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Field-testing effectiveness of window markers in reducing bird-window collisions

Georgia J. Riggs[1] · **Christine M. Barton**[2] · **Corey S. Riding**[3] · **Timothy J. O'Connell**[1] · **Scott R. Loss**[1]

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Abstract
Bird-window collisions are a major source of human-caused mortality for which there are multiple mitigation and prevention options available. Despite growing availability of products designed to reduce collisions (e.g., glass with etched patterns or markers and films adhered over existing glass), few replicated field tests have been conducted to assess their effectiveness after installation on glass. We conducted a field study to evaluate the effectiveness of a commercially marketed product (Feather Friendly® markers) in reducing bird-window collisions at glass-walled bus shelters in Stillwater, Oklahoma, USA. This study included a before-after control-impact (BACI) analysis comparing numbers of collisions at 18 bus shelters in both pre-treatment (2016) and post-treatment (2020) periods, and an analysis comparing 18 treated and 18 untreated shelters during 2020. For the BACI analysis, collisions were significantly reduced between 2016 and 2020 at shelters treated with the Feather Friendly® markers even though collisions increased at shelters that remained untreated. For the 2020 analysis, there were significantly fewer collisions at treated than untreated shelters. Relative to a baseline study in 2016, we estimated that treating half of Stillwater's bus shelters resulted in a 64% reduction in total annual bird collisions. Together, these analyses provide a rigorous field test of the effectiveness of this treatment option in reducing bird-window collisions. Our research provides a model for similar studies at both bus shelters and buildings to evaluate and compare products designed to reduce bird-window collisions, and therefore, contribute to reducing this major mortality source affecting bird populations.

Keywords BACI · Bird collisions · Bus shelters · Window collisions · Window markers · Window treatment

Introduction

As humans continue to alter landscapes, wildlife face increasing threats from human activities, including indirect threats like habitat loss and climate change (Jackson and Fahrig 2013; Weiskopf et al. 2020), and numerous sources of direct mortality (Loss et al. 2015). For birds, collisions with infrastructure like power lines, communication towers, wind turbines, and buildings, are a major source of anthropogenic mortality (Calvert et al. 2013; Loss et al. 2015; Bernardino et al. 2018). Collisions with buildings, especially their windows, are a top bird mortality source worldwide, causing 365 to 988 million deaths annually in the United States alone (Loss et al. 2014). Birds collide with glass because of their inability to perceive it as a barrier, due to its reflective and transparent qualities (Klem 1989).

Many studies identifying spatiotemporal correlates of bird-window collisions have informed the development of collision reduction approaches. For example, artificial light emitted from and near buildings at night increases collisions due to light attracting and confusing nocturnally migrating birds (Lao et al. 2020; Van Doren et al. 2021), a finding that informs recommendations to reduce lighting during key bird migration periods. Identification of temporal correlates of collisions like variation in weather and bird migration intensity (Loss et al. 2020; Elmore et al. 2021) allow targeting of management (e.g., lighting reduction) in real time. Studies finding collisions are influenced by vegetation around buildings (Klem et al. 2009; Cusa et al. 2015; Loss et al. 2019) have informed recommendations about managing amount

✉ Georgia J. Riggs
georgia.riggs@okstate.edu

[1] Department of Natural Resource Ecology and Management, Oklahoma State University, 008C Ag Hall, Stillwater, OK, USA

[2] Natural Resource Ecology Laboratory, Colorado State University, Fort Collins, CO, USA

[3] Department of Biology, Salt Lake Community College, 4600 South Redwood Rd., Salt Lake City, UT, USA

and height of nearby vegetation. Finally, the many studies showing collisions increase with amounts of glass on structures (Hager et al. 2013; Kahle et al. 2016; Riding et al. 2020) have led to development of products designed to break up large expanses of reflective and/or transparent glass to make it more visible to birds. These products include glass with built-in features (e.g., etched patterns or UV light-reflecting strips), and films, markers, and other products that adhere to or cover glass.

Researching effectiveness of products designed to reduce glass reflectivity and transparency is a crucial step in reducing bird-window collisions. Such research can increase marketability of these products and determine if they require adjustments to be more effective. Products designed to reduce collisions have primarily been studied in controlled settings outside of the context of buildings. One common approach is tunnel testing in which birds are released into a flight tunnel that provides a choice between flying toward a glass pane treated with the focal product and an untreated pane (birds are recaptured before colliding; Rössler et al. 2015; Sheppard 2019). Another approach entails field experiments with sheets of treated and untreated glass placed in open areas (Klem and Saenger 2013). Both approaches have many advantages, including use of standardized and controlled conditions, but they do not capture all the complex and variable building- and environment-related cues birds encounter when approaching glass barriers in the built environment.

