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Research Paper

Civil airports from a landscape perspective: A multi-scale approach with implications for reducing bird strikes

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ABSTRACT

Collisions between birds and aircraft are a global problem that jeopardizes human safety and causes economic losses. Although landscape features have been suggested as one of a number of factors contributing to bird strikes, no evidence exists to support this suggestion. We investigated the effects of landscape structure on the adverse effect (AE) bird strike rate at 98 civil airports in the United States. The number of reported AE bird strikes was standardized by air carrier movements between 2009 and 2015. Land use structure and composition were quantified within 3, 8, and 13 km radii extents from airports. We predicted large amounts and close arrangements of aquatic habitat, open space, and high landscape diversity would positively influence the AE strike rate based on the habitat requirements of many species hazardous to aviation. The rate of AE bird strikes was positively influenced by large areas and close proximity of wetlands, water, and cultivated crops at the 8- and 13-km extents. Within 3 km of an airport, increasing landscape diversity and the amount of crop area increased the strike rate. We conclude that landscape structure and composition are predictors of the AE bird strike rate at multiple spatial scales. Our results can be used to promote collaborative management among wildlife professionals, airport planners, and landowners near airports to create an environment with a lower probability of an AE bird strike. Specific priorities are to minimize the area of crops, especially corn, and increase the distances between patches of open water.

1. Introduction

By the early 1900s, the majority of the Earth's land surface had been converted from its original state to a human modified landscape (Ellis, Klein Goldewijk, Siebert, Lightman, & Ramankutty, 2010; Sanderson et al., 2002). Human population growth fueled this landscape conversion by increasing agricultural areas and urban developments beyond the industrial revolution (Goldewijk, 2001). These land use conversions alter wildlife communities along an urban-rural gradient, and benefit generalist and invasive species in the form of increased edge habitat, abundance of human-provided resources, and landscape heterogeneity (Hansen et al., 2005; McKinney, 2002; Melbourne et al., 2007).

Ubiquitous within current human-developed landscapes are airports, which require large amounts of space; upwards of 3306 km^2 of grassland are estimated to be contained at 2915 airports in the USA (DeVault et al., 2012). Airports are generally located on the fringes of the urban-rural interfaces (DeVault et al., 2012). These locations are close enough to city centers to fulfill their transportation needs, and yet far enough away from the backyards of city residences, thus creating a buffer from this locally unwanted land use (Wexler, 1996). Airports contain large amounts of impervious surface (harboring earth worms, an important avian food source), storm water drainage ponds that are used by a variety of waterfowl, and agricultural crop areas that are maintained for extra revenue, but all are major wildlife attractants (Blackwell, Schafer, Helon, & Linnell, 2008; DeVault, Kubel, Rhodes, & Dolbeer, 2009; Seamans, Blackwell, Bernhardt, & Potter, 2015). Furthermore, the landscape surrounding the airport will be managed differently in terms of vegetation height and deterrents for wildlife, thereby enhancing the attractiveness of the airport to wildlife (Martin et al., 2011). Given these landscape properties, airports may attract wildlife which can result in wildlife-aircraft collisions (Blackwell, DeVault, Fernández-Juricic, & Dolbeer, 2009; Blackwell, Felstul, &

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Seamans, 2013; DeVault, Begier, et al., 2013). Collisions between wildlife and aircraft, hereafter referred to as strikes, have had dire consequences including 258 human lives lost since 1988 and substantial aircraft damage (Dolbeer, Wright, Weller, Anderson, & Begier, 2015). In 2015 alone, 13,797 wildlife strikes were reported to the United States of America's Federal Aviation Administration (FAA) National Wildlife Strike Database (FAA, 2016). Over $229 million USD of direct and indirect losses from bird strikes were estimated in 2015 in the U.S. (Dolbeer et al., 2015).

Manipulations of known wildlife attractants paired with wildlife dispersal, repellents, and population management may effectively reduce damaging bird strikes occurring within the airport boundaries (DeVault, Blackwell, & Belant, 2013). However, the effectiveness of these techniques are limited to areas close to the ground and are not suitable once the aircraft is beyond the airport boundary and airborne because of the lack of airport control beyond its fence line. In recent years, the number of damaging strikes that occur outside airport boundaries (> 152 m above ground level [AGL] and > 1.5 miles from runways) has increased (Dolbeer, 2011; Dolbeer, Wright, Weller, & Begier, 2014). In 2012, more damaging bird strikes were reported away from, rather than in, the airport environment for the first time (Dolbeer et al., 2014). One infamous example is the forced landing of Flight 1549 in the Hudson River, New York, USA in 2009. The aircraft departed from LaGuardia Airport (KLGA) and collided with a flock of Canada geese (*Branta canadensis*) at approximately 884 m AGL, 8 km from the airport (Marra et al., 2009). An analysis of the species composition of birds involved in off-airport strikes found that waterbirds (cormorants, ducks, geese, and gulls) and raptors (including vultures) were most likely to cause damage when struck and were commonly involved in bird-aircraft collisions (DeVault, Blackwell, Seamans, & Belant, 2016).

