1 **Evaluating the efficacy of window treatments to reduce bird–window collisions**

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14 **Abstract**

15   Collisions with glass are a leading anthropogenic driver of avian mortality. Window

16 treatments can be highly effective at reducing collisions, however, treating windows remains

17 uncommon and many treatments are applied that do not follow evidence-based standards or

18 guidelines. To evaluate the efficacy of window treatments that meet versus do not meet

19 guidelines, and the drivers influencing collision rates, we conducted standardized collision

20 surveys during spring and fall migration in 2024 and 2025 at window façades in Ottawa, Ontario,

21 Canada. We documented 233 collisions involving 51 species, with 204 collisions at untreated

22 façades and 29 at treated façades. Using a generalized additive mixed modelling approach, we

23 found that glass area and the proportion of vegetation and tree canopy around façades were the

largest drivers of collisions. Window treatments that met guidelines had a significant negative

effect on collision risk ($\beta_{\text{treatment met guidelines}}$ = -2.24, SE = 0.74, p < 0.01). Critically, we found no

statistically significant difference in collision risk at façades with window treatments that did not

meet guidelines and collision risk at untreated façades ($\beta_{\text{treatment did not meet guidelines}}$ = -0.33, SE =

0.31, p = 0.28). Further, using a random forest model approach that used untreated window data

to predict a "no treatment" collision rate at currently treated windows, we found a significant

difference in reduced collision rates between window treatment groups. Window treatments that

did not meet guidelines reduced collision rates by 76.3% which was significantly less than the

98.4% reduction when window treatments met guidelines (t = -2.796; df = 169.96; p < 0.01, one-

tailed t-test). Window treatments should be prioritized at building façades with large windows

near vegetation and canopy and to be effective, treatments must meet guidelines.

Introduction

Bird–window collisions are a leading source of direct human-caused avian mortality

(Calvert et al. 2013). These account for an estimated 1 billion bird deaths each year in North

America (Loss et al. 2014) with annual mortality estimates of 365–998 million birds in the

United States (Loss et al. 2014) and 16–42 million in Canada (Machtans et al. 2013). Birds

collide with windows and other glass structures because they do not see glass as a barrier in the

environment due to its reflective or transparent properties (Klem 1989). Glass reflects or

provides a clear view to the surrounding habitat or sky that birds attempt to fly towards, resulting

in collision with the glass. Patterns of bird–window collisions (hereafter "collisions") are

influenced by structural features of buildings, environmental factors, time of year, and species

traits (Borden et al. 2010, Hager et al. 2013, Cusa et al. 2015). Collision risk is driven by the

amount of glass on a building and environmental factors like surrounding vegetation, tree

47 canopy, distance to water, amount of urban development, and artificial light at night (Klem et al.

48 2009, Hager et al. 2013, Cusa et al. 2015, Lao et al. 2020). However, the relationships between

49 these factors and collision risk is highly variable and context-dependent, resulting in risk that is

50 specific to the particular bird taxa, landscape, or individual building (Hager et al. 2013, 2017,

51 Tan et al. 2024).

52   Migratory birds are more vulnerable to colliding with glass, where migratory species can

53 comprise up to 90% of fall collisions (Lao et al. 2023, Tan et al. 2024). Thus, though collisions

54 occur year-round (Hager and Craig 2014, De Groot et al. 2021), rates of collisions typically peak

55 during spring and fall migration (Borden et al. 2010, Kahle et al. 2016, Colling et al. 2022). In

56 much of North America, species in the wood warbler (Parulidae) and North American sparrow

57 (Passerellidae) families typically account for the greatest number of documented collision

58 mortalities (Borden et al. 2010, Arnold and Zink 2011, Fischer and Islam 2020, Colling et al.

59 2022). Additionally, thrushes (Turdidae) have accounted for high collision counts in Canada (De

60 Groot et al. 2021, Zulian et al. 2025) and globally, along with pigeons and doves (Columbidae)

61 (Tan et al. 2024, Gómez-Martínez and MacGregor-Fors 2025). In Canada, migratory bird species

62 are protected under the *Migratory Birds Convention Act, 1994* (*MBCA*) (*Migratory Birds*

63 *Convention Act*, s.c. 1994, c. 22) and federal species at risk are protected under the *Species at*

64 *Risk Act* (*SARA*) (*Species at Risk Act,* s.c. 2002, c.29) and the *SARA,* along with recent

65 amendments to the Migratory Birds Regulations (*Migratory Birds Regulations,* 2022. SOR/2022-

66 105) under the *MBCA,* make unintentional deaths due to window collisions unlawful.

67   Effective prevention strategies to reduce collisions include commercially available visual

68 markers that are applied to glass surfaces to break up reflected images and signal a barrier that

69 birds are more likely to avoid (De Groot et al. 2022, Riggs et al. 2022a, Swaddle et al. 2023).

70   These window treatments have been tested in lab and field settings (Klem and Saenger 2013,

71   Rössler et al. 2015, Sheppard 2019) which has led to the development of window marker designs

72   that minimize collision risk. Results from these studies have informed bird-friendly building

73   design standards developed by a team of experts for the Canadian Standards Association (CSA)

74   Group (CSA A460:19) and municipal guidelines (e.g., City of Ottawa 2022). These guidelines

75   generally stipulate the visual markers are: 1) spaced a maximum of 5x5cm (or 2x2in) apart

76   horizontally and vertically, 2) applied to the exterior surface of reflective glass, 3) have a width

77   of at least 4mm, and 4) are a high contrast colour (Klem 2025, CSA A460:19). When treatments

78   are applied to meet these guidelines, field assessments comparing collision rates before and after

79   treatment application found these window treatments can reduce collisions by 92–95% (Brown et

80   al. 2021, De Groot et al. 2022, Riggs et al. 2022a).

81   Despite their effectiveness and availability, bird-friendly window treatments are not

82   common, and when applied, treatments often deviate from guidelines. Deviations can result from

83   lack of appropriate information, attempts to cut costs, or aesthetic concerns (Riggs et al. 2022b,

84   Loss et al. 2023). In Canada, guidelines are not mandatory at a national scale, and there are no

85   policies to ensure that bird-safe design specifications are followed. In Canadian cities with

86   mandated guidelines for bird-safe designs (Toronto, Ontario, and Ville Saint-Laurent, a borough

87   in Montréal, Québec), this only applies to new buildings that meet other conditions (e.g., >50%

88   surface glass in Saint-Laurent) (City of Toronto 2016, Ville Saint-Laurent RCA 08-08-0001-169

89   2024). Other Canadian municipalities including Ottawa, Ontario, have introduced guidelines for

90   bird-safe building design (City of Ottawa 2022), but these are not mandatory. This has led to

91   recent applications of window treatments that do not follow guidelines in addition to those that

92   were applied prior to adoption of these guidelines. Evidence from community science suggests

93   that collisions still occur consistently and without noticeable reductions at buildings with

94   window treatments that do not follow guidelines (Safe Wings Ottawa, *pers comm*).

95   Understanding the efficacy of different types of window treatments can ensure resources are

96   invested in measures that effectively prevent bird–window collisions. However, the efficacy of

97   window treatments that deviate from guidelines has yet to be formally assessed in a real-world

98   urban setting.

99   Here, we explored the efficacy of window treatments to reduce bird–window collisions in

100   Ottawa, Ontario, Canada using standardized collision surveys. We examined differences in the

101   efficacy of window treatments that meet versus do not meet guidelines. Across a large urban

102   area, we investigated: 1) the features of buildings and the surrounding environment that drive

103   collisions and 2) the differences in collision risk between window treatments that met guidelines

104   and those that did not meet guidelines. For our first objective, we predicted collision risk to

105   increase with increased glass area at taller buildings with highly reflective glass that are

106   surrounded by more canopy and vegetation (Hager et al. 2013, Elmore et al. 2021, Zulian et al.

107   2023). To address our second objective, we first explored empirical differences in collision risk

108   across a range of window treatments. We then estimated window treatment effectiveness by

109   comparing collision rates observed at treated windows with predicted collision rates that

110   represent a counterfactual "no treatment" scenario. We predicted that the presence of any

111   window treatment will reduce collision risk when compared to untreated windows (Rössler et al.

112   2015, De Groot et al. 2022, Riggs et al. 2022a), but that treatments which meet guidelines will be

113   more effective at reducing collisions than window treatments that do not meet guidelines.

114   **Methods**

115   *Study area and buildings*

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116   Ottawa (45.401, -75.671°) is the capital city of Canada and is located on the unceded

117   territory of the Anishinaabe Algonquin Nation within Ontario, Canada. In 2021, the city had a

118   population of 1,017,449 with a land area of 2,788 km^2 (Statistics Canada 2023). Ottawa is

119   located along an important migratory pathway for birds between the Great Lakes and the Gulf of

120   St. Lawrence that can provide quality stop-over habitat within urban areas (Poirier et al. 2024a).

121   Ottawa contains three major waterways, the Ottawa River, the Rideau River, and the Rideau

122   canal. Additionally, the city is adjacent to the Ottawa Greenbelt, which is an area of vegetated

123   land where development is limited (Campbell 2009), and the city is part of the St. Lawrence

124   Lowlands ecoregion which is designated as a priority place for Species at Risk in Canada

125   (Environment and Climate Change Canada 2023a). Both the Ottawa Greenbelt and the St.

126   Lawrence Lowlands ecoregion have experienced some of the highest rates of development and

127   urbanization in Canada (Campbell 2009, Kraus and Hebb 2020) which increases the

128   anthropogenic risks and threats faced by migrating birds.