Despite the importance of field-testing products installed on buildings, few studies have done so and most lacked replication. A study in Utah, USA, compared bird collisions before and after a commercial product (Feather Friendly® markers) was installed, finding some evidence collisions were reduced (Brown et al. 2019). A study at two buildings in São Paulo, Brazil tested bird-of-prey decals, finding a statistically non-significant reduction in collisions (Brisque et al. 2017). A study in California, USA found a significant reduction in collisions after using external shades to cover windows (Kahle et al. 2016). A study in Poland found that glass bus shelters obscured by graffiti and dust had significantly fewer collisions than clean shelters (Zyśk-Gorczyńska et al. 2020). These studies provide key insights into collision mitigation approaches. Yet, studies with greater replication that compare collisions at treated and untreated structures in the same period (e.g., before-after control-impact (BACI) analyses) (Underwood 1992), would greatly advance understanding about effectiveness of products designed to reduce bird collisions.

We conducted a well-replicated study of the effectiveness of commercially available Feather Friendly® window markers installed on glass-walled bus shelters known to cause bird collisions (Barton et al. 2017). Bus shelters provide an ideal setting for this type of study; their small size makes them highly replicable because they are easy to monitor and less expensive to treat than larger buildings. Our study included two components: (one) a BACI analysis comparing collisions at 18 shelters monitored both pre-treatment in 2016 and in 2020 after half the shelters were treated, and (two) an analysis comparing collisions between 18 treated and 18 untreated shelters in the same period in 2020. This study provides a model for similar studies evaluating effectiveness of products designed to reduce bird-window collisions. In particular, a BACI design that assesses changes in numbers of collisions from pre- to post-treatment periods in comparison to shelters that remain untreated allows isolation of effects of window products from other factors causing temporal variation in collisions (e.g., weather, changing bird populations). For the first component of our study, we hypothesized that collisions would decrease from 2016 to 2020 at shelters treated with the Feather Friendly® markers, regardless of whether numbers of collisions changed at shelters that were untreated in both years. For the second component of our study, we hypothesized that treated shelters would have fewer collisions than untreated shelters during the same period in 2020.

Material and methods

Study area

We surveyed for bird collisions at glass-walled bus shelters in Stillwater, Oklahoma, USA. Stillwater has a human population of approximately 48,000 people (U.S. Census Bureau, 2020 Census of Population and Housing) and is in the Cross Timbers ecoregion, which contains a mix of grasslands, shrublands, and woodlands. We conducted surveys at all 36 bus shelters in Stillwater, including 18 on the Oklahoma State University (OSU) campus and 18 off campus. All shelters were maintained and used by OSU's Transit Services, except two maintained by Payne County and a private apartment complex. Each shelter had an open front and three glass walls; 26 shelters had the same design with four glass panes totaling approximately 10.5 m^2 of glass (Fig. 1a), and the other 10 shelters differed slightly from this design in the number and/or size of glass panes.

Study design

For the "before" data in our BACI analysis, we used bird collision data collected in 2016 from 18 of Stillwater's 36 bus shelters (Barton et al. 2017). The "impact" we implemented and evaluated was treatment of the exterior of shelters (treatments implemented in summer 2019) with Feather Friendly® window markers in the five cm x five cm Symmetry style (Fig. 1b). Of 18 shelters monitored in 2016, the nine with

Fig. 1 **a** Example of a glass-walled bus shelter in Stillwater, Oklahoma, USA, and **b** close-up of Feather Friendly® five cm x five cm Symmetry markers installed on select shelters in this study

