Remote sensing applications for abating aircraft–bird strike risks in southeast Brazil

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Abstract: The rising number of aircraft collisions with birds requires the development of appropriate mitigation measures to control their populations in the vicinity of airports. The black vulture (*Coragyps atratus*; vultures) is considered one of the most dangerous species for aviation in Brazil. To better understand the spatial distribution patterns of flying vultures and the risks they may pose to aviation, we studied natural and anthropogenic superficial factors and then numerically estimated and mapped the risk of collision with birds over the Airport Safety Area (ASA) for the Amarais Airport and Presidente Prudente Airport in the southeast part of Brazil. To conduct our research, we surveyed soaring black vultures monthly between September 2012 and August 2013 from 26 points within 20-km ASA zones. We obtained the environmental parameters (i.e., relief, surface temperature, surface covering type, and anthropogenic pressure) from satellite imagery and georeferenced them with our vulture survey. The tabulated data were examined using Spearman's rank correlation and principal component analysis to determine if any the relationships existed between vulture flight patterns and ASA environmental characteristics. We found that the contrast in surface temperatures correlated well with the intensity of vulture soaring flights. Vultures tend to soar using the strongest thermals in their surroundings. Relief parameters, including altitude above sea level, slope exposure, and inclination, were not related with the vulture soaring activity. Water bodies and roadways were the most attractive landscapes for soaring vultures. We recorded the least number of soaring vultures over the uninterrupted urbanized lands. However, the scattered enclaves of urban settlement surrounded by natural and rural landscapes were selected by soaring birds. To mitigate the bird strike risk in ASA zones, we propose that managers should plot the objects generating thermals that attract vultures on risk assessment maps and reroute aviation to avoid them.

Key words: bird strikes, black vulture, Brazil, *Coragyps atratus*, human–wildlife conflicts, remote sensing, risk assessment map, soaring behavior, thermals

THE RISK OF aircraft–bird strikes has increased together with the global rise of air traffic (Hedayati and Sadighi 2016). From 1990–2015, 164,444 bird strikes were registered only in the United States, including 13,558 (8%) incidents with significant damage to aircrafts (Dolbeer et al. 2016). In Brazil and within its range in the Americas, the black vulture (*Coragyps atratus*; vulture) is considered one of the most significant threats to aircraft safety (Bastos 2001; DeVault et al. 2005, 2011; Oliveira and Oliveira Pontes 2012; United States Air Force 2014; Dolbeer et al. 2016; Figure 1). In Brazil, soaring vultures caused 948 collisions with aircrafts from 2011–2018 (Aeronautical Accidents Investigation and Prevention Center [AAIPC] 2019).

During daylight hours, vultures soar in flocks on thermals at high altitudes searching for food and threatening the aviation. They use natural and artificial thermals to minimize the energy losses (Newman 1958, Coleman and Fraser 1989, Freire et al. 2015). Thermals, or upward warm air fluxes, form above hotspots or zones with high contrast in surface temperatures (Stull 1988, Prem and Mackley 2005). Hence, the

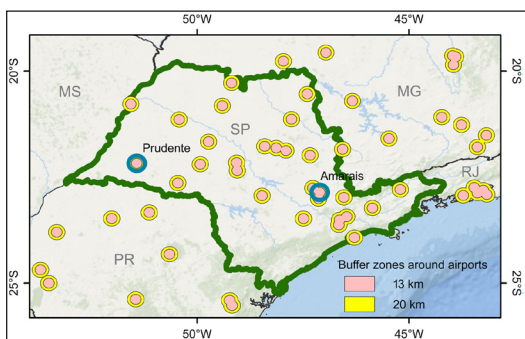**Figure 1.** Black vulture (*Coragyps atratus*).