129   We selected a total of 61 buildings in this study based on the presence of window

130   treatments, previous knowledge of collisions through Safe Wings Ottawa (a local community

131   organization that has documented collisions in Ottawa since 2014), and a range of building and

132   environmental features to represent a range of collision risks. We only selected publicly

133   accessible commercial or institutional buildings and public transit structures. Of the buildings

134   included in this study, 24 contained at least one section of treated windows while 37 were

135   untreated. Each building was divided into façades based on the primary direction the windows

136   were facing on the sides of buildings and/or similar architectural features like walkways or

137   railings (Riding et al. 2019, De Groot et al. 2022) for a total of 225 façades. This allowed us to

138   consider sections of a building that were accessible, and those with window treatment separately

139   from untreated sections. We excluded façades with ledges or overhangs that would prevent

140   detecting collisions. Window treatments included circular markers (i.e., Feather Friendly®

141   Collision Deterrent Markers), collision tape, fritted glass, or painted murals.

142   *Collision surveys*

143   We conducted standardized collision surveys Monday–Friday during spring and fall

144   migration in 2024 and 2025. We conducted 85 survey days in 2024 (Apr. 17th–Jun. 7th; Aug.

145   12th–Oct. 18th) and 75 survey days in 2025 (Apr. 21st–Jun 6th; Aug.12th–Oct.17th). A clean-up

146   survey was completed at all buildings prior to the first day of surveys to remove any carcasses

147   that occurred outside of the study period (Hager and Cosentino 2014). The lead author conducted

148   all surveys in 2024. Surveys in 2025 were conducted by two technicians, one for each season. In

149   2024, spring 2025, and from Aug.12th–Sept.1st of fall 2025, buildings were split into two

150   alternating survey routes such that each building was surveyed 2–3 times each week and the

151   longest time between a building being surveyed was three days. Due to resource limitations,

152   from Sept. 2nd–Oct.17th in fall 2025, survey buildings were split into three groups of alternating

153   routes where buildings were surveyed 1–2 times a week, and the longest time between building

154   surveys was four days.

155   Survey methods were adapted from Hager and Cosentino (2014) and protocol used by

156   Safe Wings Ottawa. We did not conduct surveys in heavy rain that limited visibility and

157   presented unsafe conditions. All surveys began at sunrise and were typically completed within

158   three hours. At onset of the survey, we recorded the daily sky condition following protocol by the

159   Breeding Bird Survey (Environment and Climate Change Canada 2023b). Surveys were

160   conducted by making single passes along each façade and searching for evidence of a collision

161   within two meters of the window. Carcasses, live and injured birds, obvious bird imprints on

162   glass, and scavenged remains (i.e., wing fragments, body parts, feather piles of at least 10

163   feathers within a 30cm diameter) were considered evidence of a collision. ESRI ArcGIS Online

164   forms (ESRI 2025) were used to collect collision data at all façades including the date and time,

165   and if a collision was detected, the species and status (dead, alive, or scavenged). We included

166   five incidental records reported by third-parties in analyses that were found at surveyed façades

167   during the survey periods.

168   All carcasses were collected and frozen for further identification and were handled under

169   the *MBCA* Scientific Permit under Environment and Climate Change Canada (Permit #: SC-OR-

170   2024-00099).

171   *Predictors of collision risk*

172   <u>Building features</u>

173   For each façade, we measured total glass area (m^2), façade area (m^2), the proportion of

174   glass, façade height (m), cardinal direction, and glass characteristics (e.g., reflectivity) as

175   potential building features driving collisions. Methods to measure window glass were adapted

176   from protocols developed by Osborne (2024). To measure glass and façade area, we took

177   photographs of each façade including a standardized reference measurement to calibrate the scale

178   of measurement for analysis in ImageJ (Schneider et al. 2012, Hager et al. 2017, Riding et al.

179   2019, Osborne 2024). In most cases, multiple photos were needed to capture the entire façade,

180   and only surveyed portions of the façade were analyzed. We calculated the proportion glass per

181   façade using the total glass and façade area measurements. Façade height was collected from

182   LiDAR data of 3D buildings in Ottawa (City of Ottawa Open Data 2023). In some instances, the

183   façade height was not available in the database and was instead calculated during window

184   analysis in ImageJ using the same reference measurement.

185   We classified direction (Borden et al. 2010) and the reflectivity of glass (Klem et al.

186   2009) as categorial predictors. Direction represented the primary cardinal direction of the façade

187   face. We created a reflectivity category using definitions from Klem et al. (2009) and the Fatal

188   Light Awareness Program (FLAP) Building Assessment (FLAP 2022) to describe glass

189   reflectivity and included four groups based on the amount of visible environment seen on the

190   glass (Appendix S1a-d). This included: (1) *Non-reflective* glass where inside of the building is

191   more visible than reflections of the environment; (2) *Reflective* glass which reflected sky or

192   vegetation more than the inside of the building could be seen; (3) *Transparent* glass where there

193   was a mostly unobstructed view towards sky or vegetation from one side of the glass and

194   primarily included walk-way structures and glass railings; and (4) *Mirrored* glass that almost

195   perfectly reflected the sky or vegetation and provided little to no view into the building.

196   Reflectivity was assessed in the morning on days with clear skies during collision surveys.

197   Environmental features

198   We chose surrounding vegetation, canopy, and distance to water for each façade as

199   environmental features. We measured vegetation and canopy as the proportion of area within a

200   100m buffer of the façade edge (Loss et al. 2014, Anderson 2018). We determined façade edges

201   using building footprints (DMTI Spatial Inc. Building Footprints Region 2023) and aerial images

202   of the City of Ottawa (City of Ottawa Orthophotos 2022, 20cm resolution). Canopy area was

203   taken from the City of Ottawa open-source polygons of forest canopy cover (City of Ottawa

204   Open Data 2024a), and we manually verified canopy by adding or removing polygons,

205 referencing trees visible in the aerial images and knowledge of the study area. We considered

206 lawn and shrubs (including mulch and gardened areas) as vegetation and measured this by

207 drawing polygons over aerial images (Hager et al. 2017, Riding et al. 2019). We measured

208 vegetation and tree canopy separately and included these terms in analyses as an interaction

209 effect. We did this to capture ranges of combinations of these variables from façades with

210 multiple structural layers of vegetation and canopy to façades with street trees surrounded by

211 impermeable surfaces. We measured distance to water as the distance from the façade centre to a

212 river or canal (City of Ottawa Open Data 2024b). All environmental variables were analysed in

213 ArcGIS Pro v.3.1.0 (ESRI 2024).

214 <u>Window treatments</u>

215 We assigned window treatment categories using the City of Ottawa Bird-Safe Guidelines

216 (City of Ottawa 2022) and the CSA bird-friendly building design standards (CSA A460:19).

217 Window treatments met guidelines if the application and design satisfied the following criteria: i)

218 5x5cm marker spacing; ii) exterior application on reflective glass, iii) marker width of ≥4mm;

219 and iv) markers have high contrast colour (Appendix S1). We considered treatments as not

220 meeting guidelines if window treatments were present but did not meet these criteria. In 2024,

221 152 façades were untreated, 41 did not meet guidelines, and 32 met guidelines. Two façades

222 were treated between survey years and in 2025, 150 façades were untreated, 41 did not meet

223 guidelines, and 34 met guidelines. To maintain consistency, the lead author assigned all

224 categorical façade attributes.

225 *Statistical analyses*

226 All analyses were performed in R statistical software v. 4.3.2 (R Core Team 2020).

Drivers of collision risk

228   To model the effects of predictor variables driving collision risk per façade we used

229 generalized additive mixed models (GAMMs) as we had no *a priori* expectations of linear

230 relationships. GAMMs were fitted using the *mgcv* package (Wood 2011) and used a tweedie

231 distribution with a log link which allowed for variation to increase with mean values (Zuur et al.

232 2009). We summarized collision data across season and year for each facade and only considered

233 non-daily predictor variables in the GAMMs (e.g., we did not include sky condition). We

234 checked for concurvity between predictor variables (i.e., the non-linear version of

235 multicollinearity) and included variables with observed concurvity <0.7 (Wood 2011). To select

236 predictor variables, we used a backward model selection approach starting with a global model

237 and sequentially removing non-significant variables. We included an interaction effect between

238 vegetation and canopy to capture the varied complexity of stratified habitat between lawn,

239 shrubs, and trees. To account for uneven sampling effort, we included the log number of surveys

240 conducted at each façade as an offset. Building was included as a random effect to account for

241 non-independence of observations at the same building. We found no significant between-year

242 variation and removed year as a variable. To further account for spatial non-independence, we

243 included a tensor product of longitude and latitude as nuisance spatial variable (Frei et al. 2024).

244 We assessed models using Akaike's information criterion metric (AICc) and considered models

245 within 2 ΔAICc equally likely candidate models (Burnham and Anderson 2002).

246   For continuous variables with non-linear effects that appeared in the top model, we

247 calculated the first derivative of the smooth term using the *gratia* package (Simpson 2024). We

248 did this to identify values for each variable that caused a significant rate of change in collision

249 risk and considered the derivative significant if the 95% confidence interval of the derivative did

250   not overlap zero (Fewster et al. 2000, Bianchini et al. 2025). For each significant single variable

251   in the top model, we obtained the conditional predicted means of the expected number of

252   collisions at each facade using the *marginaleffects* package (Arel-Bundock et al. 2024) while

253   holding all other variables at their mean values.

254   <u>Model-predicted collision risk</u>

255   To build the model to predict a counterfactual scenario of "no treatment" collision rates

256   we used a Random Forest (RF) approach (Breiman 2001). We built the predictive model using

257   only data at untreated façades to generate a counterfactual scenario of predicted collisions at

258   treated façades if they were not currently treated. For this analysis, we used daily collision data

259   and considered all predictor variables. We used a RF approach as opposed to generating

260   predictions from GAMMs as RFs can be relatively insensitive to autocorrelation, less prone to

261   overfitting, can handle large class imbalances in the response, and can be highly accurate through

262   the model training process (Breiman 2001, Siders et al. 2020).

263   The RF procedure was executed using the R packages *tidymodels* (Kuhn and Wickham

264   2020) and *ranger* (Wright and Ziegler 2017). We used a classification RF procedure with a

265   binary response variable that described if a collision was observed or not. The data was split into

266   75% training and 25% test data while maintaining similar proportions of the response classes.