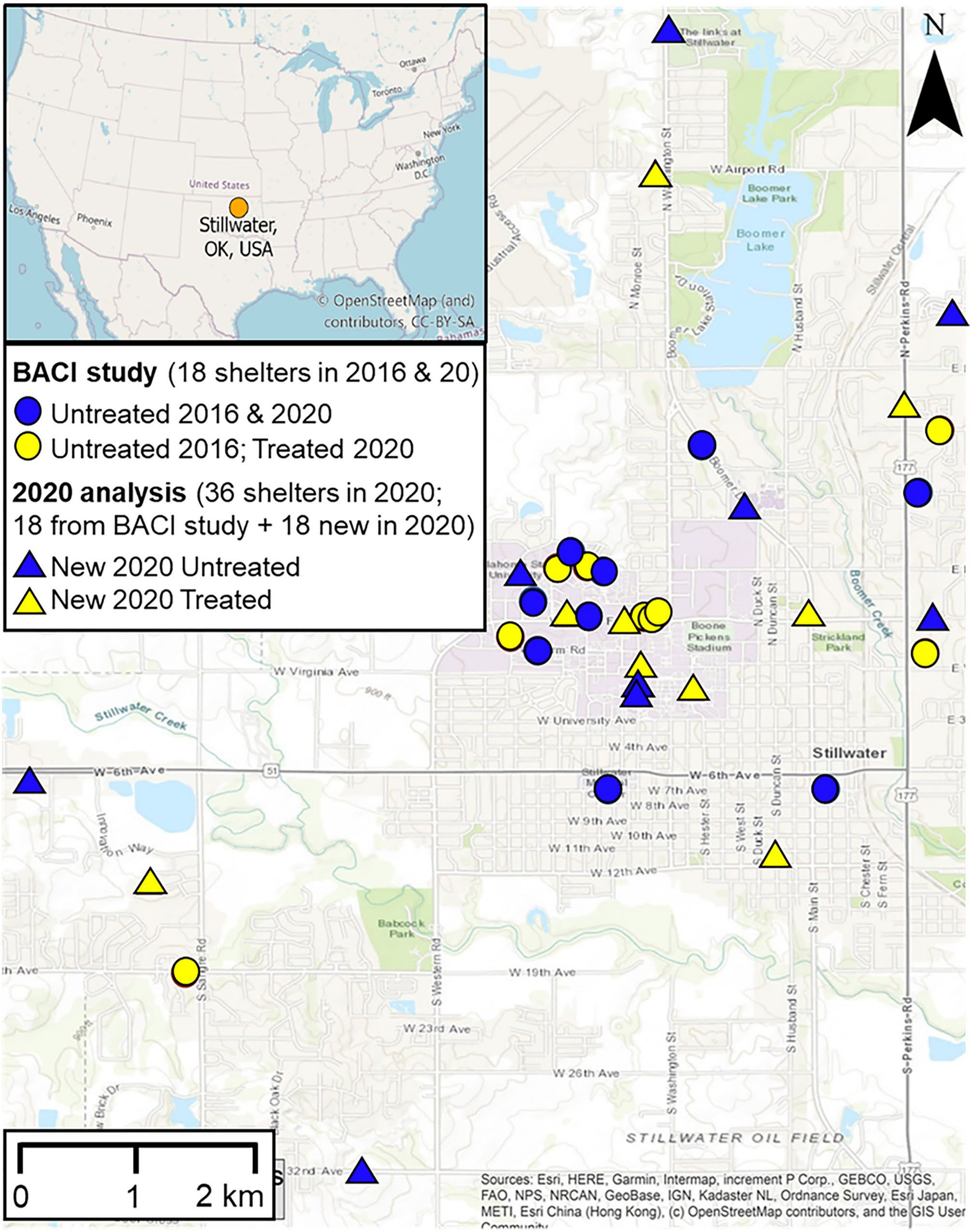
the most collisions in the baseline study were treated and the other nine remained as untreated controls. We used this approach for selecting treatment shelters, as opposed to randomized selection, due to the relatively low number of collisions observed at shelters (Barton et al. 2017) and to increase probability that any effects of the film in reducing collisions were detectable statistically. As described in "Data Analysis", the BACI design allowed us to assess effectiveness of window markers by evaluating differences in the before-after (2016 to 2020) comparison between impact (treated) and control (untreated) shelters.

In addition to these 18 shelters evaluated in 2016 and 2020 under the BACI framework, we also compared a larger sample of treated and untreated shelters during 2020. We selected an additional nine shelters for treatment from among the remaining 18 shelters not monitored in 2016. These nine shelters were selected using a stratified random sampling approach, such that approximately half of treated shelters were in relatively urbanized/developed areas (i.e., on the OSU campus and in/near downtown Stillwater) and approximately half were in less urbanized/developed locations (i.e., low-density residential and exurban settings). Combined with shelters described in the previous paragraph, these additional 18 shelters (nine treated, nine untreated) resulted in a total sample of 18 treated and 18 untreated shelters for which we compared collisions during 2020, an analysis that was separate from the BACI analysis. A map of all shelters included in analyses, including which were treated and untreated and which were monitored in 2016 and/or 2020, is in Fig. 2.

Data collection

In the baseline study (Barton et al. 2017), the 18 shelters we used for the BACI analysis were monitored for collisions twice weekly from 4 May to 30 September of 2016. In 2020, we used a similar schedule of twice-weekly surveys but expanded sampling to cover 1 April to 31 October, and to include all 36 shelters. As described in the Discussion, the SARS-CoV-2 pandemic affected OSU Transit Service's operation of buses during spring and summer 2020, but the pandemic did not affect our survey efforts (i.e., we completed all surveys regularly and on-schedule). Our protocol was adapted from Hager and Cosentino's (2014) standardized bird-window collision monitoring protocol. This included an initial "clean sweep" in which we surveyed each shelter 24 h before our first survey and removed existing carcasses and collision evidence on glass to ensure any carcasses or evidence found during surveys occurred within the previous 24 h period. In 2020, shelters were split into two 18-shelter routes, with each including an approximately equal mix of treated and untreated shelters. We alternated which route was surveyed on successive days, such that each route was monitored twice weekly (e.g., route one surveyed Monday and Thursday; route two surveyed Tuesday and Friday). The order in which shelters were surveyed on a route was shifted by one on each successive monitoring day to account for time-of-day effects (e.g., when peak numbers of collisions occur) that could bias comparisons due to individual shelters always being monitored at the same time. Additionally, survey direction around each shelter was altered on each subsequent survey (clockwise during one visit followed by counterclockwise on the subsequent visit) to account for biases associated with directional perception (e.g., shading and sunlight glare).

