dust and graffiti covering the glass panels of a bus shelter reduced the likelihood of collision. The occurrence of collisions was the highest in July-August and the lowest from November to February. Our study is the first in Europe and the first year-round study worldwide to demonstrate that such small man-made objects can cause death and injuries to birds. We suggest covering such shelters with non-transparent objects, e.g. city maps, paintings or other forms of artwork, in order to reduce the negative impact of these structures on local birds.

1. Introduction

People influence and interact with species in a multitude of ways. Species are directly affected not only by loss of habitat, predation by domestic carnivores (Lepczyk, Mertig, & Liu, 2004) and invasive species, but also by man-made structures. For example, it has been demonstrated that collisions with vehicles have a strong negative effect on resident taxa (Mineau, 2005; Calvert et al., 2013; Lepczyk, Fantle-Lepczyk, Misajon, Hu, & Duffy, 2019). In the case of birds, collisions with glass or glass-covered structures are another important reason for the global decrease in their populations (Machtans, Wedeles, & Bayne, 2013; Machtans & Thogmartin, 2014). Since birds do not recognize such structures as physical barriers, millions – a grossly underestimated figure – are killed in collisions with them (Klem, 1990; Klem, Farmer, Delacretaz, Gelb, & Saenger, 2009; Loss, Will, Loss, & Marra, 2014).

In recent decades, there has been greater focus on the problem of birds striking glass structures, mainly because the latter have been increasing in number in urban areas (Klem 1989, 1990; Hager, Cosentino, & Aguilar-Gómez, 2017). However, we still have a poor understanding of bird collisions with such structures (Martin, 2011). Factors like the habitat surrounding glass structures, building characteristics, window surface area, time of day, seasonality and bird status (migrant or resident) have been identified as significantly influencing the probability of bird collisions (O'Connell, 2001; Gelb & Delacretaz, 2009; Klem et al., 2009; Bayne, Scobie, & Rawson-Clark, 2012; Klem, 2014; Parkins, Elbin, & Barnes, 2015). Windows appear to be the most dangerous to birds when the surrounding habitat is visible through or reflected in the glass (Klem, 1989; Gelb & Delacretaz, 2009). Moreover, numbers of fatal bird collisions are positively related to the percentage of glass coverage. Consequently, skyscrapers, tall buildings or transparent noise reduction screens installed along roads are often responsible for high numbers of fatal bird collisions because of their large surface areas of glass (Cusa, Jackson, & Mesure, 2015). Nevertheless, Loss et al. (2014) found that low-rise buildings are in fact responsible for the majority of fatal bird collisions, with less than 1% of mortality occurring on high-rise buildings (more than 12 storeys tall).

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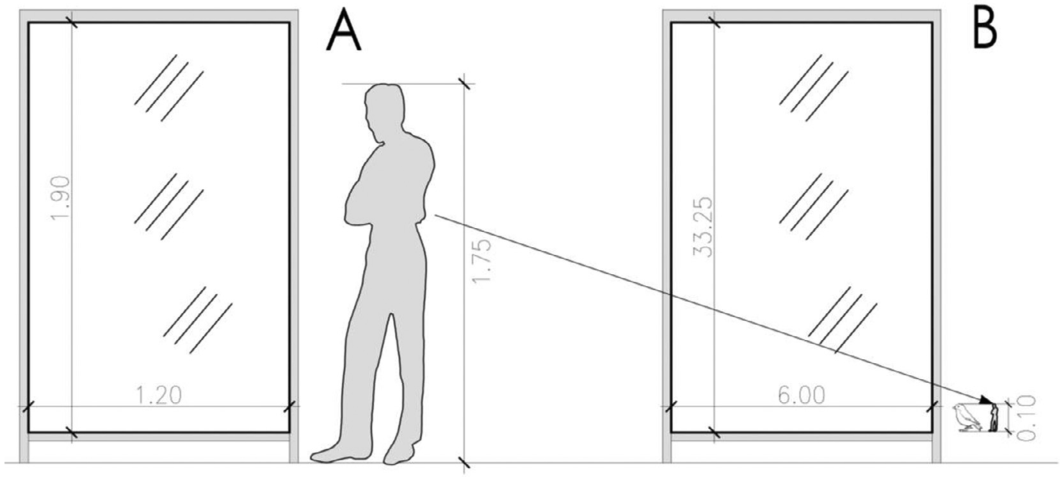

Fig. 1. A traditional glass bus shelter panel (dimensions in metres) seen (A) from the human perspective, and (B) from a passerine bird's perspective.