267   Using 5-fold cross-validation, we tuned the model hyperparameters prior to fitting a final model

268   which included 1000 trees, one variable sampled at each node (mtry = 1), and a minimum of ten

269   nodes at each split (min_n = 10). We accounted for the large class imbalance in the response by

270   using synthetic minority over-sampling technique (SMOTE). This oversampled the minority

271   response class by creating synthetic responses based on distances of the response data point to

272 nearest neighbours (Chawla et al. 2002) and performs better with high class imbalance data than

273 standard RFs (Siders et al. 2020). Other sampling methods to account for large class imbalances

274 like downsampling and upsampling were investigated in sensitivity analyses, however these did

275 not yield better performing models. We selected an optimized final model by evaluating variable

276 importance at each iteration and removing less important variables (Murphy et al. 2010)

277 (Appendix S2). Area under the curve (AUC) was used as the accuracy metric for the final model

278 where an AUC score >0.7 was considered useful for making predictions (Siders et al. 2020).

279   Once a final model was optimized, we predicted the number of window collisions at

280 treated façades if they were not currently treated using a ≥0.5 cutoff from the class probability

281 metric. To account for uneven sampling over each survey period, we calculated collision rates for

282 both predicted and observed collisions as the collision count (predicted or observed) divided by

283 the number of surveys conducted in each survey period. We use the difference between the

284 predicted "no treatment" collision rate and the observed "treatment" collision rate to measure

285 reduction in collision rates for treatments overall, treatments that did not meet guidelines, and

286 treatments that met guidelines. To compare predicted and observed collisions, we used Welch's t-

287 tests for unequal variances to account for uneven sampling between groups (Day and Quinn

288 1989). First, to measure the efficacy of window treatments overall, we used a one-tailed t-test to

289 compare the difference between predicted and observed collision rates for any window treatment.

290 Second, to identify differences in efficacy of treatments when guidelines are met and when they

291 are not, we used a two-tailed test to compare the reduction in collision rates between window

292 treatment groups and identify any difference between groups before using a one-tailed t-test to

293 identify directionality in the difference.

294 **Results**

Collision summaries

296   We documented 233 collisions over spring and fall migration in 2024 and 2025. In 2024,

297   we documented 48 collisions in the spring and 94 in the fall, and in 2025, we documented 41

298   collisions in the spring and 47 in the fall. Collisions occurred across 102 façades (45.33% of all

299   façades) at 43 buildings (70.49% of buildings) (Appendix S3). A total of 204 collisions (87.55%

300   of all collisions) occurred at untreated façades. For façades with window treatments, 27

301   collisions (11.59%) occurred at those with treatments that did not meet guidelines and two

302   collisions (0.86%) occurred at those with treatments that met guidelines. Two buildings

303   accounted for more than half (58.62%) of all collisions at treated windows, all of which occurred

304   at façades with window treatments that did not meet guidelines. We note uncertainty in the two

305   collision records at façades with window treatments that met guidelines. Both records

306   documented live birds — the first involved a Barn Swallow (*Hirundo rustica*) under a window

307   that flew away before confirmation it had collided. The second involved a Hermit Thrush

308   (*Catharus guttatus*) found under a recently damaged and replaced untreated window at a façade

309   with window treatments that met guidelines. Both records are retained to keep consistency with

310   documenting live birds and inability to determine exact location of the collision.

311   We identified 51 species from 222 collision records with 11 records that we were unable

312   to identify to species (Appendix S4). The wood warbler family (Parulidae) had the most species

313   recorded in collisions (18 species, 35.29% of species), followed by North American sparrows

314   (Passerellidae, 7 species, 13.73% of species). Top species identified included Brown Creeper

315   (*Certhia americana*; 22 collisions), White-throated Sparrow *(Zonotrichia albicollis*; 19

316   collisions), and Tennessee Warbler (*Leiothlypis peregrina*; 15 collisions). Of the 51 identified

317   species, 48 (94.12%) are listed as protected in Canada under the *MBCA*. We also documented

318   two species at risk which are additionally listed under the *SARA* including Wood Thrush

319   (*Hylocichla mustelina;* Threatened, three collisions) (COSEWIC 2012) and Barn Swallow

320   (Special Concern, one collision) (COSEWIC 2021).

321   *Drivers of bird–window collisions*

322   Two GAMMs were considered equally likely candidates (Table 1), of which we selected

323   the more saturated model as we were interested in the most informative set of drivers influencing

324   collision risk. The final GAMM included season, glass reflectivity type, and window treatment

325   group as categorical variables and glass area (m^2), façade height (m), distance to water (m), and

326   an interaction between proportion vegetation and proportion canopy as smooth (non-linear)

327   terms (adjusted R^2 = 0.256, explained deviation = 32.4%). All parameters in the final GAMM

328   except distance to water and the individual effect of vegetation, significantly explained the

329   variation in collisions. The smooth effects of glass area and the interaction of vegetation and

330   canopy were strongly non-linear (EDF ranged from 2.7–5.3; Table 2) while the individual effects

331   of vegetation, canopy, and façade height were linear.

332   Glass area had a significant positive relationship with increased collision rates, and we

333   found a significant rate of change in this effect from the minimum value of glass to a threshold

334   point ~700m^2, after which collision rates remained high (Figure 1a). The interaction between

335   vegetation and canopy had a significant positive effect at low values of both variables (~0–35%

336   canopy; ~0–50% vegetation), and this effect decreased at the upper ranges of both variables

337   (Figure 1b). As individual effects, we found canopy had a significant positive linear relationship

338   with collisions (Figure 1c), while vegetation had no individual significant effect (Figure 1d).

339   Facade height had a significant negative linear relationship with collisions where the effect

340   decreased as height increased (Figure 1e). Significantly fewer collisions were found in spring

341 than fall (β_{spring} = -0.31, SE = 0.13; p = 0.02). All types of glass increased collisions compared to

342 non-reflective glass, but this increase was significant for transparent glass ($\beta_{transparent}$ = 1.60, SE =

343 0.55, p < 0.01) and reflective glass ($\beta_{reflective}$ = 1.21, SE = 0.55, p = 0.03) but not mirrored glass

344 ($\beta_{mirrored}$ = 1.06, SE = 0.56, p = 0.58). Although non-significant, we found a positive non-linear

345 effect of water on collisions (Figure 1f).

346   Window treatments decreased collisions, but this was only significant when windows

347 treatments met guidelines ($\beta_{treatment\ met\ guidelines}$ = -2.24, SE = 0.74, p < 0.01). We found no

348 statistical difference between collision risk at windows with treatments that did not meet

349 guidelines and collision risk at untreated windows ($\beta_{treatment\ did\ not\ meet\ guidelines}$ = -0.33, SE = 0.31, p

350 = 0.28). We found a similar trend in the conditional predictions for each predictor variable by

351 window treatment group (Figure 2) where the predicted collision risk at windows with treatments

352 that did not meet guidelines was similar to the predicted collision risk at untreated windows. The

353 predicted collision risk at windows with treatments that met guidelines remained close to zero

354 across all variables.

355 *Reduction in collisions using model predictions*

356   The final optimized RF model had an ROC AUC = 0.74, an accuracy = 0.96, recall =

357 0.12, and precision = 0.08 (Appendix S5) and predicted 270 "no treatment" collisions. Across all

358 façades with window treatments, the mean predicted "no treatment" collision rate was

359 significantly lower than the mean observed treatment collision rate (89.1% reduction, t = -6.36;

360 df = 310.83; p <0.001, one-tailed t-test) (Figure 3). Between treatment groups, there was a

361 significant difference in the mean differences in RF "no treatment" predictions of collision rates

362 and observed collision rates (t = -2.79; df = 169.96; p < 0.01, two-tailed t-test). For façades with

363 window treatments that did not meet guidelines, the difference in predicted and observed

364 collision rates (76.3% reduction) was significantly lower than the difference in collision rates at

365 façades with window treatments that met guidelines (98.4% reduction) (t = -2.796; df = 169.96; p

366 < 0.01, one-tailed t-test) (Figure 4).

Discussion

368   Building and surrounding landscape features influence the risk of birds colliding with

369 windows. Window treatments can be an effective solution to preventing collisions, but when

370 implemented, often do not meet guidelines. Our study demonstrated that glass area, surrounding

371 vegetation and canopy, and reflective and transparent glass are associated with a significant

372 increased risk of collisions, while façade height was associated with a significant decreased risk

373 of collisions. Our study shows for the first time in a city-based field study that the efficacy of

374 window treatments in reducing the risk of bird–window collisions and preventing bird deaths

375 differs significantly when they meet versus do not meet guidelines. While we found that window

376 treatments overall were associated with fewer collisions, façades with window treatments that

377 met guidelines significantly reduced collision risk. In comparison, when façades had window

378 treatments that did not meet guidelines, there was no significant difference in collision risk from

379 untreated windows. Additionally, when comparing predictions of collision rates with "no

380 treatment" and observed treatment collision rates, the reduction in collision rates was

381 significantly lower when window treatments did not meet guidelines.

382 *Façade-level drivers of collision risk*

383   We found significant façade-level effects from building and environmental features on

384 bird–window collisions, with non-linear effects for glass area and the interaction between canopy

385 and vegetation. We found more collisions at façades with increased glass area, similar to other

17

386   studies that found increased collision-glass relationships at both the building-level (Klem et al.