Bird strike mitigation methods for off-airport strikes include predictive 3-D probability models (Rutledge, Moorman, Washburn, & Deperno, 2015; Walter et al., 2012), avian radar (Gauthreaux & Schmidt, 2013; Gerringer, Lima, & DeVault, 2016), and adjustments to aircraft lighting systems that can alert birds sooner to approaching aircraft (Blackwell et al., 2012; Dolbeer & Barnes, 2017; Doppler, Blackwell, DeVault, & Fernández-Juricic, 2015). Additional recommendations include minimum separation distances between the airport and specific wildlife attractants based on reviews of strike databases (DeVault, Blackwell, et al., 2013; Dolbeer, 2006). The International Civil Aviation Organization (ICAO) recommends a minimum separation distance of 13 km (Dolbeer, 2006; International Civil Aviation Organization, 2002), whereas the U.S. FAA recommends a minimum separation distance of 3 km for airports servicing turbine-powered aircraft (FAA Advisory Circular 150/5200-33B, FAA, 2007). The FAA further recommends against land uses within 8 km of airports if they have the potential to attract hazardous birds (e.g. Canada goose) into the approach and departure corridors of aircraft (FAA & Hazardous wildlife attractants on or near airports, 2007). Furthermore, the FAA advises airports that attractants even beyond 8 km from the airport should be managed if they draw birds into approach and departure corridors.

Although several studies have investigated the influence of specific habitat attractants on bird use in the context of bird strikes (e.g., Iglay et al., 2017; Schmidt, Washburn, Devault, Seamans, & Schmidt, 2013; Washburn, 2012), only one study has investigated the influence of the comprehensive landscape on bird use (Coccon et al., 2015). The latter study found that agricultural fields, wetlands, and urban areas contributed most to bird use near the airport; however, the study included only two airports and failed to replicate the results at the second airport (Coccon et al., 2015). A landscape analysis must include more than just area, because it is reflecting just one of the landscape processes at work (Marzluff, 2001; McKinney, 2002).

Along the rural-urban gradient, land use varies which creates edge habitat and habitat isolation (Hansen et al., 2005; McKinney, 2002). As distances between preferred land uses increase, habitat specialists relocate and habitat generalists begin to dominate and increase the chances of finding these species in this habitat (Marzluff et al., 2001). Many species commonly struck by aircraft prefer turf grass over mature grassland and could be considered habitat generalists (Blackwell, Seamens, et al., 2013; McKinney, 2002). Therefore, to understand the role of the landscape matrix on the strike rate, landscape processes associated with fragmentation and arrangement of land uses must be investigated.

Our objective was to determine if landscape features, especially those associated with species generalists, on and off airport property, have an effect on the adverse effect (AE) strike rate (i.e. damaging and negative effect-on-flight strikes). More specifically, we used a multi-scale (3, 8, and 13 km inclusive buffers) approach to investigate the synergistic effects created by different land uses on the bird strike rate with aircraft at multiple airports with similar air carrier movements. We predicted that: 1) the AE strike rate would be influenced by land use composition and structure quantified for the airport property and beyond because of the surrounding landscape matrix and land use characteristics of fragmentation that are favored by the generalist species commonly involved in bird strikes (Blackwell, Seamens, et al., 2013; DeVault et al., 2016); 2) the influence of landscape variables on the AE strike rate would differ at the three spatial scales because of different bird and aircraft movements and land use variability; 3) as distance between wildlife attractant patches increases, the amount of time the animal resides in the patch, and thus the AE strike rate, would decrease (Brown, 1988); 4) as edge habitat of wildlife attractant patches increases, so would the abundance of generalist species that are involved in AE strikes (Whitcomb et al., 1981); and 5) overall landscape diversity would lead to increases in the AE strike rate because of an increase in suitable habitats for avian generalists (Huston, 1994; Whitcomb et al., 1981).