Apart from buildings and other large structures, there are also increasing numbers of small ones made from glass, such as advertising hoardings, enclosures for pedestrian crossings and shelters for people using public transport (train stations, bus and tram stops) (Johnson & Hudson, 1976; Sabo, Hagemayer, Lahey, & Walters, 2016; Barton, Riding, & Loss, 2017). In many developed countries, old bus shelters, made from wood, steel or concrete, are being replaced with new ones made from transparent materials (mainly glass). Moreover, the number of bus stops is increasing along with the global expansion in public transport and road networks (Pojani & Stead, 2015; Ibisch et al., 2016). From the human perspective, these objects seem small, but to birds they present large, invisible surfaces (Fig. 1). A recent study from the USA has shown that despite their small size, these structures do have a negative impact on local bird populations (Barton et al., 2017): for example, at least 34 birds are killed each year between May and September as a result of collisions with the 36 bus stops in the city of Stillwater (Oklahoma, USA).

Importantly, these glass structures are often erected in habitats attractive to birds, like the edges of wooded areas or rural areas. As it takes less than a day to put up one such glass shelter, the local birds have no time to get used to their presence. Moreover, they are ubiquitous along almost all types of road and railway lines. In Poland, for example, the average density of bus stops varies between 1.7 and 2.5 per km (Zych & Baran, 2012). With a total road length in Poland of 420,000 km (GDKA, 2018), this adds up to about 714–1050 thousand bus stops, more than half of which have shelters of glass (Anonymous, 2010). Therefore, it is likely that glass bus shelters create an important, yet underestimated, fatal hazard to birds along roads.

Even though glass shelters are becoming more common, the frequency of bird collisions with these structures is not known. Consequently, the threat posed by such shelters to birds remains poorly understood as well. With the exception of a few studies (e.g. Barton et al., 2017), very little evidence has been forthcoming concerning drivers of collision risk, like the type of shelter and its size, the surrounding habitat or landscape type, and the temporal patterns of such collisions.

The aim of our study was to evaluate the temporal variation and frequency of bird collisions with small, man-made, glass structures. Based on this aim, we made two a priori predictions. First, we predicted seasonal differences in collisions reflecting the number of birds present in an area, with there being fewer collisions in winter but more in late spring and summer owing to the occurrence of young, inexperienced individuals (Borden, Lockhart, Jones, & Lyons, 2010; Hager & Craig, 2014; Klem, 2014). Second, we predicted that collision frequency would differ between rural and urban habitats; this difference would be governed by the variation in species composition and the abundance of bird communities along the urbanization gradient (O'Connell, 2001; Bayne et al., 2012; Klem, 2014; Rosin et al., 2016). Finally, we also considered how glass shelter size, the manner of its maintenance (e.g. whether the glass was cleaned or not), and incidents of vandalism (graffiti) could affect collision frequency.

2. Methods

2.1. Study area

Over the course of a year we monitored 81 glass bus shelters in urban and rural habitats of south-western Poland (Fig. 2). The shelters were situated along a ca 180 km long route stretching from the outskirts of Wrocław in the north-east (coordinates: N51°06′36″, E17°01′20″) to Wałbrzych, ca. 65 km to the south as the crow flies (coordinates: N 50°46′15″, E16°16′26″). 47 of the shelters were situated in the suburbs of larger towns and cities and were surrounded mainly by built-up areas, while 34 were in rural areas, mainly in or near villages in landscapes dominated by small farms, fields and small woods. The average surface area of glass per bus shelter ranged from 5.6 m^2 to 18.2 m^2.