387   2009, Gelb and Delacretaz 2009, Elmore et al. 2021) and façade-level (Riding et al. 2019, Zulian

388   et al. 2023). Collision risk increased significantly with glass area from the lowest range at ~4m²

389   up to an area of 700m², after which, the average risk remained stable and high. We found that

390   façade height had a significant negative relationship with collision risk, suggesting that the first

391   30m of façade height with glass covering 4–700m^2 pose the greatest collision risk. At the

392   building-level, greater building size and height have increased collision risk (Hager et al. 2017,

393   Elmore et al. 2021), though these high collision counts are better explained by landscape context

394   than height (Gómez-Martínez and MacGregor-Fors 2025). It is possible the difference in our

395   findings is also related to scale where the façade-level relationship with height may reflect that

396   façades <30m are more likely to have vegetation or canopy visible through transparent glass or

397   reflected in building glass, resulting in more collisions (Zulian et al. 2023). However, we could

398   not determine this without measurements of canopy height. Additionally, we found that reflective

399   and transparent glass, particularly at walkways with habitat visible from both sides, significantly

400   increased collision risk compared to non-reflective glass. Mirrored glass has been associated

401   with increased collisions (Evans Ogden 2002, Klem et al. 2009, Brown et al. 2019) but this was

402   not supported in our analyses. Though understudied as a driver of window-collisions, some

403   studies found no difference in collisions between transparent and reflective glass (Klem et al.

404   2009, Anderson 2018), but Ocampo-Peñuela et al. (2016b) attributed the high number of

405   collisions at their deadliest building to two transparent glass-walkways. Our findings suggest that

406   prioritizing façades with 4–700m^2 of transparent or reflective glass within the first 30m of the

407   façade height for bird-friendly window treatments would be the most effective in reducing

408   collision risk.

409   Environmental features significantly influenced collision risk at the façade-level. We

410   found the interaction between surrounding canopy and vegetation had a significant effect on

411   increased collision risk. This could suggest that both vegetation and canopy draw birds into an

412   area where collisions are more likely to occur (Loss et al. 2019) and that stratified habitat use by

413   birds moving between lawn, shrub, and canopy results in increased collisions. Canopy may

414   directly cause more collisions than vegetation, as we found that canopy alone significantly

415   increased collision risk while vegetation alone did not. In conjunction with building features that

416   drive collisions, the reflections and images of surrounding canopy may drive increased collisions

417   (Borden et al. 2010, Brown et al. 2019, Zulian et al. 2023) compared to understory vegetation

418   like shrubs which are less likely to be reflected in glass. At the building-level, collisions have

419   been found to increase with higher amounts of vegetation and canopy cover (Hager et al. 2013,

420   2017, Cusa et al. 2015, Loss et al. 2019). Our findings suggest even low amounts (~0–40%) of

421   both variables relative to the surrounding urban area have a strong effect on collision risk. Given

422   these effects, treating windows at facades adjacent to landscaping and tree canopy would avoid

423   unintended negative consequences of these environmental features.

424   Proximity to water could increase collision risk by drawing birds into an area where

425   collisions are more likely to occur, although there has been limited support for the effect of water

426   on collisions (Loss et al. 2014, Nicols et al. 2018). Though non-significant, we found collision

427   risk to increase non-linearly with distance to water and was highest in areas further away from

428   water like an urban centre. It is possible the strength of this effect was influenced by the presence

429   of three large waterbodies in our study area, or by canopy near riparian edges masking an effect

430   from water on collisions.

431   *Efficacy of window treatments*

432   Understanding how to reduce bird–window collisions is needed to prevent up to a billion

433 bird fatalities yearly in the U.S. alone. We found that collision risk did not differ between treated

434 windows that did not meet guidelines and untreated windows. In contrast, when windows were

435 treated to meet guidelines, we found a significant two-fold decrease in collision risk compared to

436 untreated windows, with an expected 98.4% reduction in collision rates, supporting the efficacy

437 of window treatments that meet guidelines to reduce collisions in real-world settings (Brown et

438 al. 2021, De Groot et al. 2022, Riggs et al. 2022a). In comparison, we found no significant

439 difference in collision risk between untreated windows and windows with treatments that did not

440 meet guidelines. While there was an expected 76.3% reduction in collision rates for window

441 treatments did not meet guidelines, this was significantly lower than that of window treatments

442 that met guidelines.

443   Previous field studies investigating collision rates before and after window treatment

444 have found that window treatments that met guidelines reduced collisions by 92% at two

445 university campus buildings (Brown et al. 2021), by 95% at a low-rise building in a wildlife

446 management area (De Groot et al. 2022), and by 92% at transparent glass bus shelters (Riggs et

447 al. 2022a). Our results expand on these studies by showing window treatment efficacy across a

448 range of sites and conditions (Riding et al. 2019, Elmore et al. 2021, De Groot et al. 2022).

449 While studies on buildings comparing the efficacy of window treatments that do not meet

450 guidelines are limited (but see Oviedo and Menacho-Odio 2015, Brisque et al. 2017, Ribeiro and

451 Piratelli 2020), they support our findings that windows treated with methods that do not meet

452 guidelines do not effectively reduce collision risk. Window treatments that meet guidelines can

453 effectively reduce collision risk and prevent collisions across buildings with varying degrees of

454 collision risk.

Limitations and strengths

456   While this study was place-based, its standardized approach across a large urban area

457   renders the findings broadly applicable and adds to the current state of knowledge on solutions to

458   bird–window collisions. We found façade-level effects on collisions from building and

459   environmental features but were unable to incorporate other factors like canopy height or the

460   amount of canopy or vegetation reflected in glass that could reveal finer aspects of collision risk.

461   Species respond to collision risks differently depending on their life-history, morphological traits,

462   or behaviours (Cusa et al. 2015, Loss et al. 2019, Elmore et al. 2021), leading to differences in

463   species vulnerability to collisions (Arnold and Zink 2011, Loss et al. 2014) which we were

464   unable to assess. We did not consider the effect of artificial light at night in the scope of this

465   study, which could have drawn in migrating birds and increased collision risk (Lao et al. 2020).

466   We recognize our counterfactual predictions are likely imperfect despite efforts to build the best

467   predictive model with the available data. However, our analysis represents an underestimate of

468   mortalities occurring because we were unable to account for carcasses removed by scavengers

469   prior to our surveys and imperfect carcass detection by surveyors. As window treatments are

470   implemented, robust documentation of collision rates before-and-after treatment can reveal

471   further nuances in window treatment efficacy in real-world settings and differences when

472   guidelines are met or not.

473   *Conclusion and conservation implications*

474   In the built environment, there are features of buildings and the surrounding landscape

475   that pose significant collision risk to birds. Clear, evidence-based standards and guidelines exist

476   on how to effectively prevent bird–window collisions with window treatments (City of Ottawa

477   2022, CSA A460:19). However, these guidelines are rarely mandatory, and our findings support

478   recommendations to make guidelines mandatory for window treatment efforts to ensure they

479   effectively reduce collision risk. Our results can help guide enforcement of the updated

480   Migratory Birds Regulations (2022) under the *MBCA* (*Migratory Birds Convention Act*, s.c.

481   1994, c. 22) where bird deaths from collisions with windows may be deemed as a contravention

482   of the Act. Our results demonstrate that window treatments that do not meet guidelines likely

483   will not significantly reduce collision risk and thus may not represent "due diligence" to prevent

484   harm to migratory birds.

485   We recognize that there are many constraints and barriers to treating windows effectively

486   (Lysyk and Khan et al. 2026). Improved access to standards and guidelines for effective window

487   treatments would support architects, urban planners, decision makers, and other stakeholders in

488   implementing treatments effectively (Riggs et al. 2022b, Loss et al. 2023). These stakeholders,

489   along with homeowners have also identified that policy makers and governance should play a

490   role in preventing window collisions including improved guidelines and potential incentives or

491   subsidies to alleviate costs (Warren 2013, Riggs et al. 2022b, Lysyk and Khan et al. 2026). To

492   improve efforts to treat windows at residences, our findings that window treatments applied

493   according to guidelines reduce bird–window collisions can support efficacy-based messaging,

494   which is the most effective messaging type to bird-enthusiasts (Carlson and Philips 2025). In

495   developing bird-safe policies, our findings can help prioritize efforts to treat buildings by

496   identifying high-risk areas of building façades. Our finding that window treatments not meeting

497   guidelines does not effectively reduce collision risk can avoid potential social implications that

498   may be associated with "greenwashing" through sustainable development or urban greening

499   initiatives. Often, buildings with environmental or sustainable certifications do not incorporate

500   bird-friendly designs despite posing high collision risk either through building or landscaping

501   features (Ocampo-Peñuela et al. 2016, Menacho-Odio 2018, Schneider et al. 2018). New glass

502   technology reduces energy costs, while green spaces benefit people by improving mental health,

503   local biodiversity, and providing important habitat and resources to wildlife including migratory

504   birds (Poirier et al. 2024b, Buxton et al. 2024). Treating windows with bird-safe measures that

505   meet guidelines can avoid unintended negative consequences to biodiversity from urban

506   developments that benefit people. When implementing window treatments to prevent bird–

507   window collisions, following bird-safe guidelines can achieve this more effectively than

508   deviations from bird-safe guidelines.

518   **References**

519   Anderson, A. W. 2018. Modeling bird-window collisions in core urban environments. M.Sc
520   Thesis, University of Minnesota Twin Cities, Minneapolis Saint Paul, Minnesota, United
521   States of America.

522   Arel-Bundock, V., N. Greifer, and A. Heiss. 2024. How to interpret statistical models using
523   marginal effects for R and Python. Journal of Statistical Software 111:1–32.

524   Arnold, T. W., and R. M. Zink. 2011. Collision mortality has no discernible effect on population
525   trends of North American birds. PLoS ONE 6.

526   Bianchini, K., B. Frei, A. R. Cox, and C. Roy. 2025. Evaluating occurrence and abundance of
527   displaying male American woodcock (*Scolopax minor*) north of the current Singing-
528   Ground Survey range. The Journal of Wildlife Management 1–28

529   Borden, W. C., O. M. Lockhart, A. W. Jones, and M. S. Lyons. 2010. Seasonal, taxonomic, and
530   local habitat components of bird-window collisions on an urban university campus in
531   Cleveland, OH. Ohio Journal of Science 110:44–52.

532   Breiman, L. 2001. Random Forests. Machine Learning 45:5–32.

533   Brown, B. B., E. Kusakabe, A. Antonopoulos, S. Siddoway, and L. Thompson. 2019. Winter
534   bird-window collisions: Mitigation success, risk factors, and implementation challenges.
535   PeerJ.