To conduct surveys, we walked slowly around the perimeter of each shelter looking for bird carcasses within two meters of the shelter's interior and exterior. When a carcass was found, we recorded the species and its location relative to the shelter (i.e., whether it was found inside or outside the shelter, and how many meters from glass it was found). To help identify bird species and prevent duplicated recordings of carcasses, we took photographs of the carcass in the context of its surroundings and close-up photographs of its dorsal, lateral, and ventral sides. Carcasses were left in place for scavenger removal trials described below. We also examined each pane of glass for evidence of collisions, including feathers attached to glass or smudge marks clearly made from a bird (i.e., smudges in the shape of a bird/wings or accompanied by feathers). When such collision evidence


United States
Stillwater, OK, USA
Los Angeles
Phoenix
Ottawa
Toronto
New York
Washington D.C.
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BACI study (18 shelters in 2016 & 20)
● Untreated 2016 & 2020
● Untreated 2016; Treated 2020
2020 analysis (36 shelters in 2020; 18 from BACI study + 18 new in 2020)
▲ New 2020 Untreated
▲ New 2020 Treated
N
The links at Stillwater
W Airport Rd
Boomer Lake Park
Boomer Lake
Boomer Creek
Strickland Park
Boone Pickens Stadium
W Virginia Ave
Stillwater Creek
W University Ave
W 4th Ave
W 6th Ave
W 7th Ave
W 8th Ave
W 9th Ave
W 10th Ave
W 11th Ave
W 12th Ave
Stillwater
Babcock Park
W 19th Ave
W 23rd Ave
W 26th Ave
32nd Ave
STILLWATER OIL FIELD
N Perkins Rd
S Perkins Rd
S Western Rd
S Sangre Rd
S Washington St
S Husband St
S Main St
0 1 2 km
Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), (c) OpenStreetMap contributors, and the GIS User Community

◂**Fig. 2** Locations of 36 bus shelters in study evaluating effectiveness of Feather Friendly® markers in reducing bird collisions in Stillwater, Oklahoma, USA. In 2019, 18 shelters were treated with markers and 18 remained untreated. Effectiveness was evaluated using: (1) a before-after control-impact analysis at 18 shelters monitored in both 2016 and 2020, 9 that had markers installed in 2019 (yellow circles) and 9 remaining untreated (blue circles); and (2) an analysis of all 36 shelters monitored in 2020, 18 treated 18 untreated (all yellow and blue symbols, respectively)

was found, we recorded its description and location (interior or exterior of shelter) and took photographs of it. Evidence was removed with glass cleaner to avoid duplicated recording on future surveys.

Both humans and animal scavengers remove bird carcasses that result from window collisions, which biases mortality estimates and comparisons if not accounted for (Hager et al. 2012; Riding and Loss 2018). To minimize human removal of carcasses, we contacted organizations that managed bus shelters to request that carcasses be left in place when found by maintenance personnel. In both years, we also conducted removal trials (fully described in Barton et al. 2017) to account for scavenger removal and any removal of carcasses by humans that we were unable to prevent. These trials were designed to estimate probability that carcasses persist between the collision event and the subsequent monitoring survey; data from trials thus allowed us to generate estimates of total collisions that account for carcass removal. For removal trials, we left all carcasses found at shelters in place and monitored their presence during each subsequent survey until they were undetectable due to removal or decomposition.

Data analyses

All analyses were performed in R (Team 2020). Values of response variables for below analyses were raw counts of total collisions (carcasses plus collision evidence) because we lacked replication of removal trials to generate adjusted fatality estimates for each bus shelter and year combination (Barton et al. 2017). However, as described below, we used data from removal trials to generate total adjusted estimates of collisions across all shelters. Because response variables were counts and data were over-dispersed, we used generalized linear models (GLMs) and conducted a likelihood ratio test (LRT) to determine whether to use a Poisson or negative binomial distribution. LRT results were statistically significant for the BACI analysis ($X_2=7.82$; $p=0.005$), indicating the need to use a negative binomial model. For the analysis using only 2020 collision data at all 36 shelters, LRT results were non-significant ($X_2=2.07$; $p=0.149$), so we used a Poisson model. The proportion of replicates with zero values was 38% and 52% for BACI and 2020 analyses, respectively, so we conducted Vuong tests to determine if zero-inflated models were appropriate (Vuong 1989). For both BACI and 2020 analyses, there was no support for using zero-inflated models (BACI analysis: Raw z-statistic = -0.52; AIC-corrected z-statistic = 0.06; BIC-corrected z-statistic = 0.52; all p-values ≥ 0.3; 2020 analysis: Raw z-statistic = 1.61; AIC-corrected z-statistic = 1.1; BIC-corrected z-statistic = 0.69; all p-values ≥ 0.05).