2.2. Bird collision surveys

This year-long survey of glass bus shelters took place from July

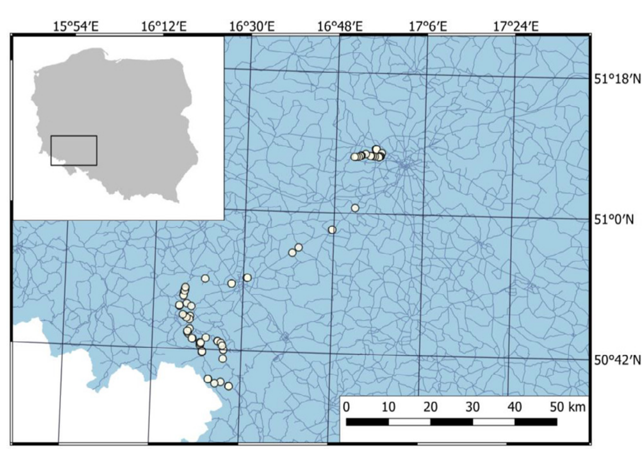

Fig. 2. Map of the study area showing the locations of glass bus shelters in south-western Poland.

Fig. 3. Examples of bus stops with glass shelters. (L) a vandalized glass bus shelter (graffiti); (R) a well-maintained, clean shelter.

Fig. 4. Examples of bird fatalities and traces of bird collisions with glass shelters: a) a Song Thrush *Turdus philomelos* found near the shelter, b) feathers left on the glass, c) Great Tit *Parus major*, d) the outline of a bird's body left on a glass shelter.

2017 to July 2018 (Fig. 3). We divided the study period into four seasons: summer (from June to August, when young, inexperienced birds disperse from their natal territories), autumn (September - November, i.e. the autumn migration season), winter (December – February, when mostly resident bird species are present) and spring (March – June, i.e. spring migration and breeding). We visited the shelters before noon every one or two weeks, on average every 12 days, each shelter being visited from 19 to 38 times during the study period (30.1 visits on average, SD = 7.12). During each visit, bird carcasses were first searched for within 3 m of the bus shelter (Fig. 4A, C). Next, all the shelter sides made from glass were carefully checked for traces of collisions, like feathers and bird contours (Fig. 4B, D). All traces that could not be classified unequivocally as being the result of collisions were ignored. All bird carcasses found were – if possible – identified to species level; their sex and age were also determined according to Busse (1990). Then all carcasses were removed. Likewise, all traces of collisions remaining on the glass were obliterated in order to prevent them being counted again during subsequent visits. During each visit we recorded the presence on the shelter glass of dust and mud (present vs absent) and of graffiti (classified as present if it covered > 50% of the glass, absent otherwise).

2.3. Statistical analysis

We performed two sets of models explaining bird-bus stop collisions and two sets of models explaining bird carcases. First, we analysed the annual number of collisions per bus stop. For this purpose, we pooled the number of collisions recorded at a given bus stop during the whole year and inserted it as a dependent variable into a generalized linear model (hereafter "$GLM_{collisions}$") with negative binomial error distribution and log link. There were 81 single data records in the model (i.e. the number of bus shelters), while four attributes of a bus shelter (averaged across all visits at a given bus stop) were introduced as explanatory variables: habitat type (urban or rural; termed HABITAT), dust on the glass panels of a bus shelter (DUST), graffiti on the glass bus stop shelter (GRAFFITI) and total surface area of glass of the shelter (AREA OF GLASS). We also tested interaction between HABITAT and AREA. As the number of visits to each bus stop during the year was not the same, it was log-transformed and introduced as an offset into the $GLM_{collisions}$.

Second, we analysed the occurrence of collisions separately for each visit to each bus stop. This approach enabled us to address the temporal variation of collision risk. A total of 2421 single visits were included as data records in the model. Here we used a generalized additive mixed model ($GAMM_{collisions}$) with binomial error distribution and logit link. In this model the occurrence of a collision (1 = present, 0 = absent) was introduced as a dependent variable, while five attributes of a visit to a bus stop were introduced as explanatory variables: habitat type (HABITAT), dust/mud on the bus shelter glass (DUST), graffiti on the bus shelter glass (GRAFFITI), total surface area (m^2) of glass in the bus shelter (AREA OF GLASS), day of the year (DAY). The day effect was fitted with a cyclic cubic regression spline whose ends match (i.e. it is assumed that day = 1 and day = 365 correspond to the same level of probability of a collision, Wood 2017) but allow for the nonlinear variation of the probability of a collision over time. Bus stop identity (ID) was introduced as a random effect because each bus stop was visited more than once. We used the '*gamm4'* package (Wood & Scheipl, 2017) in R (R Core Team, 2018) for statistical modelling.