Figure 2. Distribution of airports in southeast Brazil (OpenFlights 2018). The map represents the Airport Safety Areas of 20-km radius established by the Ministry of Environment of Brazil, where any human activity attracting birds is restricted (SP – São Paulo state, MG – Minas Gerais, MS – Mato Grosso do Sul, PR – Paraná).

distribution patterns of soaring vultures can be linked to the uneven heating of surface objects. Additionally, the abundance of anthropogenic food sources may also attract vultures (Novaes and Cintra 2013). However, even the complete removal of all feeding sources from the ground may not clear the sky from soaring vultures (Bastos 2001, Blackwell and Wright 2006, Novaes and Cintra 2013). It is expected that soaring birds can be met more often near their nesting and perching sites. Vultures require remote locations for communal roosts, where they spend night hours and raise their young (Beauchamp 1999, Stolen and Taylor 2003, Blackwell and Wright 2006). The communal roosts are usually located in safe areas with limited human activities and near natural and anthropogenic objects generating thermals

(Thompson et al. 1990, Mandel and Bildstein 2007, Novaes and Cintra 2013). Vultures may also roost in areas of intense human activity, such as street markets, if those areas are located near the permanent sources of food for birds (Coleman and Fraser 1989, Novaes and Cintra 2013). In Brazil, vultures have adapted to life in big cities like São Paulo and Manaus and forage above all types of landscapes impacted by human activities (Carrete et al. 2010, Novaes and Cintra 2013, Novaes and Alvarez 2014; Novaes and Cintra 2015, Freire et al. 2015).

Most of the aviation incidents caused by bird strikes occur near airports during take-off and landing when aircrafts fly at altitudes of <600 m (Bastos 2001, Civil Aviation Authority [CAA] 2008, Cauville 2010). Aircrafts descend to this height at ~13 km from the runway (CAA 2008). Therefore, the International Civil Aviation Organization (ICAO) identifies a 13-km circle centred on the aerodrome reference point as a zone of bird strike risk (ICAO 2002). To further reduce bird strike risks, in 1995 the Brazilian Ministry of the Environment established the Airport Safety Area (ASA) with a radius of 13 and 20 km for airports with visual and automatic sky monitoring, respectively. In 2012, the legislative amendments extended the radius of the ASA zones around all airports to 20 km (Jusbrasil 2012). Any activity attractive for vultures (i.e., slaughterhouses, tanning and fish industries, garbage dumps, and even farming) were further restricted in the ASA buffer zones (National Environmental Council 1995, Bastos 2001, Oliveira and Oliveira Pontes 2012). However, those legal requirements were not fully implemented because the ASA zones include the vast urban and private agricultural lands. Therefore, although the issue of garbage dumps has improved in Brazil since the 1990s (Oliveira and Oliveira Pontes 2012), other sources of food may still remain near airports.

Many airports have implemented preventive measures that may impact vulture populations. These measures include resettlement of birds, modification of their habitats, falconry, and culling (Cauville 2010). Considering the 20-km buffer zones (e.g., in São Paulo state, the ASA zones occupy ~14% of total state territory; Figure 2), the measures for reduction of the bird strike risk should mitigate the impacts to the species in natural ecosystems. Currently,

14 of 23 vulture species living all over the world are threatened with extinction due to considerable human-caused changes in the conditions of their habitats (Deygout et al. 2009, Cortés-Avizanda et al. 2010, Ogada et al. 2012, Buechley and Şekercioğlu 2016).

Our objective was to better understand the factors influencing the distribution of soaring black vultures in the ASA zones. We investigated surface temperature, thermal gradient, and surface covering as they related to thermals used by soaring vultures. Because topography affects thermals (Stull 1988, Prem and Mackley 2005), we also considered relief features, namely altitude, slope exposure, and inclination. We sought to predict the spatial variability of those factors and visualize zones with elevated bird strike risk around airports on risk assessment maps. Finally, we considered how the distribution patterns of the soaring vulture could be applied to bird strike abatement without impacting the populations.

Study area

We recorded the distribution of soaring vultures between September 2012 and August 2013 in the ASA buffer zones (20 km) around the Amarais Airport (22.86293°S, 47.10528°W) and Presidente Prudente Airport (22.17656°S, 51.427389°W). Those airports typically handle small and medium class aircrafts. Both study areas were located in the São Paulo state, Brazil (Figure 2), and characterized by tropical climate with pronounced rainy and dry seasons. The average annual low/high temperatures are 15.5/27.1°C in Campinas and 18.8/29.1°C in Presidente Prudente. The city of Presidente Prudente is located in the west and Campinas is in the central east region of São Paulo state, and their airports are a distant ~450 km from one other. Although the buffer zones around both airports include dense urban areas (~800 people per km²), the major difference between sites was the degree of anthropogenic impact. Highly urbanized lands dominate around Amarais Airport (~60% of the total area), while the surroundings of Presidente Prudente Airport are distinguished by the prevalence of natural and rural landscapes (~85%). Accordingly, we considered the black vulture populations around the Presidente Prudente Airport as rural and that around the Amarais Airport as urban. The soaring birds in the study sites were represented almost exclusively by vultures.