For the BACI analysis of the 18 bus shelters monitored in both 2016 and 2020, we tested for the effect of an interaction between time period (2016 vs. 2020) and whether the shelter was treated between 2016 and 2020 (treatment vs. control shelter). Because length of the sampling season differed between 2016 and 2020, we included an offset term for the number of collision surveys at each shelter in each year. This approach allows separation of any treatment-related effect on collisions from other factors that could cause changes in collisions between pre- and post-treatment periods that would manifest in changes in numbers of collisions at control shelters (e.g., inter-annual fluctuations in weather, human disturbance, or bird abundance). Even if factors unrelated to glass treatment led to a reduction in collisions across all shelters, this approach would allow us to detect if there was a greater reduction in collisions at treated than untreated shelters. Likewise, if some external factor caused an increase in collisions at all shelters, this approach would allow us to detect if there was a smaller increase, or even a decrease, in collisions at treated shelters. For the analysis of all 36 shelters during 2020, we only assessed the effect of treatment to determine if collisions varied between the 18 treated and 18 untreated shelters during the same time period.

We used data from removal trials to generate estimates of total collisions, adjusted for removal bias, across all 36 shelters in 2020. This analysis mirrors one conducted by Barton et al. (2017) to estimate total collisions across the same 36 shelters during a period when none were treated. Comparing our adjusted fatality estimate to the one from the previous study allows approximate assessment of the change in total collisions achieved by treating half of Stillwater's bus shelters. To generate an adjusted fatality estimate, we used the R package "carcass" (Korner-Nievergelt et al. 2015) and the function "phuso" to implement a statistical estimator that is widely used in studies of bird-structure collisions (Huso 2011). While a newer, more-generalized estimation approach can be implemented in the R package "GenEst" (Simonis et al. 2018), we used the above approach to maintain consistency with and allow direct comparisons to the baseline study. We followed the same steps as in Barton et al. (2017), including implementation of the functions "persistence.prob" and "phuso". The first function estimates carcass persistence probability using data from removal trials; we assumed constant persistence probability over time due to similarities in scavenger communities and climatic characteristics (e.g., temperature, humidity) across our study area and due to our short search intervals and high searcher efficiency (Korner-Nievergelt et al. 2015; Riding and Loss 2018). Persistence estimates from this function were averaged across shelters, and the mean was used in “phuso” to generate fatality estimates adjusted for removal, assuming searcher efficiency of 100% and search interval of 3.5 days. We assumed 100% searcher efficiency for the same reasons as in Barton et al. (2017), including the small carcass search areas around shelters (approximately 36–70 m^2), the high visibility of carcasses with contrasting substrates like concrete and mowed grass, and few obscuring structures around shelters. The search interval of 3.5 days was obtained by averaging our search intervals of three and four days. We estimated the minimum number of birds killed in 2020 at all 36 shelters between April and October by dividing the total number of carcasses found across all shelters by the estimate of carcass persistence probability. We generated a similar estimate for the total number of birds killed annually by calculating the total estimated number of birds killed per shelter per month and multiplying by the number of shelters (36) and months in the year (12); this extrapolation assumes monthly mortality rates were the same in unmonitored months.

Results

Descriptive results

From April to October 2020 and across all 36 bus shelters, we found 15 total bird carcasses and 17 observations of collision evidence with no accompanying carcass (i.e., 32 total collision observations). Six species collided, including six American Robins *(Turdus migratorius)*, three House Sparrows *(Passer domesticus)*, two Cedar Waxwings *(Bombycilla cedrorum)*, two Great-tailed Grackles *(Quiscalus mexicanus)*, one Northern Mockingbird *(Mimus polyglottos)*, and one Scissor-tailed Flycatcher *(Tyrannus forficatus)*. Of 18 shelters monitored in 2016 (all of which were untreated at the time), the nine that were eventually treated had 13 total bird carcasses and 19 observations of collision evidence (i.e., 32 total collisions, or 94.1% of all 2016 collisions). After treatment in 2020, these nine treated shelters had four total bird carcasses and one observation of collision evidence (i.e., five total collisions, or 26.3% of all 2020 collisions). The nine shelters that would remain untreated had zero carcasses and two observations of collision evidence in 2016 (i.e., two total collisions, or 5.9% of all 2016 collisions) (Barton et al. 2017), and in 2020 had six carcasses and eight observations of collision evidence (i.e., 14 total collisions, or 73.7% of all 2020 collisions).