2. Methods

2.1. Study area

As of February 2017, there were 474 Part 139 certificated airports located within the conterminous U.S. (FAA, 2017a). Part 139 certificated airports serve air carrier aircraft with more than 30 seats, agree to maintain certain operational/safety standards, and create a Wildlife Hazard Management Plan (FAA, 2015). A Part 139 airport usually includes a fence around the property for security and the FAA has certain restrictions over agricultural production around the airport (FAA & Hazardous wildlife attractants on or near airports, 2007). John F. Kennedy International Airport in New York City, USA, is an example of a Part 139 airport. The number of itinerant air carrier movements per airport per annum was tallied using the FAA terminal area forecast (TAF) from 2009 to 2015 (FAA, 2017b). For this study, only Part 139 air carrier movements and strikes were considered. A total of 102 Part 139 airports had more than 10,000 mean air carrier movements per annum from 2009 to 2015. Two airports reported no AE bird strikes; these airports were removed from the analysis for statistical purposes. We have the highest confidence in the reporting of AE strikes at Part 139 airports with a high number of air carrier movements, hence we focused on airports that satisfied this criteria (Dolbeer, 2015). Two airports were removed because of their close proximity to Mexico, as land use GIS rasters were only available for the U.S. Therefore, 98 Part 139 airports (Fig. 1) were used in the analysis.

2.2. Bird strike data

Wildlife strike data were obtained from the FAA National Wildlife Strike Database (FAA, 2016). Bird strikes reported to the FAA strike database are submitted primarily using a standard form (FAA Form 5200–7), and reviewed for quality control (Dolbeer et al., 2015). Although strike reporting is largely voluntary in the U.S., between 2009

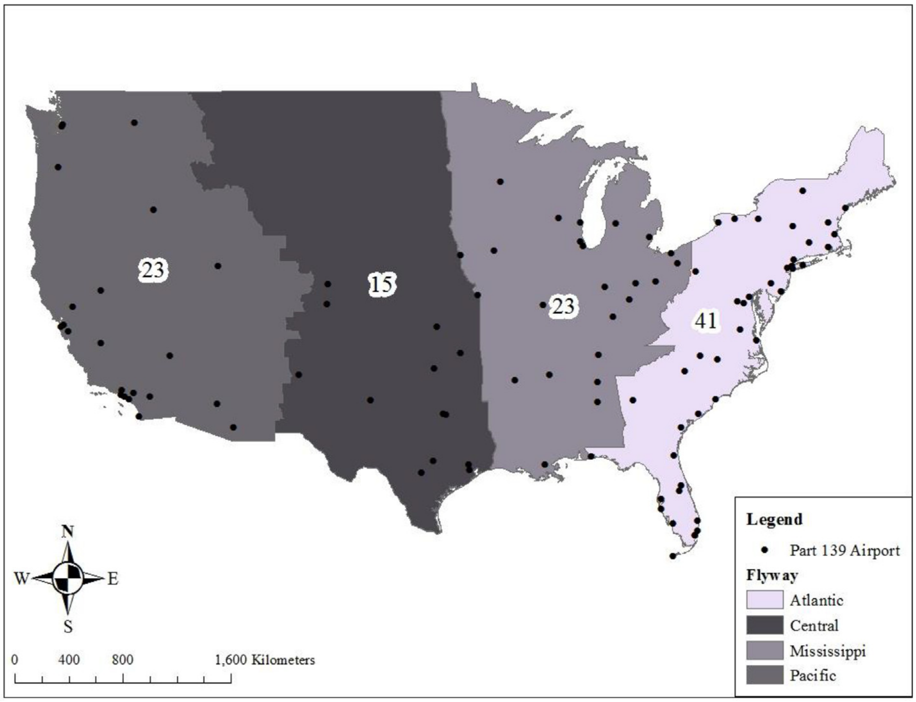

Fig. 1. Part-139 certification airports (n = 98) within the conterminous Unites States that average over 10,000 air carrier movements a year between 2009 and 2015.

and 2013 the FAA strike database received approximately 93% of all damaging bird strike records with air carriers, which was a dramatic improvement from the 1990 to 2003 time period (Dolbeer, 2015). This accuracy estimate was calculated by comparing the strike database records to those of the independent Air Traffic Organization Mandatory Occurrence Report system (Dolbeer, 2015). The forced landing of Flight 1549 in the Hudson River in 2009 was thought to have increased the reporting of strike events due to an intense awareness campaign by the FAA and United States Department of Agriculture (USDA, Dolbeer, 2015; Marra et al., 2009). We thus used strike records submitted between 2009 and 2015 for our analysis; during that time there were 79,322 total strikes reported to the FAA.