536   Brown, B. B., S. Santos, and N. Ocampo-Peñuela. 2021. Bird-window collisions: Mitigation
537   efficacy and risk factors across two years. PeerJ 9:1–23.

538   Burnham, K. P., and D. R. Anderson, editors. 2002. Formal inference from more than one model:
539   Multimodel Inference (MMI). Pages 149–205 Model Selection and Multimodel
540   Inference. Springer New York, New York, NY.

541   Buxton, R. T., E. J. Hudgins, E. Lavigne, P. J. Villeneuve, S. A. Prince, A. L. Pearson, T. Halsall,
542   C. Robichaud, and J. R. Bennett. 2024. Mental health is positively associated with
543   biodiversity in Canadian cities. Communications Earth & Environment 5:310.

544   Calvert, A. M., C. A. Bishop, R. D. Elliot, E. A. Krebs, T. M. Kydd, C. S. Machtans, and G. J.
545   Robertson. 2013. A synthesis of human-related avian mortality in Canada. Avian
546   Conservation and Ecology 8.

547   Campbell, M. O. N. 2009. The impact of habitat characteristics on bird presence and the
548   implications for wildlife management in the environs of Ottawa, Canada. Urban Forestry
549   and Urban Greening 8:87–95.

550   Canadian Standards Association Group. CSA A460:19. 2019. Bird-friendly building design.

551   Carlson, S. C., and T. B. Philips. 2025. Mitigating collision-caused bird mortality through
552   message faming: Insights from residents' intentions for bird-safe windows. Biological
553   Conservation 312.

554   Chawla, N. V., K. W. Bowyer, L. O. Hall, and W. P. Kegelmeyer. 2002. SMOTE: Synthetic
555   Minority Over-sampling Technique. Journal of Artificial Intelligence Research 16:321–
556   357.

557 City of Ottawa. 2022. Bird-Safe Design Guidelines. Available from:
558   https://documents.ottawa.ca/sites/default/files/birdsafedesign_guidelines_en.pdf.
559   Accessed September 23, 2024.

560 City of Ottawa Open Data. Water [Shapefile geospatial data]. Updated October 28, 2024.
561   https://open.ottawa.ca/maps/cf115a7a107f4938afb934ca7fe4f10c/explore?location=45.39
562   8410%2C-75.735318%2C5.66. Accessed November 27, 2024.

563 City of Ottawa Open Data. 3D Buildings LOD1 [Shapefile geospatial data]. Jean-Francoise
564   Dionne. Created using Esri ArcGIS 13.0.3.36057. Accessed June 26, 2023.

565 City of Ottawa Open Data. Forest Canopy Cover [Shapefile geospatial data]. Updated July 8,
566   2024. https://open.ottawa.ca/maps/ottawa::forest-canopy-
567   cover/explore?location=45.419108%2C-75.698637%2C7.56. Accessed November 27,
568   2024.

569 City of Ottawa Orthophotos 1928-2022. Ottawa, 2022. Available: Carleton University GIS
570   Library. Accessed September 12, 2024.

571 City of Toronto. Bird-friendly Guidelines. 2016. Available from:
572   https://www.toronto.ca/citygovernment/planning-development/official-plan-
573   guidelines/design-guidelines/bird-friendlyguidelines/. Accessed September 23, 2024.

574 Colling, O. M., C. G. Guglielmo, S. J. Bonner, and Y. E. Morbey. 2022. Migratory songbirds and
575   urban window collision mortality: vulnerability depends on species, diel timing of
576   migration, and age class. Avian Conservation and Ecology 17.

577 COSEWIC. 2012. COSEWIC assessment and status report on the Wood Thrush *Hylocichla*
578   *mustelina* in Canada. Committee on the Status of Endangered Wildlife in Canada.
579   Ottawa. ix + 46 pp.

580 COSEWIC. 2021. COSEWIC assessment and status report on the Barn Swallow *Hirundo rustica*
581   in Canada. Committee on the Status of Endangered Wildlife in Canada. Ottawa. ix + 37
582   pp.

583 Cusa, M., D. A. Jackson, and M. Mesure. 2015. Window collisions by migratory bird species:
584   urban geographical patterns and habitat associations. Urban Ecosystems 18:1427–1446.

585 Day, R. W., and G. P. Quinn. 1989. Comparisons of treatments after an analysis of variance in
586   ecology. Ecological Monographs 59:433–463.

587 De Groot, K. L., A. N. Porter, A. R. Norris, A. C. Huang, and R. Joy. 2021. Year-round
588   monitoring at a Pacific coastal campus reveals similar winter and spring collision
589   mortality and high vulnerability of the Varied Thrush. Ornithological Applications 123:1–
590   15.

591 De Groot, K. L., A. G. Wilson, R. McKibbin, S. A. Hudson, K. M. Dohms, A. R. Norris, A. C.
592   Huang, I. B. J. Whitehorne, K. T. Fort, C. Roy, J. Bourque, and S. Wilson. 2022. Bird
593   protection treatments reduce bird-window collision risk at low-rise buildings within a
594   Pacific coastal protected area. PeerJ:1–17.

595 DMTI Spatial Inc. Building Footprints Region - 2023. Markham Ontario, Canada. Created using
596   Esri ArcGIS 10.6.1. Updated November 9, 2023. Accessed November 27, 2024.

597 Elmore, J. A., S. B. Hager, B. J. Cosentino, T. J. O'Connell, C. S. Riding, M. L. Anderson, M. H.
598   Bakermans, T. J. Boves, D. Brandes, E. M. Butler, M. W. Butler, N. L. Cagle, R.
599   Calderón-Parra, A. P. Capparella, A. Chen, K. Cipollini, A. A. T. Conkey, T. A. Contreras,
600   R. I. Cooper, C. E. Corbin, R. L. Curry, J. J. Dosch, K. L. Dyson, E. E. Fraser, R. A.
601   Furbush, N. D. G. Hagemeyer, K. N. Hopfensperger, D. Klem, E. A. Lago, A. S. Lahey,
602   C. S. Machtans, J. M. Madosky, T. J. Maness, K. J. McKay, S. B. Menke, N. Ocampo-
603   Peñuela, R. Ortega-Álvarez, A. L. Pitt, A. Puga-Caballero, J. E. Quinn, A. M. Roth, R. T.
604   Schmitz, J. L. Schnurr, M. E. Simmons, A. D. Smith, C. W. Varian-Ramos, E. L. Walters,
605   L. A. Walters, J. T. Weir, K. Winnett-Murray, I. Zuria, J. Vigliotti, and S. R. Loss. 2021.
606   Correlates of bird collisions with buildings across three North American countries.
607   Conservation Biology 35:654–665.

608 Environment and Climate Change Canada. 2023a. Priority Places for Species at Risk.
609   https://www.canada.ca/en/services/environment/wildlife-plants-species/species-risk/pan-
610   canadian-approach.html#toc1. Accessed January 15, 2026.

611 Environment and Climate Change Canada. 2023b. Breeding Bird Survey instructions.
612   Government of Canada. Available from: https://www.canada.ca/en/environment-climate-
613   change/services/bird-surveys/landbird/north-american-breeding/instructions.html.
614   Accessed September 3, 2023.

615 Environmental Systems Research Institute. ArcGIS Pro. Version 3.1.0. Redlands, CA:
616   Environmental Systems Research Institute. 2023.

617 Environmental Systems Research Institute. ArcGIS Online Survey123. Version 3.24.23.
618   Redlands, CA: Environmental Systems Research Institute. 2025.

619 Evans Ogden, L. 2002. Summary Report on the Bird Friendly Building Program: Effect of Light
620   Reduction on Collision of Migratory Birds.

621 Fatal Light Awareness Program (FLAP) Canada. BirdSafe DIY Building Risk Assessment. 2022.
622   BirdSafe©. FLAP Canada, Toronto, Ontario, Canada. https://www.flapapp.ca/. Accessed
623   March 11, 2025.

624 Fewster, R. M., S. T. Buckland, G. M. Siriwardena, S. R. Baillie, and J. D. Wilson. 2000.
625   Analysis of population trends for farmland birds using generalized additive models.
626   Ecology 81:1970–1984.

627   Fischer, S. and K. Islam. 2020. Identifying bird-window collisions on a university campus during
628   spring and fall migration. Proceedings of the Indiana Academy of Science 129:47–55.

629   Frei, B., A.R. Cox, A. Brown, M.R. Dyson, S. Meyer, A. Hanson, K. Hick, S.G. Gilliland, C.
630   Lepage, M. Tétreault, and C. Roy. 2024. Uncovering habitat association and thresholds –
631   insights for managing breeding waterfowl in Eastern Canada. Landscape Ecology 39.
632   doi.org/10.1007/s10980-024-01946-5

633   Gelb, Y. and N. Delacretaz. 2009. Windows and vegetation: Primary factors in Manhattan bird
634   collisions. Northeastern Naturalist 16:455–470.

635   Gómez-Martínez, M. A., and I. MacGregor-Fors. 2025. A tale of deadly strikes: A century-long
636   literature review of bird-window collisions. Animal Biodiversity and Conservation 48.2.

637   Hager, S. B., B. J. Cosentino, M. A. Aguilar-Gómez, M. L. Anderson, M. Bakermans, T. J.
638   Boves, D. Brandes, M. W. Butler, E. M. Butler, N. L. Cagle, R. Calderón-Parra, A. P.
639   Capparella, A. Chen, K. Cipollini, A. A. T. Conkey, T. A. Contreras, R. I. Cooper, C. E.
640   Corbin, R. L. Curry, J. J. Dosch, M. G. Drew, K. Dyson, C. Foster, C. D. Francis, E.
641   Fraser, R. Furbush, N. D. G. Hagemeyer, K. N. Hopfensperger, D. Klem, E. Lago, A.
642   Lahey, K. Lamp, G. Lewis, S. R. Loss, C. S. Machtans, J. Madosky, T. J. Maness, K. J.
643   McKay, S. B. Menke, K. E. Muma, N. Ocampo-Peñuela, T. J. O'Connell, R. Ortega-
644   Álvarez, A. L. Pitt, A. L. Puga-Caballero, J. E. Quinn, C. W. Varian-Ramos, C. S. Riding,
645   A. M. Roth, P. G. Saenger, R. T. Schmitz, J. Schnurr, M. Simmons, A. D. Smith, D. R.
646   Sokoloski, J. Vigliotti, E. L. Walters, L. A. Walters, J. T. Weir, K. Winnett-Murray, J. C.
647   Withey, and I. Zuria. 2017. Continent-wide analysis of how urbanization affects bird-
648   window collision mortality in North America. Biological Conservation 212:209–215.