BACI and 2020 analyses

For the BACI analysis, there was a significant effect of the interaction between year and treatment ($p = 3.31e\text{-}08$; coefficient estimate ± standard error [SE] $= 7.249 \pm 1.31$; $df = 32$). The interaction plot (Fig. 3) indicated a slight increase in collisions from 2016 to 2020 at untreated shelters and a substantial reduction in collisions from 2016 to 2020 at shelters treated in 2019 with Feather Friendly® markers. For the 18 treated and 18 untreated shelters compared in 2020, we found 10 bird carcasses and 15 observations of collision evidence (25 total collisions) at untreated shelters and five carcasses and three observations of collision evidence (eight total collisions) at treated shelters. For these 36 shelters, there were significantly fewer collisions at treated than untreated shelters in 2020 (p-value $= 0.005$; coefficient estimate ± SE $= 1.139 \pm 0.406$; $df = 34$).

Although the Feather Friendly® markers were applied only to the exterior of bus shelters, they appeared to reduce numbers of collisions on both exterior and interior surfaces. For the nine shelters treated for the BACI analysis, numbers of interior collisions (including carcasses and collision evidence) declined from 13 to one from 2016 to 2020 (exterior collisions declined from 19 to four from 2016 to 2020). For 2020 data at all 36 shelters, treated shelters had lower numbers of both interior and exterior collisions (one and seven collisions, respectively) than untreated shelters (nine and 15 collisions, respectively).

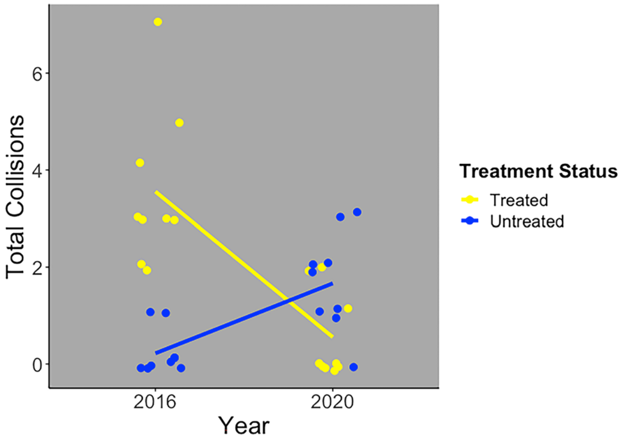

Fig. 3 Plot of interaction between year and treatment status of bus shelters for before-after control-impact analysis of effectiveness of Feather Friendly® markers based on monitoring at 18 shelters in 2016 and 2020 in Stillwater, Oklahoma, USA. Half of shelters were treated in 2019 and half remained untreated. Points indicate total collisions observed per shelter and were jittered on both axes for display purposes

Scavenger removal trials and adjusted mortality estimates

For carcass removal trials using bird carcasses we found as collision casualties, left in place, and monitored on each successive survey (15 total trials in 2020, five at treated shelters and 10 at untreated shelters), we estimated that the average length of time a carcass persisted until it was no longer detectable was 13.47 days. This corresponded to an estimated 0.857 daily probability of carcasses persisting (probability based on averaging across all shelters with carcasses observed). Applying this persistence probability to raw carcass counts, and assuming constant mortality across all shelters, we estimated at least 17.4 total fatal bird collisions across all 36 shelters (18 treated; 18 untreated) from 1 April through 31 October 2020. Using this value, we estimated that 30 total birds were killed throughout 2020, compared with an estimate of 82.4 birds killed throughout 2016 (Barton et al. 2017). In other words, we estimated that treating half of Stillwater's bus shelters in 2019 reduced the total number of annual bird collisions by approximately 64%.

Discussion

All of the analyses we conducted support the effectiveness of Feather Friendly® markers in reducing bird-window collisions. These included a replicated BACI analysis with before-after treatment data for treated and control shelters, an analysis comparing treated and untreated shelters during the same time period, and our estimate of a 64% reduction in total bird collisions from 2016 to 2020 after treating half of Stillwater's bus shelters. As one of the first replicated field tests of the effectiveness of a product designed to reduce bird-window collisions, and the first with a replicated BACI analysis, our results have important implications and add valuable information to the body of knowledge about bird-window collisions. Results from the BACI analysis are especially compelling, as we showed that collisions decreased at treated bus shelters even with a slight increase in collisions observed during the same period at untreated shelters.

This study builds on past research, adding further support for the effectiveness of the Feather Friendly® markers we tested. Our results, along with studies conducted in Utah, USA (Brown et al. 2019, 2020), indicate that this product is effective in alerting birds that glass is a barrier. Specifically, Brown et al. (2019) tested the effectiveness of the same Feather Friendly® markers on a single façade of one university building during one winter season and found a 71% reduction in collisions after marker installation. A subsequent study (Brown et al. 2020) tested the same markers on the same building façade during one fall season and documented a similar reduction in collisions. While these studies highlight the effectiveness of this product in reducing bird collisions, their small sample size of one building façade and their geographical setting limited generalizations about product effectiveness. One of the few other studies to monitor glass-walled bus shelters for collisions found that shelters obscured with graffiti and dust had the fewest collisions, lending broader support to the success of window treatments that function by breaking up glass transparency and reflectivity (Zyśk-Gorczyńska et al. 2020).