We focused our analysis on AE strikes, which are strikes that caused damage to the aircraft or had a negative effect on flight. After removing all non-AE strike records from our sample, we removed strike records that met one or more of the following criteria: 1) aircraft was private, business, government, military, unknown or other; 2) strikes that involved helicopters; 3) strikes for which distance from the airport was greater than 13 km and/or strikes when the aircraft was ≥ 2270 m AGL (the maximum AGL height based on an average 10° aircraft departure angle); and 4) strikes with mammals or reptiles. As the ICAO regulations recommend the largest separation distances of 13 km between the airport and hazardous land uses, this was the largest extent examined. Strike records were included if the species was not identified, as long as it was documented as an avian AE strike. Although we treated all AE strikes identically in our analysis to maintain a robust sample size, future investigations could generate models for individual species or species groups as the FAA database receives more strike records over time. The AE strike rate (Dolbeer & Begier, 2012) was calculated for each airport using the following equation:

$$AE\ strike\ rate = \frac{total\ AE\ strikes}{total\ air\ carrier\ movements} * 10,000$$

2.3. Landscape variables

In this study, we defined the overall landscape extent as land use and crop type contained within the 13 km radius of airport runways (13-km extent). The landscape was represented by the 2011 National Land Cover Dataset (NLCD) and the Crop Data Layers (CDLs) from 2009 to 2015 (Homer et al., 2015; USDA, 2017), which are both available for the entire U.S. and use the same data collection processes to represent land use at a 30 m × 30 m resolution.

The NLCD and CDLs were clipped to each of the three extents (3, 8, or 13 km). The NLCD was reclassified from 16 to 9 categories (Table S1). The CDLs for the study period (2009–2015) were merged using the blend method (ESRI ArcGIS Desktop, 2011). The composite CDLs for each airport extent were reclassified (Table S2) to reflect common row crops (corn, soy bean, and wheat) that are found around airports and are considered a wildlife attractant (Cerkal, Vejrazka, Kamler, & Dvorak, 2009; Iglay et al., 2017). To prevent misinterpretation, cells with a double crop/crop rotation value were not included in crop diversity or row crop calculations (Table S2).

The NLCD and CDL datasets were imported into FRAGSTATS (McGarigal, Cushman, & Ene, 2012). Five class-level and two landscape-level metrics were calculated (Table S3). Class-level metrics included area, edge, shape, and aggregation measurements for four land use categories (cultivated crops, water, wetland, and open space) that are considered attractants to the species involved in off-airport strikes (DeVault et al., 2016). Depending on the number and position of runways, the total area differed between airports, especially at the 3-km extent. Therefore, we calculated the percentage of landscape of specific land uses, which is independent of area, but for simplicity we refer to percentage of landscape as area. At the 8- and 13-km extents, total areas were essentially equal. The modified Simpson's diversity index and the contagion index were measured on the landscape-level as representations of landscape diversity and aggregation (Cushman, McGarigal, & Neel, 2008). Diversity and percentage of landscape for each row crop (corn, soybean, and wheat) were calculated for the composite CDL rasters for each airport. These metrics are considered suitable for analyzing landscape patterns over time and spatial scales (Cushman et al., 2008). Because region can affect the probability of a damaging off-airport bird strike (DeVault et al., 2016), we included flyway (Atlantic, Mississippi, Central, and Pacific) as a categorical variable.

Table 1
Results from the top GLMs ($\Delta AIC_c < 2$) of orthogonal landscape predictor variables that influence the adverse effect bird strike rate within 3-km (a), 8-km (b) and 13-km (c) extents of 98 Part 139 certificated airports in the USA.

	df	logLik	AIC_c	ΔAIC_c	w_i
(a) 3-km extent models					
Crop area/edge + landscape diversity	4	−109.00	226.4	0.00	0.49
Wetland patch/edge + crop area/edge + landscape diversity	5	−108.55	227.7	1.31	0.25
(b) 8-km extent models					
Wetland patch/edge + crop area/edge + water patch/edge	5	−98.07	206.8	0.00	0.18
Wetland patch/edge + crop area/edge + corn patch + water patch/edge	6	−97.10	207.1	0.31	0.16
Landscape diversity + wetland patch/edge + crop area/edge + water patch/edge	6	−97.45	207.8	1.03	0.11
Wetland patch/edge + crop area/edge + open space corridor/wetland area + water patch/edge	6	−97.58	208.1	1.28	0.10
Landscape diversity + wetland patch/edge + crop area/edge + corn patch + water patch/edge	6	−96.49	208.2	1.42	0.09
Wetland patch/edge + crop area/edge + corn patch + open space corridor/wetland area + water patch/edge	7	−96.59	208.2	1.63	0.08
(c) 13-km extent models					
Wetland area/edge + crop area/edge + water distance/edge	5	−90.12	190.9	0.00	0.28
Open space/dispersion + wetland area/edge + crop area/edge + water distance/edge	6	−89.20	191.3	0.44	0.22
Wetland area/edge + crop area/edge + water distance/edge + aquatic shape	6	−89.76	192.4	1.56	0.13
Wetland area/edge + crop area/edge + water distance/edge + landscape diversity/crop area	6	−89.93	192.8	1.90	0.11