Finally, we addressed the problem of the detectability of collisions. In theory, signs of collisions (e.g. feathers adhering to the glass) may be less visible when the bus shelter glass is covered with dust or graffiti. This limitation, however, does not apply to the detectability of bird carcasses found at the bus stops. We thus used the explanatory variables already considered in $GLM_{collisions}$ and $GAMM_{collisions}$ described above to explain the number of carcasses ($GLM_{carcasses}$) and the occurrence of carcasses ($GAMM_{carcasses}$) so as to exclude possible detectability bias.

All the models were checked for spatial autocorrelation of residuals with the help of Moran's coefficient computed for ten distance classes. The computed coefficients were very low (< 0.07 for all models), thus indicating no problem with spatial data dependency. We also checked the collinearity of the explanatory variables using variance inflation factors and concurvity diagnostics; neither indicated any problems with collinearity: variance inflation factors were < 1.3, estimated concurvity < 0.16.

We used the Akaike information criterion corrected for sample size (AICc) to compare the predictive power of different combinations of explanatory variables included in all four models. In the case of $GLM_{collisions}$ and $GLM_{carcasses}$, however, we kept the number of visits as an offset in all the models. Similarly, in the case of $GAMM_{collisions}$ and $GAMM_{carcasses}$ we always took the random bus stop effect into consideration in all the models. Next, we compared AICc scores for all possible combinations of explanatory variables and reported best models, i.e. those with ΔAIC < 2.0. Finally, we performed model averaging within the set of best models and presented 95% confidence intervals for each parameter as a final result. However, owing to the small number of carcasses found (n = 36) and the complete separation between carcasses and graffiti (not a single carcass was found at any of the bus stops with graffiti), in $GLM_{carcasses}$ and $GAMM_{carcasses}$ we obtained parameter estimates of the graffiti effect with extremely large standard errors. As a consequence, multi-model averaging was not very useful in the case of the graffiti effect and was thus supplemented with the Spearman rank correlation between the number and occurrence of carcasses and presence of graffiti. Multi-model inference was performed with the aid of the "MuMIn" package in R (Bartoń, 2012).

3. Results

Evidence pointing to 155 collisions was found at 40 out of the 81 glass shelters. In 119 cases we recorded traces of a collision with a shelter, while in the other 36 cases we recorded both traces and bird carcasses under it. The traces left on the glass included feather remains (70%) and whole bird contours (30%) (Fig. 4). Traces were recorded on both the inner (n = 56) and outer (n = 63) sides of shelters. Six of the 36 carcasses could not be identified to species level; the 30 identified ones were mostly passerines, with Blackbird *Turdus merula* being the most common (Table 1). Adults predominated (n = 18) among the dead birds, followed by young ones (n = 9); the ages of the other nine carcasses could not be determined. Carcasses were found both inside (n = 19) and outside shelters (n = 17).

The number of bird collisions per bus stop shelter ranged from 0 to 18 (mean = 1.9; SD = 3.43). The presence of dust and graffiti, as well as habitat type were selected as the best set of explanatory variables explaining the number of collisions per shelter (Table 2, $GLM_{collisions}$). Dust and graffiti occurred in two best models as found by AICc ranking, while the null model containing only the intercept appeared to be substantially less parsimonious (ΔAICc > 28, see Table 2). Averaged parameter estimates indicated that both dust and graffiti were strong negative predictors of the number of bird collisions per shelter (Table 3, $GLM_{collisions}$).

The presence of dust, presence of graffiti and the day of the year were the most important variables explaining the occurrence of bird-bus shelter collisions: these three variables were included in all three

Table 1
Number of bird carcasses found at the glass bus shelters monitored in south-western Poland in 2017–2018.