Methods
Field data collection

We conducted field observations in 26 viewpoints (13 viewpoints in each study site), uniformly distributed with a distance between nearest nodes of about 6 km. Hills and open spaces were preferred to provide better visibility of the surroundings. The geographical coordinates of the viewpoints were determined with a handheld global positioning system (GPS) Garmin Montana 650 unit (Garmin International, Olathe, Kansas, USA) and then used for calculation of geographical positions of flying birds.

Every 15 minutes, 2 professional ornithologists recorded all black vultures visible from viewpoints during 1 day of each month from 0800–1800 hours local time, except for short periods of rainy weather when birds do not fly. We completed 12,480 sky views. To measure the distance, and the horizontal and vertical angles to vultures, they used 12-powered binoculars CSR 12 x 50, 87/1,000 m (Centro Sul Representações Comércio, Guarulhos, São Paulo, Brazil) equipped with a compass and inclinometer. One individual or a few black vultures located close to each other and characterized by identical registration parameters were recorded as a single ornithological object (Figure 3). For each observation, we identified the following characteristics attributed to intervals of values: (1) direction (8 equal intervals ranged between 0 and 360° [i.e., 22.5–67.5°, 67.5–112.5°...292.5–337.5°, 337.5– 22.5°]), (2) vertical angle (18 intervals – 2.5–7.5°, 7.5–12.5°, 12.5–17.5°… 77.5–82.5°, 82.5–87.5°, 87.5–90°), (3) 4 distance intervals (100–200 m, 200–400 m, 400–700 m, 700–6,000 m), (4) geographical coordinates and identification number of viewpoint, and (5) time of observation by 15-minute intervals (e.g., 01.09.2012 8:00, 01.09.2012 8:15). The distance (D, m) was estimated with binoculars using the angular distance (α, milliradian) measured by the graticule lines marked on its eyepiece:

$$D = L \cdot \cot \frac{\alpha}{1000} \qquad (1)$$

where L is a size of black vulture in meters. The wingspan of this species is 1.33–1.67 m
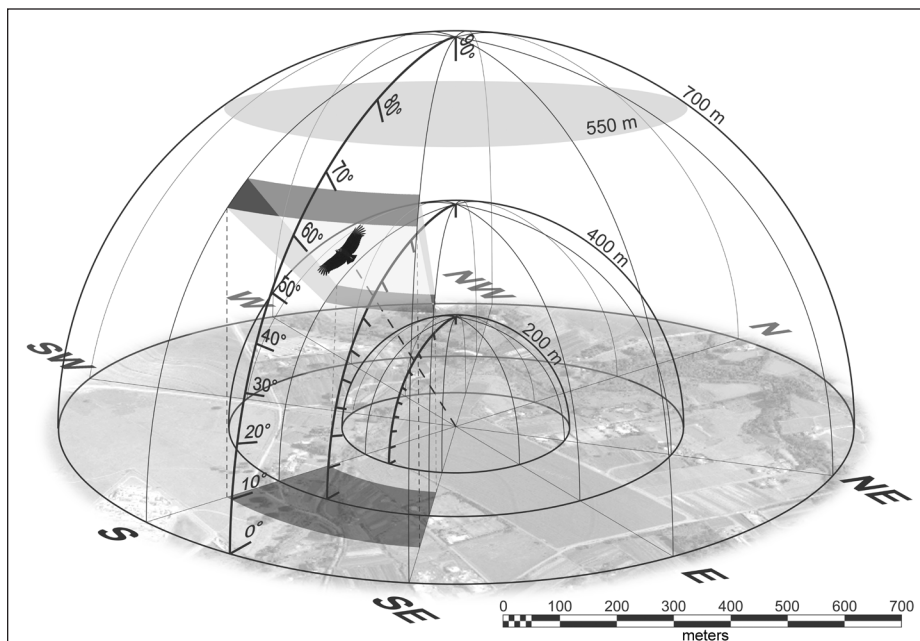
Figure 3. The record of black vulture (*Coragyps atratus*) coordinates and construction of projected polygons within 20-km Airport Safety Area of the Amarais Airport and Presidente Prudente Airport in southeast Brazil, September 2012 to August 2013. The maximum recorded height of bird flights was 550 m.