df, degrees of freedom; logLik, model's loglikelihood value; *wi*, Akaike weight.

2.4. Statistical analysis

Strike records were filtered to match each of the three extents from airport runways: 1) 0–3 km, 157–529 m AGL was considered the 3-km extent, 2) 0–8 km, 157–1410 m AGL was considered the 8-km extent, and 3) 0–13 km, 157–2292 m AGL was considered the 13-km extent. Height criteria were calculated using the 3° glideslope for an aircraft on approach and the average 10° angle of an aircraft during departure (Dolbeer & Begier, 2012). At least one of the criteria had to be met to be included in that extent. Distance from the airport was often not reported. Correlations between landscape variables were calculated using the 'stats' R package (R Core Team, 2017). Each extent contained at least 18 correlated variable pairs ($|\rho| > 0.5$, $p < 0.05$), therefore a factor analysis with a varimax rotation was performed on the landscape variables to reduce complexity and create orthogonal factors. Furthermore, as landscapes matrices can be complex and inherently correlated, the factor analysis approach can remove these biases (Cushman et al., 2008). Factors were included if their eigenvalue was > 1 (Liu, Lin, & Kuo, 2003). Predictor variables with loadings < 0.45 were removed from the final set of factors to improve the interpretation of each factor (Comrey & Lee, 1992). Factors were added until the cumulative variance explained reached at least 65% (Liu et al., 2003) and were created using the 'factanal' command in the 'stats' R package. The factor analysis was conducted separately for each extent.

The retained factors were used as predictor variables in a generalized linear model (GLM) constructed for each extent and added based on *a priori* hypotheses until model convergence was reached to avoid over-fitting. We log transformed the AE strike rate and created a global model with AE strike rate as the response variable using the 'glm' function in the 'stats' R package with a Gaussian distribution and an identity link. The response and predictor variables were standardized by dividing by 2 standard deviations using the 'standardize' command in the 'arm' R package. An automated set of model combinations of the global model were created using the 'dredge' function in the 'MuMIn' R package (Grueber, Nakagawa, Laws, & Jamieson, 2011). As the global model of each extent was based on orthogonal factors, sequential omission of predictors was redundant. Models were ranked by the Akaike Information Criterion (AIC_c) adjusted for small sample sizes and model averaging was performed with the top models ($\Delta AIC \leq 2$) (Burnham & Anderson, 2003). Akaike weights (w_i) were used to assess model performance (Burnham & Anderson, 2003). We used the 'modavg' function in the 'AICcmodav' R package to generate model-averaged predictor variable coefficients and their 95% confidence intervals. All regression models were constructed in R 3.4.1 (R Core Team, 2017).

3. Results

At the 98 Part-139 airports in our sample, 1772 AE bird strikes were reported from 2009 to 2015. A total of 10 airports had overlapping 13-km extents, which might have altered the response because of overlapping wildlife management programs, however a post hoc Tukey's test revealed no effects ($p = 0.42$). The median standardized AE strike rate across all airports was 0.24 within 13 km, 0.23 within 8 km, and 0.18 within 3 km. The majority (72%) of all AE strikes reported at our sample of Part 139 airports were within 3 km. There were 137 identified species involved in the AE bird strikes. Birds involved in more than 25 AE strikes ($n = 11$) that were identified to species level were three species of raptors, five species of waterbirds, and three species of urban exploiters (Table S4). Only 30% (527 strikes) were not identified to species level.