Species	N
Blackbird (*Turdus merula*)	8
Unknown	6
Robin (*Erithacus rubecula*)	3
House Sparrow (*Passer domesticus*)	3
Great Tit (*Parus major*)	2
Song Thrush (*Turdus philomelos*)	2
Blue Tit (*Cyanistes caeruleus*)	1
Bullfinch (*Pyrrhula pyrrhula*)	1
Common Linnet (*Linaria cannabina*)	1
Collared Dove (Streptopelia decaocto)	1
Common Starling (Sturnus vulgaris)	1
Greenfinch (Chloris chloris)	1
House Martin *(Delichon urbicum)*	1
Hawfinch (*Coccothraustes coccothraustes*)	1
Sparrowhawk (*Accipiter nisus*)	1
Siskin (*Spinus spinus*)	1
Eurasian Nuthatch (Sitta europaea)	1
Yellowhammer *(Emberiza citrinella)*	1
Total	36

Table 2
Best models, i.e. those within ΔAICc < 2.0, explaining the cumulative number of collisions per bus stop during all visits (1. GLM), the occurrence of collisions during a single visit (2. GAMM), the cumulative number of carcasses per bus stop during all visits (3. GLM) and the presence of carcass during a single visit (4. GAMM), ranked by AICc scores. For each model a set of explanatory variables is given, followed by the AICc score, the difference between the best model and a certain model (ΔAICc) and the weight of a certain model (ωAICc).

#	Explanatory variables	AICc	ΔAICc	ωAICc
1. $GLM_{collisions}$ explaining number of collisions per bus stop				
1.1	DUST + GRAFFITI + HABITAT	263.3	0.00	0.501
1.2	DUST + GRAFFITI + HABITAT + AREA OF GLASS	263.3	0.01	0.499
1.3	Null model, i.e. Intercept only	291.4	28.10	0.000
2. $GAMM_{collisions}$ explaining probability of collision per single visit at a bus stop				
2.1	DUST + GRAFFITI + AREA OF GLASS + S(DAY OF YEAR)	807.3	0.00	0.420
2.2	DUST + GRAFFITI + HABITAT + AREA OF GLASS + S(DAY OF YEAR)	807.4	0.06	0.407
2.3	DUST + GRAFFITI + HABITAT + S(DAY OF YEAR)	809.1	1.77	0.173
2.4	Null model, i.e. Intercept only	991.2	183.89	0.000
3. $GLM_{carcasses}$ explaining number of carcasses per bus stop				
3.1	DUST + GRAFFITI + HABITAT	119.9	0.00	0.555
3.2	DUST + GRAFFITI + HABITAT + AREA OF GLASS	120.4	0.44	0.445
3.3	Null model, i.e. Intercept only	138.2	18.26	0.000
4. $GAMM_{carcasses}$ explaining probability of carcass presence per single visit at a bus stop				
4.1	DUST + GRAFFITI + HABITAT + AREA OF GLASS + S(DAY OF YEAR)	302.8	0.00	0.407
4.2	DUST + GRAFFITI + HABITAT + S(DAY OF YEAR)	303.7	0.96	0.252
4.3	DUST + HABITAT + AREA OF GLASS + S(DAY OF YEAR)	304.4	1.65	0.178
4.4	DUST + HABITAT + S(DAY OF YEAR)	304.6	1.82	0.164
4.5	Null model, i.e. Intercept only	342.2	39.41	0.000

Table 3
Results of model averaging within the set of competing models listed in Table 2 (except spline fits).

Explanatory variables	Averaged parameter estimates (95% confidence interval)	Relative variable importance
1. $GLM_{collisions}$ explaining the number of collisions per bus stop		
DUST: present	−2.54 (−3.88; −1.19)	1.00
GRAFFITI: present	−2.60 (−4.61; −0.60)	1.00
HABITAT: rural	0.93 (0.17; 1.70)	1.00
AREA OF GLASS	−0.13 (−0.31; 0.04)	0.50
2. $GAMM_{collisions}$ explaining the occurrence of collisions per single visit to a bus stop		
DUST: present	−1.00 (−1.60; −0.41)	1.00
GRAFFITI: present	−1.89 (−3.85; 0.07)	1.00
HABITAT: rural	0.62 (−0.20; 1.43)	0.58
AREA OF GLASS	−0.21 (−0.42; −0.002)	0.83
DAY OF YEAR	Non−parametric fit	1.00
3. $GLM_{carcasses}$ explaining the number of carcasses per bus stop		
DUST: present	−2.34 (−4.376; −0.305)	1.00
GRAFFITI: present	−154.35 (−40852139;40851830)	1.00
HABITAT: rural	1.92 (0.673; 3.174)	1.00
AREA OF GLASS	−0.17 (−0.443; 0.107)	0.45
4. $GAMM_{carcasses}$ explaining the occurrence of carcasses per single visit to a bus stop		
DUST: present	−1.21 (−2.164; −0.257)	1.00
GRAFFITI: present	−26.95 (−3893509; 3893455)	0.75
HABITAT: rural	1.41 (0.225; 2.589)	1.00
AREA OF GLASS	−0.29 (−0.593; 0.014)	0.70
DAY OF YEAR	Non-parametric fit	1.00