649   Hager, S. B., B. J. Cosentino, K. J. McKay, C. Monson, W. Zuurdeeg, and B. Blevins. 2013.
650   Window area and development drive spatial variation in bird-window collisions in an
651   urban landscape. PLoS ONE 8.

652   Hager, S. B., and M. E. Craig. 2014. Bird-window collisions in the summer breeding season.
653   PeerJ 2014.

654   Hager, S., and B. Cosentino. 2014. Surveying for bird carcasses resulting from window
655   collisions: a standardized protocol. PeerJ PrePrints:1–11.

656   Kahle, L. Q., M. E. Flannery, and J. P. Dumbacher. 2016. Bird-window collisions at a west-coast
657   urban park museum: Analyses of bird biology and window attributes from golden gate
658   Park, San Francisco. PLoS ONE 11:1–23.

659   Klem, D. 1989. Bird –window collisions. The Wilson Bulletin 101:606–620.

660   Klem, D., C. J. Farmer, N. Delacretaz, Y. Gelb, and P. G. Saenger. 2009. Architectural and
661   landscape risk factors associated with bird-glass collisions in an urban environment.
662   Wilson Journal of Ornithology 121:126–134.

663   Klem, D., D. C. Keck, K. L. Marty, A. J. Miller Ball, E. E. Niciu, and C. T. Platt. 2004. Effects of
664   window angling, feeder placement, and scavengers on avian mortality at plate glass.
665   Wilson Bulletin 116:69–73.

666   Klem, D., and P. G. Saenger. 2013. Evaluating the effectiveness of select visual signals to
667   prevent bird-window collisions. Wilson Journal of Ornithology 125:406–411.

668   Klem, D. 2025. Bird-window collisions: An attempt to inspire and encourage more research and
669   advocacy. Animal Biodiversity and Conservation 48.2.

670   Kraus, D., and A. Hebb. 2020. Southern Canada's crisis ecoregions: identifying the most
671   significant and threatened places for biodiversity conservation. Biodiversity and
672   Conservation 29:3573–3590.

673   Kuhn, M., and H. Wickham. 2020. Tidymodels: a collection of packages for modeling and
674   machine learning using tidyverse principles.

675   Lao, S., A. W. Anderson, R. B. Blair, J. W. Eckles, R. J. Turner, and S. R. Loss. 2023. Bird–
676   building collisions increase with weather conditions that favor nocturnal migration and
677   with inclement and changing weather. Ornithological Applications 125:1–12.

678   Lao, S., B. A. Robertson, A. W. Anderson, R. B. Blair, J. W. Eckles, R. J. Turner, and S. R. Loss.
679   2020. The influence of artificial night at night and polarized light on bird-building
680   collisions. Biological Conservation 241:108358.

681   Loss, S. R., S. Lao, J. W. Eckles, A. W. Anderson, R. B. Blair, and R. J. Turner. 2019. Factors
682   influencing bird-building collisions in the downtown area of a major North American
683   city. PLoS ONE 14:1–24.

684   Loss, S. R., B. V. Li, L. C. Horn, M. R. Mesure, L. Zhu, T. G. Brys, A. M. Dokter, J. A. Elmore,
685   R. E. Gibbons, T. Z. Homayoun, K. G. Horton, P. Inglet, B. J. Jones, T. Keys, S. Lao, S.
686   S. Loss, K. L. Parkins, H. L. Prestridge, G. J. Riggs, C. S. Riding, K. R. I. Sweezey, A. C.
687   Vallery, B. M. Van Doren, J. Wang, C. Zuzula, and A. Farnsworth. 2023. Citizen science
688   to address the global issue of bird–window collisions. Frontiers in Ecology and the
689   Environment:418–427.

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

692   Lysyk, A. J. V., A. I. Khan, D. Conners, and R. T. Buxton. 2026. Barriers and opportunities to
693   preventing residential bird–window collisions. PLoS ONE 21:e0342330.

694   Machtans, C. S., C. H. R. Wedeles, and E. M. Bayne. 2013. A first estimate for Canada of the
695   number of birds killed by colliding with building windows. Avian Conservation and
696   Ecology 8:6.

697   Menacho-Odio, R. M. 2018. Local perceptions, attitudes, beliefs, and practices toward bird-
698   window collisions in Monteverde, Costa Rica. UNED Research Journal 10.

699   *Migratory Birds Convention Act, 1994. s.c. 1994, c. 22*

700   *Migratory Birds Regulations, 2022. SOR/2022-105*.

701   Murphy, M. A., J. S. Evans, and A. Storfer. 2010. Quantifying *Bufo boreas* connectivity in
702   Yellowstone National Park with landscape genetics. Ecology 91:252–261.

703   Nichols, K. S, T. Homayoun, J. Eckles, and R.B. Blair. 2018. Bird-building collision risk: An
704   assessment of the collision risk of birds with buildings by phylogeny and behavior using
705   two citizen-science datasets. PLoS ONE 13.

706   Ocampo-Peñuela, N., R. S. Winton, C. J. Wu, E. Zambello, T. W. Wittig, and N. L. Cagle. 2016.
707   Patterns of bird-window collisions inform mitigation on a university campus. PeerJ.

708   Osborne, J. 2024a. Bird Window Collision Study Protocol: Surveying for building facade
709   attributes. [pdf, provided by author].

710   Osborne, J. 2024b. Bird Window Collision Study Protocol: Analysing images for building facade
711   attributes. [pdf, provided by author].

712   Oviedo, S., and R. M. Menacho-Odio. 2015. Actitud en la preferencia de metodos para evitar el
713   choque de aves contra puertas y ventanas de vidrio en Costa Rica. Zeledonia 19.

714   R Core Team. 2020. R: A language and environment for statistical computing. R Foundation for
715   Statistical Computing, Vienna, Austria.

716   Poirier, V., B. Frei, M. Lefvert, A. Morales, and K. H. Elliott. 2024a. Moult migrant Tennessee
717   Warblers undergo extensive stopover in peri-urban forests of southern Québec. Canadian
718   Journal of Zoology 102:272–285.

719   Poirier, V., K. H. Elliott, and B. Frei. 2024b. Peri-urban forest margins are important stopover
720   sites for moult-migrating songbirds. Journal for Nature Conservation 77:126539.

721   Riding, C. S., and S. R. Loss. 2018. Factors influencing experimental estimation of scavenger
722   removal and observer detection in bird–window collision surveys. Ecological
723   Applications 28:2119–2129.

724   Riding, C. S., T. J. O'Connell, and S. R. Loss. 2019. Building façade-level correlates of bird-
725   window collisions in a small urban area. Condor 122:1–14.

726 Riggs, G. J., C. M. Barton, C. S. Riding, T. J. O'Connell, and S. R. Loss. 2022a. Field-testing
727   effectiveness of window markers in reducing bird-window collisions. Urban Ecosystems
728   26:713–723.

729 Riggs, G. J., O. Joshi, and S. R. Loss. 2022b. Stakeholder perceptions of bird-window collisions.
730   PLoS ONE 17:1–20.

731 Rössler, M., E. Nemeth, and A. Bruckner. 2015. Glass pane markings to prevent bird-window
732   collisions: Less can be more. Biologia (Poland) 70:535–541.

733 Safe Wings Ottawa. 2025. Collisions in Ottawa. Ottawa, Canada. Available from:
734   https://safewings.ca/faqs/collisions-in-ottawa/. Accessed June 7, 2025.

735 Schneider, C. A., W. S. Rasband, and K. W. Eliceiri. 2012. NIH Image to ImageJ: 25 years of
736   image analysis. Nature Methods 9:671–675.

737 Schneider, R. M., C. M. Barton, K. W. Zirkle, C. F. Greene, and K. B. Newman. 2018. Year-
738   round monitoring reveals prevalence of fatal bird-window collisions at the Virginia Tech
739   Corporate Research Center. PeerJ 2018:1–19.

740 Sheppard, C. D. 2019. Evaluating the relative effectiveness of patterns on glass as deterrents of
741   bird collisions with glass. Global Ecology and Conservation 20.

742 Siders, Z., N. Ducharme-Barth, F. Carvalho, D. Kobayashi, S. Martin, J. Raynor, T. Jones, and R.
743   Ahrens. 2020. Ensemble Random Forests as a tool for modeling rare occurrences.
744   Endangered Species Research 43:183–197.

745 Simpson, G. 2024. gratia: Graceful ggplot-Based Graphics and Other Functions for GAMs Fitted
746   using mgcv.

747 *Species at Risk Act, s.c. 2002, c. 29*

748 Statistics Canada. 2023. [Table]. Census profile. 2021 Census of Population. Statistics Canada
749   Catalogue no 98-316-X2021001. Ottawa. Available from:
750   https://www12.statcan.gc.ca/census-recensement/2021/dp-pd/prof/index.cfm?Lang=E.
751   Accessed January 14, 2026.

752 Swaddle, J. P., B. Brewster, M. Schuyler, and A. Su. 2023. Window films increase avoidance of
753   collisions by birds but only when applied to external compared with internal surfaces of
754   windows. PeerJ 11.

755 Ville Saint-Laurent, Montréal. 2024. Règlement numéro RCA08-08-0001-169 modifiant le
756   règlement numéro RCA08-08-0001 sur le zonage.