Three factors were generated for the 3-km extent, seven factors for the 8-km extent, and six factors for the 13-km extent (Table S5). For the 3-km extent, the factors were interpreted based on high loadings of wetland patches/edge, crop area, and landscape diversity. At the 8-km extent, the factors were interpreted as landscape diversity, wetland area/edge, crop area/edge, number of corn patches, open space corridor/wetland area, aquatic shape, and water patch/edge. The six interpreted factors at the 13-km extent were open space edge/dispersion, wetland area/edge, crop area/edge, distance between water patches/water edge, aquatic shape, and landscape diversity/crop area. The flyway categorical variable was not included in any of the top models ($\Delta AIC_c < 2$) at any extent, therefore none of the results changed. Data were suitable for model averaging because of their simplicity, lack of interactions, and the predictor variables were uncorrelated (Cade, 2015).

Within the 3-km extent, two models out of eight had $\Delta AIC_c < 2$ and a collective *wi* of 0.74 (Table 1). All orthogonal factors were included in the top models collectively. Landscape diversity and crop area/edge were important predictor variables (relative importance = 1.00) and were the only variables without confidence intervals that overlapped zero (Table 2). There was a positive association between increased landscape diversity and crop area/edge and the AE bird strike rate (Figs. 2 and 3).

Within the 8-km extent, six models out of 64 had $\Delta AIC_c < 2$ and a collective *wi* of 0.72 (Table 1). Using all the generated orthogonal factors in the global model resulted in a failure of the models to converge, possibly because of too many parameters relative to the sample size. Therefore, the factor with the lowest relative importance (aquatic shape = 0.21) was removed, which improved model fit (Grueber et al., 2011). Number of wetland patches/edge, cultivated crop area/edge and

Table 2
Model-averaged coefficients of orthogonal landscape predictor variables that influence the adverse effect bird strike rate within (a) 3 km, (b) 8 km, and (c) 13 km of 98 Part 139 certificated airports in the USA.

Parameter	Estimate[a]	Unconditional se	z	Confidence intervals 2.5%	97.5%	RI[b]
(a) 3-km extent						
(Intercept)	−1.70	0.08	22.25	−1.85	−1.55	–
Landscape diversity	0.47	0.15	0.93	0.17	0.77	1.00
Crop area/edge	0.32	0.15	3.05	0.02	0.62	1.00
Wetland patch/edge	0.14	0.15	2.09	−0.16	0.44	0.34
(b) 8-km extent[*]						
(Intercept)	−1.49	0.07	22.66	−1.62	−1.35	–
Wetland patch/edge	0.49	0.14	3.53	0.22	0.76	1.00
Crop area/edge	0.37	0.14	2.69	0.10	0.64	1.00
Water patch/edge	0.34	0.14	2.43	0.06	0.61	1.00
Corn patch	0.08	0.13	0.65	−0.08	0.46	0.46
Open space corridor/wetland area	0.03	0.09	0.37	−0.14	0.40	0.25
Landscape diversity	0.04	0.10	0.37	−0.12	0.42	0.28
(c) 13-km extent						
(Intercept)	−1.43	0.06	22.6	−1.56	−1.31	–
Water distance/edge	0.49	0.13	3.83	0.24	0.74	1.00
Crop area/edge	0.47	0.13	3.72	0.23	0.72	1.00
Wetland area/edge	0.44	0.13	3.44	0.19	0.69	1.00
Open space/dispersion	0.17	0.13	0.49	−0.08	0.41	0.30
Aquatic shape	−0.10	0.13	0.07	−0.35	0.14	0.17
Landscape diversity/crop area	−0.10	0.13	0.06	−0.35	0.14	0.15

[a] Effect sizes have been standardized on 2 sd following Gelman (2008).
[b] Relative importance.
[*] Aquatic shape was removed because of low relative importance (0.21).

number of water patches/edge were important in predicting the AE strike rate (relative importance = 1.00). These were the only three variables considered significant at this extent (Table 2). Large crop areas were a strong positive predictor of the AE strike rate. Numerous aquatic patches (water or wetland) and the associated increase in edge habitat were also strong positive predictors of the strike rate.

Within the 13-km extent, four models out of 64 had $\Delta AIC_c < 2$ and a collective *wi* of 0.74 (Table 1). All orthogonal factors were included in the top models, collectively. Wetland area/edge, cultivated crop area/edge, and water distance/edge were the most important predictor variables (relative importance = 1.00). These three variables were considered significant at this extent (Table 2). Similar to the 8-km extent, large wetland and cultivated crop areas were associated with higher AE strike rates. Longer segments of water edge positively influenced AE strike rate, whereas larger distances between water patches negatively influenced the AE strike rate (Fig. 3).