best models (Table 2, $GAMM_{collisions}$). Similarly, null model was much less informative (ΔAICc > 180, Table 2). Averaged parameter estimates showed that the presence of graffiti on a bus shelter had a stronger negative effect (−1.89) than the presence of dust (−1.00), although the graffiti effect was more uncertain, with 95%CI marginally overlapping zero (Table 3, $GAMM_{collisions}$). We also recorded a clear seasonal pattern (non-parametric effect and thus not shown in Table 3). At the beginning of the year, the probability of collisions was low, but increased from the beginning of March and peaked in summer. The probability decreased in late summer and was generally low in autumn and winter (Fig. 5).

The variation in the number of carcasses generally mirrored patterns reported for collisions, and the models ranked as best were substantially more informative as compared to the null models (Table 2, $GLM_{carcasses}$, $GAMM_{carcasses}$). However, because of the complete separation between the number and occurrence of carcasses and graffiti, the model parameters for graffiti cannot be estimated, although model ranking suggests that graffiti acts as an important driver of the number and occurrence of carcasses (Tables 2 and 3).

The pooled number of bird carcasses found at bus stops was negatively correlated with the presence of graffiti on the shelter glass (Spearman correlation, rho = −0.24, p = 0.030). Similarly, the presence of bird carcasses during a single visit to a bus stop was negatively correlated with the presence of graffiti (rho = −0.04; p = 0.039).

4. Discussion

Our study revealed distinct temporal 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 as compared to urban landscape but dust or graffiti covering glass bus shelters decreases collision risk. We, therefore, confirmed our predictions posed in the introduction and showed that both landscape-level and local factors are important for the final risk of bird collisions with glass bus shelters. Below we discuss possible drivers of the observed pattern.

The higher number of bird collisions during the breeding period was most likely caused by the birds' increased activity as a result of mate searching and nest building. However, the probability of collisions was the highest in July-August, when young, inexperienced individuals started to disperse from their natal territories (Erritzoe, Mazgajski, & Rejt, 2003). We found that eighteen of the dead birds were adults and nine were juveniles (we were unable to determine the age of the remaining nine individuals). Furthermore, during this part of the year both adult and young birds move around in larger flocks and usually make use of much larger areas than during the breeding period (Herzon, Marja, Menshikova, & Kondratyev, 2014). This heightened activity may explain the higher collision risk in summer. A seasonal pattern also emerged from studies of bird collisions with bus shelters