757 Warren, E. J. 2013. A clear threat to conservation: Using public policy to reduce bird collisions
758   with windows in homes. M.P.P. Thesis, Simon Fraser University, Burnaby, British
759   Columbia.

760   Wood, S. 2011. Fast stable restricted maximum likelihood and marginal likelihood estimation of
761   semiparametric generalized linear models. Journal of the Royal Statistical Society (B)
762   73:3–36.

763   Wright, M., and A. Ziegler. 2017. ranger: A fast implementation of random forests for high
764   dimensional data in C++ and R. Journal of Statistical Software 77:1–17.

765   Zulian, V., A. R. Norris, K. L. Cockle, A. N. Porter, L. G. Do, and K. L. De Groot. 2023.
766   Seasonal variation in drivers of bird-window collisions on the west coast of British
767   Columbia, Canada. Avian Conservation and Ecology 18.

768   Zulian, V., L. K. Blight, J. Obsorne, A. C. Smith, A. R. Norris, R. Golat, and K. L. De Groot.
769   2025. Seasonally frugivorous forest birds and window collision fatalities: novel
770   integration of bird counts in fall improves assessment of species vulnerability to
771   collisions. PeerJ.

772   Zuur, A. F., E. N. Ieno, N. J. Walker, A. A. Saveliev, and G. M. Smith. 2009. Mixed effects
773   models and extensions in ecology with R. Springer New York.

774 **Tables and Figures**

775 Table 1. Model selection table of candidate generalized additive mixed models (GAMMs)
776 evaluating factors influencing bird-window collisions ranked using Akaike's information
777 criterion adjusted for small sample sizes (AICc).

Variables	df	-logLik	AICc	ΔAICc	Weight[i]	Dev.[ii]
Season + reflectivity + treatment + glass area + façade height + vegetation + canopy + vegetation:canopy	45	-250.44	597.0	0.00	0.55	32.9%
Season + reflectivity + treatment + glass area + façade height + water + vegetation + canopy + vegetation:canopy	44	-252.47	598.0	1.05	0.32	32.4%
Season + reflectivity + treatment + glass area + water + vegetation + canopy + vegetation:canopy	42	-255.74	600.2	3.18	0.11	31.6%
Season + reflectivity + treatment + direction + glass area + façade height + water + vegetation + canopy + vegetation:canopy	46	-251.88	602.7	5.68	0.03	32.5%
Null (intercept only)	43	-285.40	662.5	65.49	0.00	24.3%

778

[i] Akaike weight used in model selection
[ii] Percent deviance explained by each model

779　Table 2. Summary of variables from the final generalized additive mixed model (GAMM) used
780　to investigate influences of variables on bird–window collision rates in Ottawa, Ontario, Canada
781　in 2024 and 2025 with significant variables in **bold** (p-value < 0.05).

Parametric coefficients

Variables	Estimate	Std. Error	t-value	*p*-value
Intercept	-5.31	0.53	-10.09	**2.0×10^{-16}**
Treatment did not meet guidelines	-0.33	0.31	-1.08	0.282
Treatment met guidelines	-2.24	0.74	-3.01	**0.003**
Season: spring	-0.31	0.13	-2.32	**0.021**
Reflective glass	1.21	0.55	2.22	**0.027**
Transparent glass	1.60	0.55	2.91	**0.004**
Mirrored glass	1.06	0.56	1.90	0.576

Approximate significance of smooth terms

	EDF[i]	Ref. df[ii]	F-statistic	*p*-value
Glass area	5.28	6.25	6.62	**5.54×10^{-7}**
Proportion canopy	1.00	1.00	8.22	**0.004**
Proportion vegetation	1.00	1.00	0.46	0.499
Vegetation:canopy (tensor interaction)	2.71	3.52	4.32	**0.003**
Distance to water	2.23	2.56	2.99	0.055
Façade height	1.00	1.00	3.86	**0.050**
Coordinates (tensor interaction)	1.00	1.00	1.23	0.268
Building ID	16.75	61.00	0.55	**<0.001**

782

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[i] EDF = effective degrees of freedom for the spline representing each variable
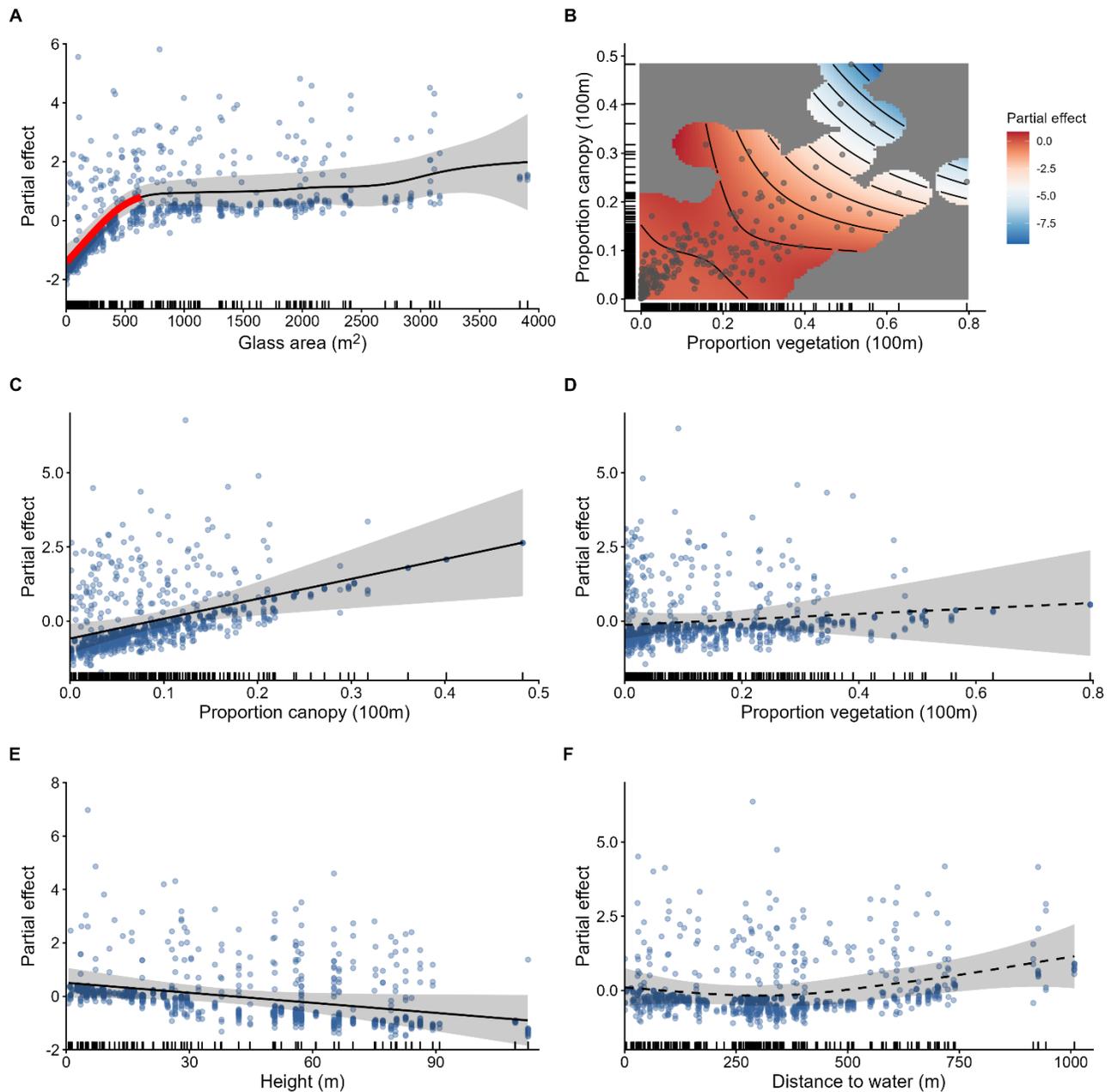[ii] Reference degrees of freedom used in the statistical test of "no smooth" for each smooth variable

Figure 1. Partial effects plots of the fitted splines from the final generalized additive mixed model for glass area (m²) with the significant rate of change indicated with a thick red line (a), the interaction between proportion vegetation and proportion canopy within 100m buffer of the facade edge (b), proportion canopy (c), proportion vegetation (d), façade height (m) (e), and distance to water (m) (f) on collision rates with non-significant effects shown with a dashed line (points show partial residuals, shaded areas indicate ± 95% confidence interval, and tick marks on the x-axis indicate variable values recorded at each façade).