4. Discussion

The AE bird strike rate was strongly influenced by the landscape matrix at all three of our demarcated spatial scales as defined by the high support of the top models (Grueber et al., 2011). Landscape characteristics associated with increased fragmentation were strong predictors at the 3-km spatial extent. The diversity of land uses near airports may harbor resources for hazardous wildlife, whereas a homogenous landscape may provide only some of those resources (DeVault, Blackwell, et al., 2013; Huston, 1994; Whitcomb et al., 1981). The least diverse individual airport landscape was located completely in an urban center and magnifies the effects of the homogenous city landscape (McKinney, 2006; Savard, Clergeau, & Mennechez, 2000). There was a 73% change in the AE strike rate between the least and the most diverse airport landscapes. Beyond the homogenous city center, the fragmentation typical of the urban-rural interface is an attractant to

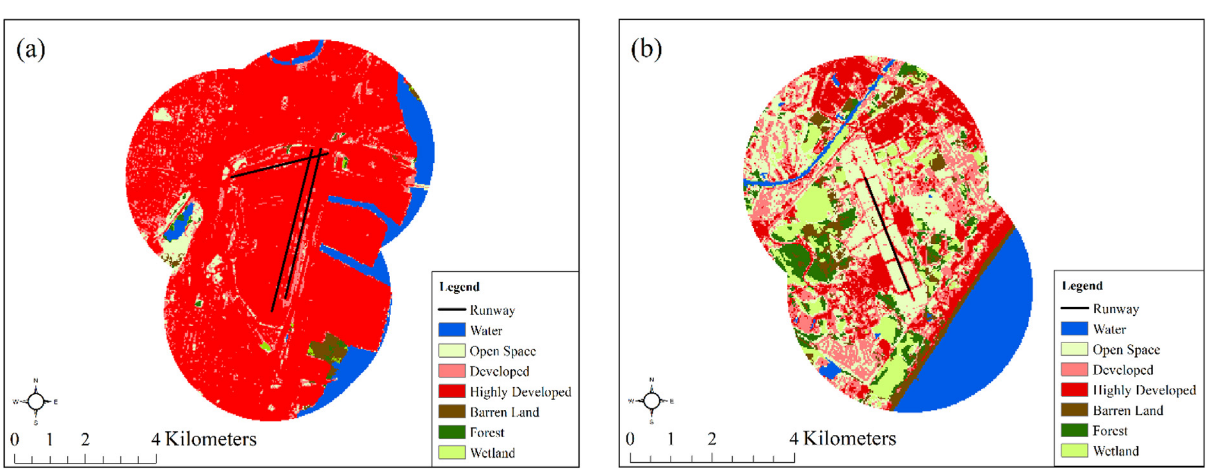

Fig. 2. Comparison of the extremes for the landscape diversity factor for the 3-km extent buffered from the airport runways. KEWR, New Jersey (a) contained the lowest value for landscape diversity factor and KMYR, South Carolina (b) contained the highest value for the landscape diversity factor.

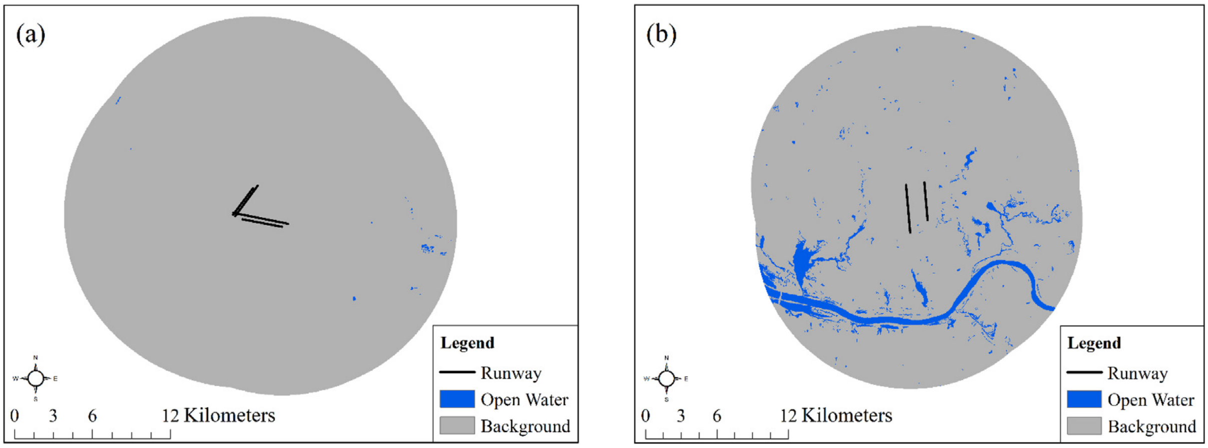

Fig. 3. Comparison of the extremes for the open water patch/edge factor for the 13-km extent. KLAS, Nevada, USA (a) displayed the lowest value for the water distance/edge factor and KHSV, Alabama, USA (b) displayed the highest value.