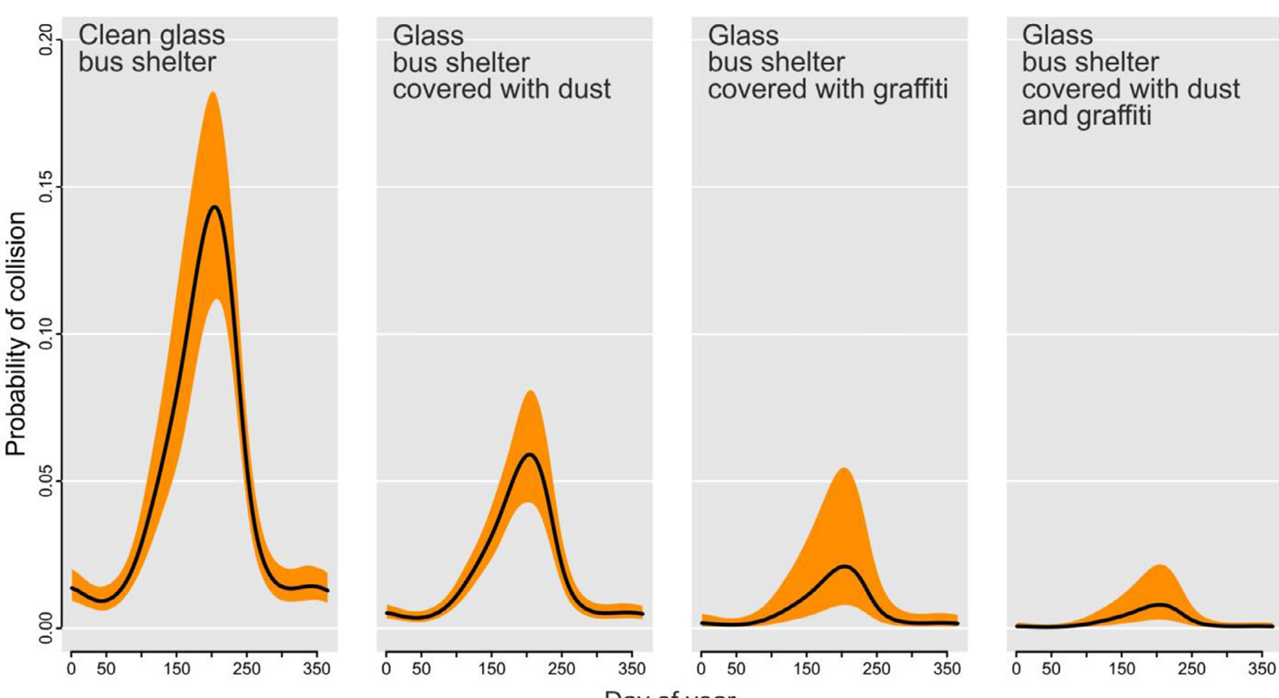

Fig. 5. Probability of bird collisions with glass bus shelters during a 12-day period, as predicted by the GAMM model summarized in Table 2.

and other small glass structures (Johnson & Hudson, 1976; Sabo et al., 2016; Barton et al. 2017). A study of 36 bus shelters in Oklahoma reported the highest number of collisions in June (Barton et al. 2017). The risk of bird collisions with large glass-covered structures like skyscrapers, tall buildings or transparent noise reduction barriers installed along roads is at its highest during the breeding and migratory seasons (Hager & Craig, 2014; Sabo et al., 2016). Moreover, the migrant or resident status of birds is also important for predicting collision risk (Kahle, Flannery, & Dumbacher, 2016): migrants are more susceptible to window collisions than residents, probably because the latter can learn to avoid local glass traps (Sabo et al., 2016). In our study we found that both migrating (n = 6 species) and resident species (11) were killed in collisions, indicating that both groups are vulnerable to the risk of collisions.

The number of collisions per bus stop was higher in the countryside than in towns and cities, which confirms that the level of urbanization is important in the context of the collision risk to birds (Bayne et al., 2012; Stracey & Robinson, 2012; Hager et al., 2013; Cusa et al., 2015; Hager et al., 2017). The simplest explanation for this pattern is that birds are more abundant in rural than in urban areas (Rosin et al., 2016), so glass bus shelters are exposed to a larger number of birds in the country. However, some bird species are known to be "urban dwellers", meaning that their population dynamics are independent of remnants of natural habitats (Fischer, Schneider, Ahlers, & Miller, 2015). These species may therefore be able to learn to avoid anthropogenic hazards like glass barriers within their home ranges (Klem, 1989). Moreover, the risk of collision with glass surfaces is higher when the surrounding habitat attracts birds and is clearly visible through or reflected in the glass (Klem, 1990; Gelb & Delacretaz, 2009; Cusa et al., 2015). On the other hand, the density of glass bus shelters is higher in towns than in the country, so while the overall impact of glass shelters, i.e. the total number of birds killed per unit surface area of glass, may be higher in towns, the collision risk estimated per single shelter will probably be lower than in rural areas.

Numbers of collisions with smaller shelters (with a smaller area of glass) tended to be higher than with large bus shelters: this contradicts earlier findings pointing to the surface area of glass as a major factor responsible for collision risk (Klem, 1990; Klem et al., 2009; Borden et al., 2010; Hager et al., 2013; Cusa et al., 2015; Kahle et al. 2016). This may be because bus shelters situated in more natural and less densely populated areas (and thus more attractive to birds) are smaller, i.e. designed for lower numbers of passengers, but this issue needs further investigation.