(Campbell 2015) and does not depend on sex and age (Harel et al. 2016). We assumed the wingspan of all soaring black vultures to be equal to 1.5 m. The applied method of determining the distance to bird by binoculars is well known in ornithology (e.g., Stolen 2000).

Vultures never flew closer than 100 m to the observer. Also, we assumed that the maximum distance to see the bird through binoculars was constrained by its technical characteristics and physiological limit of the human eye to 6,000 m (Land and Nilsson 2012). However, the geographical position of all vultures recorded at the fourth distance interval is very uncertain. For these reasons, we considered mostly the ornithological objects observed between 100 m and 700 m. The exclusion was made only for the construction of the risk maps of small scale and low accuracy, in which all distance intervals were used.

Satellite imagery processing

The relationships between the soaring activity of black vultures and the following surface characteristics were studied: surface temperature (°C), contrast of surface temperatures (slope degrees), altitude above sea level (meters), slope exposure (circular degrees), slope inclination (slope degrees), and landscape type (i.e., the type of surface covering coupled with the level of anthropogenic pressure). All those parameters were obtained from the remote sensing products handled in the ArcGIS 10.0 software (Environmental Systems Research Institute, Redlands, California, USA).

We estimated surface temperatures at spatial resolution of 90 m per pixel using the on-demand L2 surface kinetic temperature satellite multispectral images (AST_08) obtained by advanced spaceborne thermal emission and reflection radiometer (ASTER) satellites (ASTER 2018, Land Processes Distributed Active Archive Center [LP DAAC] 2018). The surface temperature characteristics were generated from 5 thermal infrared bands of ASTER image within a spectral range between 8 and 12 μm (AST_08 2018). The AST_08 products were obtained through satellite imagery shot during the mid-day time of a single day in 2013 and well suited for analyzing the temperature distribution in the study areas. Due to shooting time of this area, we could choose satellite imagery without cloud shielding and with strongest surface heating by

Table 1. Landscape types and levels of anthropogenic stress within 20-km Airport Safety Area of the Amarais Airport and Presidente Prudente Airport in southeast Brazil, September 2012 to August 2013.

Landscape type	Level of anthropogenic stress	Description
Natural area	1	Natural and rural landscapes including agricultural fields, grassy wastelands, forest fragments, and vegetation along rivers
Natural water object	1	Rivers and lakes with unpolluted water and their shorelines
Suburb	2	Moderately urbanized zone comprising both natural lands and scattered buildings
Artificial water object	2	Reservoirs of polluted water
Roadway	2	Automobile roads
Dense residential zone	3	Densely populated residential areas
Industrial zone	4	Power stations, industrial complexes and related infrastructure, waste treatment facilities

the sun. We applied the ASTER global digital elevation model version 2 (ASTER GDEM v2) to produce the relief parameters. This is a digital elevation model of the Earth surface designed for the entire world using the collection of ASTER images of years 2000–2011 (Tachikawa et al. 2011, ASTER Global Digital Elevation Model 2018). This technique provided the spatial resolution of 30 m per pixel. The surface covering types were recognized and manually digitized as polygonal shapefiles of landscape maps based on true-color DigitalGlobe images of high resolution (~1 m per pixel) produced in years 2010–2013. Those images were taken from the fee-free Basemap gallery available in ArcGIS. The digitalization was conducted according to the elaborated classification of study sites, containing 7 types of surface covering linked with 4 levels of anthropogenic stress (Table 1). All recognized roadways had asphalt pavement and a width of >50 m. There are small rivers and ponds in both regions. Because of their sizes, pixels attributed to natural water bodies often included shorelines.