the raptors, waterbirds, and urban exploiters involved in AE strikes (DeVault et al., 2012; Hansen et al., 2005). For example, Red-tailed hawks (*Buteo jamaicensis*) in Connecticut, USA preferred locations near large green spaces in urban areas and not the highly urbanized core city area, hence this allows them to thrive in an urban environment (Morrison, IGottlieb, & Pias, 2016).

As expected, increases in the AE strike rate were positively associated with the arrangement and edge characteristics of aquatic land uses (Blackwell et al., 2008). Numerous wetland patches with large perimeters likely attract waterfowl, which are commonly involved in off-airport strikes (Andersson, Davis, Blackwell, & Heinen, 2017; DeVault et al., 2016; Fairbairn & Dinsmore, 2001). Shorter distances between water patches were considered an important predictor only at the 13-km scale, which is further than previous studies that quantified avian use of storm water retention ponds, but found similar trends (Blackwell et al., 2008; Fox, Holland, Boyd, Blackwell, & Armstrong, 2013). Shorter distances between open water patches encourages long term use of the landscape, because as one resource patch is depleted, another patch is located nearby that increases overall foraging efficiency (Brown, 1988). Although it might be impossible to manipulate all open water patches because of their ubiquitous presence in certain ecoregions, alterations to storm water ponds to minimize their attraction to waterbirds can be performed (Blackwell, Felstul, et al., 2013). Our results suggest these alterations could reduce the AE strike rate within 13 km of the airport.

At all extents, cultivated crop areas and patches were among the strongest predictors of the AE strike rate. The cultivated crop land use category was a culmination of all cultivated crops, regardless of type. However, the number of corn patches in the landscape was included as a factor at the 8-km extent and had a high importance value of 0.46. Wheat and soybean percentage of the landscape had low loadings in the factor analysis and were removed. Iglay et al. (2017) also found that multiple crop types (soybean, corn, and wheat) attracted hazardous bird species to airports, but corn and wheat attracted large flocks and therefore are a slightly more hazardous land use around airports. Cultivating corn within 8-km of an airport could increase the AE strike rate. Further investigations are needed as we were limited by the inability to include crop rotations in the analysis, which may have altered the influence of specific crops on the strike rate. For example, excluding these rotations may have excluded large areas of crops which could have lessen their avian attractive influence and effect on the strike rate. Furthermore, our analysis encompassed a variety of ecoregions in which the effect of crops on bird distribution may differ. To remedy these shortcomings, information on the temporal variability of crop rotations is needed across a large spatial extent. The FAA strike database currently receives approximately 14,000 strike records each year (FAA, 2016). Given increased strike reporting coupled with high confidence in reporting rates and improved species identification, this study likely can be extended to include analyses at the guild and species level in the future.

4.1. Management implications

The high likelihood of the landscape matrix as a driver of AE bird strikes is informative for mitigation efforts. Our results highlight the need to address land use with a multi-scale approach (Blackwell et al., 2009; Martin et al., 2011). Furthermore, our findings can be used as a tool to help guide interactions between airport management and surrounding landowners in identifying landscape hazards and addressing management efforts to mitigate their risk to aircraft operations. These results can aid in planning airport construction or runway expansion in which changes in the surrounding land uses can be weighed in terms of economic and environmental impacts for stakeholders. Although the airport has no control outside its boundary, the airport and neighbors can work towards common goals, such as reducing the number of Canada geese through round-ups and pond habitat modifications that will reduce the risk of a bird strike and decrease the amount of goose feces in the area (Smith, Craven S. R., & P. D., 2000). Current FAA recommendations advise against hazardous land uses within 8 km of an airport, but our results suggest land uses beyond this extent might also contribute to the AE bird strike rate. Specific priorities for habitat management should include reducing the area of cultivated crops, especially corn, and increasing the distances between patches of open water. These strategies should be used in conjunction with other techniques, such as implementation of Wildlife Hazard Management Plans, predictive space use models, and avian radar (Blackwell et al., 2009; DeVault, Blackwell, Seamans, Lima, & Fernandez-Juricic, 2015).

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.landurbplan.2018.07.004.

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