A
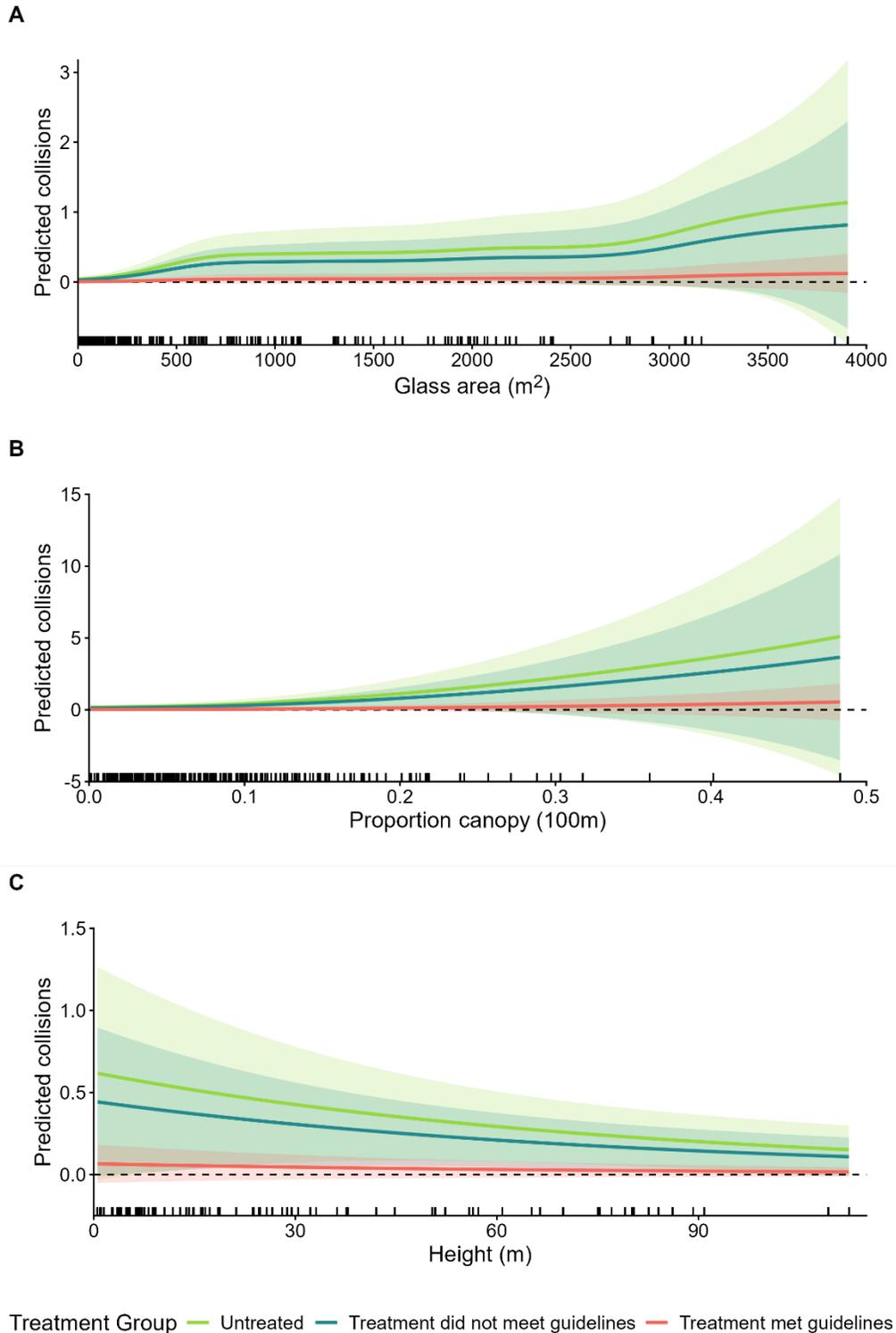

B

C

Treatment Group — Untreated — Treatment did not meet guidelines — Treatment met guidelines

Figure 2. Plots of conditional predictions for individual effects from glass area (m²) (a), proportion canopy within a 100m buffer (b), and façade height (m) (c) by treatment group from the final generalized additive mixed model on collision rates recorded for Ottawa, Ontario, Canada during the spring and fall of 2024-2025 (shaded areas indicate ± 95% confidence intervals and tick marks on the x-axis indicate variable values recorded at each facade).
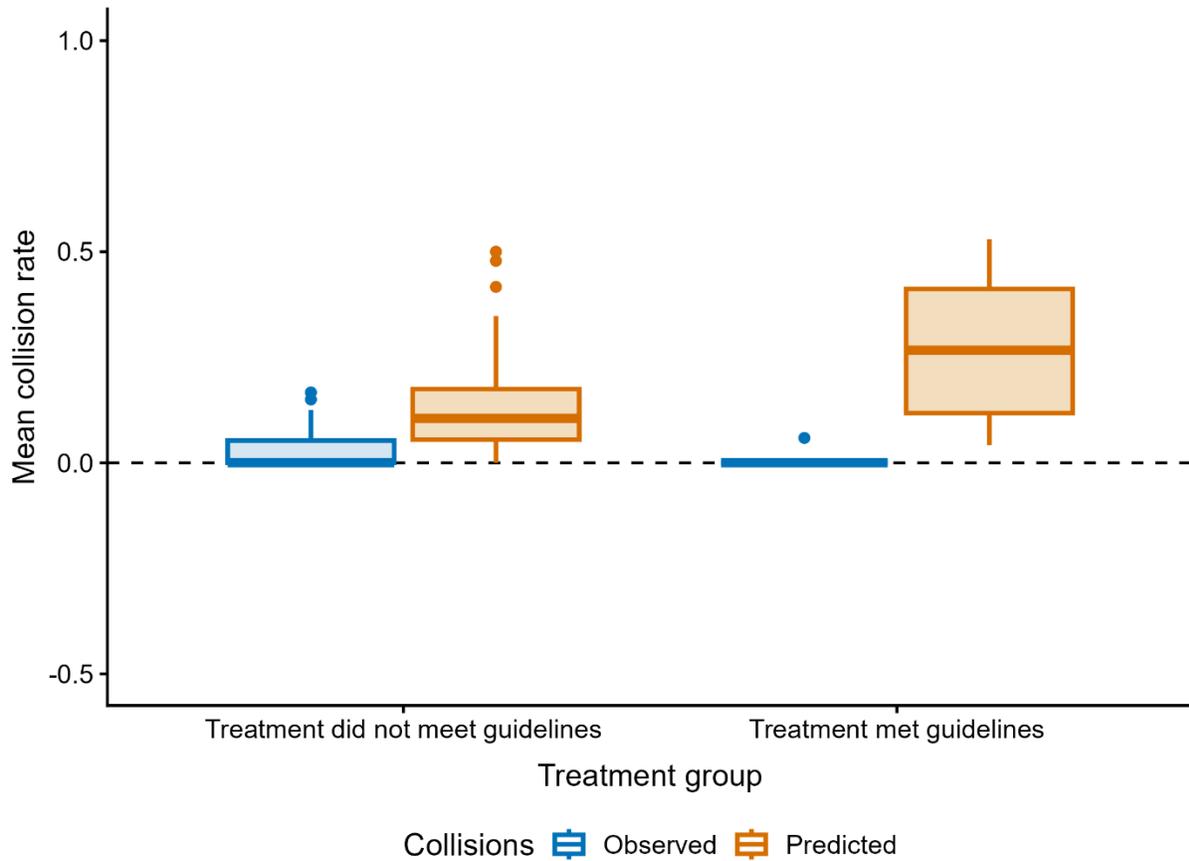
Figure 3. Boxplot of mean collision rates for predicted "no treatment" (orange) and observed "treatment" (blue) values for all façades, showing a significantly lower observed collision rate than predicted (t = -6.36; df = 310.83; p <0.001, one-tailed t-test), and grouped by façades with window treatments that did not meet guidelines and façades with window treatments that met guidelines.
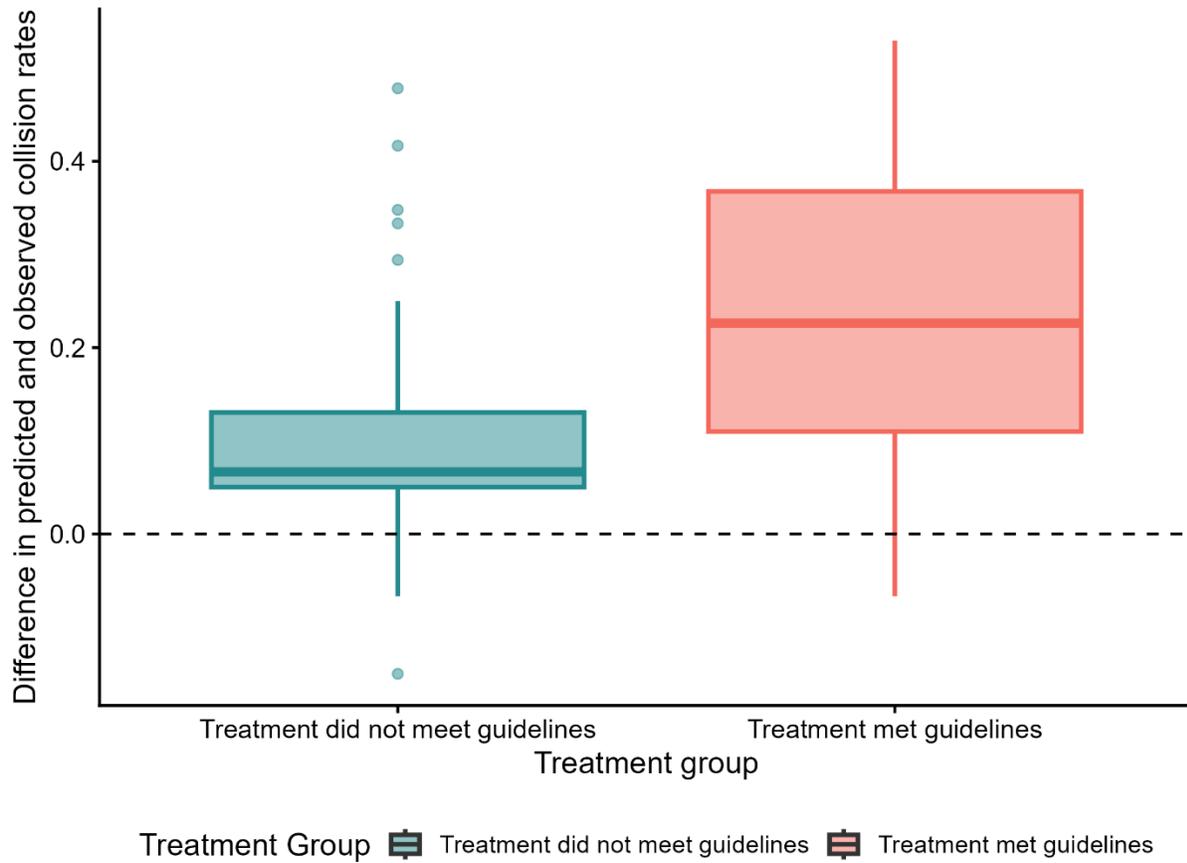
786

Figure 4. Boxplot comparing the differences in predicted "no treatment" and observed "treatment" collision rates for façades with window treatments that did not meet guidelines (blue) which was significantly lower than the difference at façades with window treatments that met guidelines (pink) (t = -2.796; df = 169.96; $p < 0.01$, one-tailed t-test).

787