Our study documented 155 instances of bird collisions with glass shelters (1.9 collisions per bus stop); for methodological reasons, however, these results should be interpreted with caution. First of all, the detectability of bird collisions was imperfect because many of them (up to 25%) left no visible or lasting traces (Klem et al., 2009). Barton et al. (2017) reported an incident involving three fatal collisions at one shelter with only a single feather mark to prove that anything had happened; such traces are easily overlooked and may disappear quickly. Moreover, we ignored any traces that could not be unequivocally attributed to collisions, e.g. smudges on the glass which have sometimes been identified as evidence of bird collisions (Barton et al. 2017). Secondly, scavengers had probably reduced the number of carcasses found (Klem et al., 2004). A carcass removal experiment suggests that scavengers can reduce the probability of carcass detection around glass structures (Hager, Cosentino, & McKay, 2012). Moreover, a recent study by Riding and Loss (2018) has shown that most scavenger species are nocturnal, and that 68% of scavenging events occur at night. Hence, carcasses must have often been removed before we arrived at a bus stop to monitor it. Another factor that may influence carcass detectability is shelter cleaning, which takes place 1–2 times per week. Thus, the real number of collisions was probably higher than that deduced from the observed numbers of traces and carcasses.

The number of collisions that resulted in bird mortality is also unknown. It has been estimated that about half of such collisions result in the bird's death (Klem, 1990). Birds may die immediately after a collision, but death is sometimes not instantaneous: many victims die as a result of subsequent shock, injury, or being more vulnerable to predator attack (Klem, 1990; Parkins et al., 2015). Indeed, some studies have reported an almost 90% mortality rate among birds that have collided with a glass surface (Agudelo-Álvarez, Moreno-Velasquez, & Ocampo-Peñuela, 2010). Collision detectability and the proportion of fatal collisions need to be considered when assessing the impact of collisions with glass bus shelters on bird populations.

Our study showed that both dust and graffiti covering the glass panels of bus stop shelters substantially lowered the probability of collisions. Glass covered with patterns is no longer transparent and is most likely better visible to birds (see Fig. 3), which can then easily avoid flying into it. Graffiti and dust can also reduce reflections in the glass. In the case of glass shelters, the activities of graffiti artists should actually be viewed as an effective conservation measure which can significantly reduce the number of bird collisions. In accordance with current legislation in Poland, graffiti is illegal and treated as vandalism, for which the artists face fines. We therefore suggest that such glass shelters should be utilized as an official opportunity to encourage artistic expression, e.g. by local artists or in projects by conservation groups or schools. By making such good use of bus shelters as public spaces, this approach would spread awareness about bird collisions.

5. Conclusion

Billions of birds die every year after hitting glass structures (Machtans et al., 2013; Loss et al., 2014; Machtans & Thogmartin, 2014) and our results suggest that collisions with glass bus shelters may be an important source of bird mortality. Rough estimates suggest that there are up to half a million bus stops with glass shelters in Poland (Anonymous, 2010). Extrapolation of the annual collision rate recorded in our study, i.e. 1.9 collisions per bus stop, indicates that up to a million of birds collide with these man-made structures annually in Poland. Thus, glass shelters should be seen as a serious hazard for local bird populations throughout the year, but especially in summer, when young birds start to disperse. Avoiding the use of transparent shelter panels/walls would seem to be the best practice for reducing bird collisions with public transport infrastructure. But this would require profound changes in architectural or design conceptions. Alternatively, existing glass shelters could be covered with images or paintings visible to birds that would reduce the number of collisions. Aesthetically pleasant graffiti art reducing glass transparency may be justified as well, since it fulfils an important conservation role. As few studies on bird collisions with small structures have yet been carried out, several issues important for predicting and minimizing bird-glass collisions remain unclear. We recommend that future studies should focus on: 1) the relationship between local bird abundance and collision risk, 2) the importance of the type of habitat surrounding glass shelters and 3) the empirical evaluation of practical solutions reducing collision frequency.

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