Bus shelters are structurally unique in that most only have three walls and are open on one side. This causes the transparent and reflective properties of glass to pose a collision threat to birds at both interior and exterior surfaces of the glass. A window of five m^2 on a building presents a surface area of five m^2 over which birds can collide, but the same amount of glass on a bus shelter creates a 10 m^2 area of potential collision risk. This effect results in birds becoming entrapped inside shelters and/or colliding on the inner glass surface (Zyśk-Gorczyńska et al. 2020), as evidenced by the baseline research in our study area that found 41% of collisions occurred on the interior of shelters (Barton et al. 2017). Our results provide tentative evidence that Feather Friendly® window markers installed on the exterior of bus shelters may not only be effective at reducing collisions on the exterior but could potentially also be effective in reducing collisions on the interior, untreated sides of glass panes. Specifically, although we did not conduct formal analyses that separately evaluated differences in numbers of interior and exterior collisions, our descriptive results suggest that markers reduced interior collisions. The observed number of interior collisions decreased 92% between 2016 and 2020 at treated shelters, and there were 89% fewer interior collisions at treated shelters than untreated shelters in 2020. Despite these promising results, there is a need for further research to evaluate the degree to which exterior markers are visible to birds from the interior of shelters, and to conduct formal analyses that separately evaluate differences in interior and exterior collisions between treated and untreated shelters. Further, even if treating glass on one side does reduce both interior and exterior bird collisions in some cases, this may not necessarily be the case with all types of glass. For example, glass that is thicker or tinted/colored may reduce visibility of window markers from the opposite side, such that numbers of collisions on the untreated surface are not reduced.

Evaluating applicability of Feather Friendly® markers and other similar products at a wide variety of structure types requires consideration of how bus shelters differ from buildings in the context of bird collisions. Factors known to influence bird-window collisions at buildings, such as bird abundance, surrounding vegetation, structure size, and amount of artificial light emitted at night (Cusa et al. 2015; Hager et al. 2017; Van Doren et al. 2021), can vary between bus shelters and buildings. These distinctions can result in varying importance of factors influencing collision rates. For example, Zyśk-Gorczyńska et al. (2022) found that bird abundance, species composition, and land-use types surrounding glass-walled bus shelters were poor predictors of collisions, emphasizing the differences between bus shelter and buildings. Additionally, there is generally little or no nighttime lighting emitted from bus shelters, which may reduce the importance of this factor compared at buildings (Barton et al. 2017). Variation in such collision correlates may also lead to differences between buildings and bus shelters in which bird species collide most frequently and which seasons experience peak collision rates. Collisions at building windows usually consist primarily of migratory bird species, and in many contexts, occur most frequently during migration periods (Arnold and Zink 2011; Loss et al. 2014; Riding et al. 2021). However, our study and the earlier baseline study (Barton et al. 2017) indicate that collisions at bus shelters consist mostly of non-migratory resident species and migrants during their summer residency period, with collisions occurring more evenly throughout spring, summer, and fall. Because of the above differences, effectiveness of various mitigation techniques and products may also differ between bus shelters and buildings. Further well-replicated studies, including those with a BACI component, are needed at buildings to test effectiveness of this and other types of products designed to reduce bird-window collisions.

Glass-walled bus shelters provide an opportunity to test effectiveness of window treatments in reducing bird collisions, but further research at both bus shelters and buildings is needed. For example, replicated field research could compare effectiveness of different spacing distances for elements used in collision deterrent products (e.g., five cm x five cm spacing, such as the markers we tested, compared to the often-recommended five cm horizontal × 10 cm vertical spacing pattern; Klem 1990; 2009). This research will be important because certain patterns may be more or less likely to be purchased and installed due to factors like aesthetic appearance and amount of natural light admitted into buildings. Well-replicated studies of treatments at diverse locations would also help determine product effectiveness in varying conditions and in relation to the above types of factors that vary between bus shelters and buildings (e.g., different collision correlates, species affected, and seasonal collision patterns). Comparing different products in the same study area or on different parts of the same building could allow identification of relative strengths or weaknesses of each treatment in different settings, including on different structure types, with different communities of affected bird species, and with varying levels of glass transparency and reflectivity, surrounding vegetation, and nighttime lighting. Additionally, evaluating combinations of mitigation approaches, such as films, markers, or decals along with management steps like altering vegetation or nighttime lighting, would clarify if and how multiple approaches interact to reduce collisions (e.g., a product could be more effective with less nearby vegetation to be reflected on the glass). Given benefits of controlled testing, such as tunnel tests and field experiments that facilitate replication and direct observation of interactions between birds and glass (Klem 2009; Klem and Saenger 2013; Sheppard 2019), research could also evaluate the relationship between effectiveness of products in controlled and real-world situations. This would further facilitate predictions about product effectiveness based solely on results of controlled testing. The above types of studies of products installed on buildings may soon become more feasible as more entities (e.g., commercial businesses and universities) treat problem areas of building glass as a result of increased research, additional enactment of bird-friendly building guidelines and regulations, and increased public awareness of and support for addressing this issue (Riggs et al. 2021).

Although our study design was rigorous and our results valuable, it is crucial to acknowledge limitations of this study. Our estimates of total annual bird collisions across all bus shelters in Stillwater, Oklahoma, should be interpreted with caution as we only monitored for collisions from April to October and assumed monthly collision rates during this period were similar to the rest of the year. Bird abundance and species composition change throughout the year, typically resulting in most collisions occurring in spring, summer, and fall (especially spring and fall migration in many areas), with fewer in winter (Borden et al. 2010; Bayne et al. 2012; Hager et al. 2013; Nichols et al. 2018; but see De Groot et al. 2021). Thus, estimates of total annual collisions were likely inflated in both the baseline and current studies. Additionally, the average interval between our collision surveys (3.5 days), although selected to align with the interval used in the baseline study, may have contributed uncertainty to both our scavenger removal and fatality estimates, and when possible, future studies should implement daily surveys to limit such uncertainty. We also did not account for searcher detection bias and instead assumed 100% detection of collision events, a likely overestimation (Riding and Loss 2018). However, we made the same assumption in the baseline study, so any introduced bias should not have greatly affected comparisons between years. Another limitation is that the before and after periods for the BACI analysis each consisted of one field season of collision monitoring. Likewise, the analysis comparing all treated and untreated shelters in 2020 was based on a single field season. Monitoring bus shelters across more years would capture greater "background" variation in collisions due to factors like variation in bird abundance, and therefore, provide a better understanding of the product's effectiveness.

Despite this limitation, the major differences in collisions for both the BACI and 2020 analysis provide compelling evidence for the product's effectiveness in reducing collisions.

Finally, we note that the Stillwater bus system was not operational from March through July of 2020 due to the SARS-CoV-2 pandemic. For the same reason, OSU classes were held online starting in March 2020 resulting in few students and staff being on campus throughout the summer. Anecdotally, bus use was lower than normal even after restoration of transit services in July 2020. This change in human activity in the study area, including near bus shelters, could have resulted in more birds being near shelters and thus contributed to the slight increase in collisions from 2016 to 2020 at untreated shelters. The difference in length of the collision monitoring season (4 May–30 Sep in 2016; 1 Apr–31 Oct in 2020) could also have contributed to this increase, although we accounted for varying numbers of collisions surveys in analyses by using an offset term. Regardless of whether altered bus services influenced bird collisions, the BACI study design allowed us to document that glass markers were highly effective even if confounding factors caused changes in numbers of collisions from 2016 to 2020.

Conclusions

Our study of 36 bus shelters, including a before-after control-impact analysis for 18 shelters and a comparison between all treated and untreated shelters in 2020, provides strong evidence of the effectiveness of a commercially marketed product (Feather Friendly®) in reducing bird-glass collisions. These results also highlight an opportunity for municipalities and other entities that manage public transit systems to reduce bird-glass collisions at bus shelters, and thus contribute to addressing the many human-related threats affecting bird populations. We estimated that treating half of Stillwater's bus shelters reduced bird collisions by 64%, and even greater reductions would be likely with treatment of all shelters. Our research provides a model for similar studies at both bus shelters and buildings to evaluate and compare products designed to reduce bird-window collisions and to facilitate expanded use of effective products across a variety of structure types. Additional replicated research is needed to test effectiveness of many types of collision-reducing products after installation on buildings, including glass with built-in features designed to reduce collisions (e.g., etchings and UV-reflecting patterns), and films, markers, and other products that cover or adhere to glass. Nonetheless, this study bodes well for the effectiveness of Feather Friendly® markers and other similar products in substantially reducing the number of bird-window collisions and thus greatly benefitting bird populations.

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Author contributions GJR, CMB, CSR, TJO, and SLR conceptualized idea; GJR and CMB curated data; GJR conducted formal analysis; GJR wrote original draft; CMB, CSR, TJO, and SLR reviewed and edited drafts; CSR and SLR acquired funding. All authors contributed critically to the drafts and gave final approval for publication.

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Data availability All data are provided as Supporting Information.

Code availability All code developed using R and RStudio software are provided as Supporting Information.

Declarations

Ethics approval For data collection efforts of this study, all bird carcasses were handled under Scientific Collector's Permits obtained through the U.S. Fish and Wildlife Service (Permit #MB05120C-0) and Oklahoma Department of Wildlife Conservation (multiple permits during the study). Protocols were also approved by the Institutional Animal Care and Use Committee at OSU (IACUC protocols #AG-14–8 and #AG-20–13).

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