Surface temperatures, altitudes above sea level, and types of landscape were obtained directly from corresponding satellite products. Slope inclination, slope exposure, and contrast of surface temperature were recalculated from them. The calculation procedures were conducted directly in corresponding raster files in ArcGIS. The slope tool of ArcGIS was used to calculate the slope inclination parameter from the raster of ASTER GDEM v2 and contrast of surface temperatures from AST-08 (ArcGIS Resource Center 2018*b*). The values of slope exposure were obtained from the raster of ASTER GDEM v2 by means of the aspect tool (ArcGIS Resource Center 2018*a*). Eventually, the georeferenced raster maps were designed for all surface characteristics (Table 1).

Data preparation for analysis

The data were prepared for statistical tests, landscape analysis, and risk map construction by dint of ArcGIS 10.0 (ArcMap software). At first, separately for Amarais and Prudente sites, the data of vultures' census were tabulated, joined by the identical time of observation parameter and georeferenced using the mean values of the recorded intervals of distance, vertical angle and direction. The resulting summary database (as 2 point shapefiles) represents each ornithological object as a vector point attributed to its registration parameters. The technical steps of georeference of each observed bird and preparation of the summary database (titled the "Georeferenced birds and meteorological parameters database") were considered with more details in the Algorithm A1.

During field observations, the position of each ornithological object was constrained by

intervals of horizontal and vertical angles and distances to the observer. To compare each bird record with superficial characteristics, we designed a 3-dimensional planform (Figure 3). For this, the conversion of vector points depicting recorded birds into projected polygons was implemented by several technical steps considered in the Algorithm A1. A projected polygon of each ornithological object can be interpreted as a region on Earth's surface above which those birds were at the moment of registration. This transformation allows taking into account the uncertainty in calculation of geographical positions of flying birds caused by the interval character of registered parameters. Also the modified birds' records can be easily compared with superficial characteristics.

The projected polygon corresponded to a circle so long as the recorded ornithological object located exactly above the viewpoint and the vertical angle approached 90°. In all other cases, the projection looks like an annular sector. Those polygons overlap each other, so the number of crossing layers at each point varies from several dozen to only 3 above the viewpoint. To avoid this effect, the parameter titled the weight of birds (W_{birds}) can be calculated at any point of studied areas:

$$W_{birds} = 3\frac{\sum birds}{\sum polygons} \qquad (2)$$

where $\sum birds$ represented the number of recorded black vultures in all 3-dimensional shapes above the given point (i.e., in all overlapped projected polygons) and $\sum polygons$ is a total amount of their overlapping projections. The ratio was multiplied by 3 to bring the value of index at each point to the central position of viewpoint and to improve the representation of the actual number of registered birds (Figure 3). The W_{birds} depicts the relative density of soaring vultures above a given point during a chosen period of time. Here we considered all records collected during the year. This parameter was used in statistical and landscape analyses as a numerical measure of the activity of black vultures flying over the area. We also applied it as a quantitative measure of the hazard of aircraft collision with these birds over the soaring terrain.

We used a template of polygonal shapefiles created separately for Amarais and Prudente sites. Each shapefile consisted of square cells with a size of 30 m on which the whole studied territory was divided. Those cells were prepared from the ASTER GDEM v2 product. For each cell, the W_{birds} index was calculated by Equation 2 and the superficial parameters (surface temperature, contrast of surface temperatures, altitude above sea level, slope inclination, slope exposure, and level of anthropogenic pressure) were identified using the prepared georeferenced raster maps. The resulted polygonal shapefiles were combined in the W_{birds} and superficial parameters geo-referenced database or W_{birds} database. The attribute tables of those shapefiles became the basis for statistical test implementation. The technical details of W_{birds} database preparing for statistical analyses are considered in the Algorithm A2.

To prepare the data for the landscape analysis, the parameters listed below were calculated based on the attribute tables of landscape maps for each landscape type separately for the study sites. Those parameters were: (1) the total area of lands occupied by each landscape type (S, ha); (2) the percent of area of each landscape type in respect to the total area of the studied site ($\acute{S}$, %); (3) the total amount of birds that were recorded above each landscape type during the observation period (H_{birds}); and (4) the percent of H_{birds} of each landscape type, where 100% is a sum of H_{birds} for all landscape types of the study site ($\dot{H}_{birds}$, %). Using those parameters, the relative density of soaring vultures (ρ, birds ha^{-1}) above all landscape types were calculated:

$$\rho = \frac{H_{birds}}{S} \qquad (3)$$

To compare the attractiveness of distinct landscapes, the percent deviation from the mean density ($\hat{\rho}$, %) was calculated:

$$\hat{\rho} = \frac{\rho - \bar{\rho}}{\bar{\rho}} \cdot 100\% \qquad (4)$$

where $\bar{\rho}$ depicts the mean density of soaring vultures (birds ha^{-1}) recorded in the study sites:

$$\bar{\rho} = \frac{\sum H_{birds}}{\sum S} \qquad (5)$$

where $\sum H_{birds}$ is a sum of all H_{birds} indices of all landscape types; $\sum S$ is a sum of areas of all

landscape types (or the total area of the studied site). A landscape type was considered to be attractive for black vultures if the percent of recorded birds above this landscape exceeds its area portion (i.e., $\dot{H}_{\text{birds}}$, % > $\dot{S}$, %) and the $\hat{\rho}$ parameter is positive. In contrast, the landscape is not attractive to vultures if $\dot{H}_{\text{birds}}$, % < $\dot{S}$, % and the $\hat{\rho}$ value is negative. The neutral attractiveness corresponds to $\dot{H}_{\text{birds}}$, % ≈ $\dot{S}$, % and $\hat{\rho}$ near 0.

Data analysis

The principal component analysis (PCA) was conducted in R 3.6.0 (R Core Team, 2017) with use of the FactoMineR package (Kassambara, 2017). We applied PCA to visualize collected datasets, examine relationships between superficial characteristics (independent variables), and indicate links with the response variable depicting the number of soaring vultures (W_{birds}). The FactoMineR package allowed us to plot the supplementary variables in PCA factor maps. We also performed a Spearman's rank correlation analysis (SRCA) in Microsoft Excel. We studied links between W_{birds} and 2 temperature parameters. The landscape analysis was implemented to study the dependence of soaring activity of vultures (H_{birds}) on the types of surface covering and levels of anthropogenic stress by means of analysis of the summary tables and histograms.

Mapping of the risk of collision

The designed risk assessment maps were built in the ArcGIS software with the following algorithm. The polygonal shapefile Grid-1 consisting of the uniform cells of 100 x 100 m (1 ha) was created using the Create Fishnet ArcGIS tool. Then, the Grid-1 was superposed on the shape polygonal theme of projected polygons and the W_{birds} index was calculated for each cell of Grid-1. Finally, the resulting W_{birds} values were visualized in each cell of the grid as a map. The technical details of the construction of the risk assessment maps in ArcGIS software were considered in the Algorithm A3.

The cartographic visualization depicted the study area. The maps were built by means of the interpolation method applied on the grid with calculated W_{birds}. We used the Natural Neighborn interpolation tool of ArcGIS to build 2 maps that covered the ASA zones of each airport. Alternatively, the detailed risk maps comprised only the precise records collected in 700-m zone surroundings of viewpoints. This technique of mapping does not demand the interpolation procedure and displays the W_{birds} indices directly.

Assumptions and limitations

The uncertainty of analyses and hazard estimates plotted on maps stems from 5 components: human factor, uncertainties on the wingspan of vultures, the equipment constraints, the georeferencing procedure, and the cartographic visualization of the recorded birds. Human factor doubtless impacted the precision of birds' records. The probability to miss a bird increases exponentially with increasing distance from the observer, which is numerically difficult to estimate. However, we assumed that the resulting error was negligible at the first 3 distance intervals between 100 m and 700 m, and it increased sharply in the fourth interval (700–6,000 m), where the distance to observed birds approaches the distance to the visible horizon. This phenomenon is also one of the reasons why we did not consider the data of the fourth interval in the statistical analyses.

The wingspan of black vultures could differ from 1.5 m used in the distance estimation. Therefore, considering the real wingspans ranging from 1.33–1.67 m (Campbell 2015), the mean standard deviations were 5.7 % or 8.6, 17.2, 31.6, and 192.3 m for each distance interval, respectively. In other words, the mean uncertainty on birds' coordinates applied in research was 22.8 m.

Because of the technique used, it was impossible to determine the precise geographical coordinates of the birds. All collected data are attributed to the intervals of parameters, which projections to the surface present the extended polygons with a form of annular segments (Figure 3). Those polygons constructed in the GIS software illustrate the ambiguity concerning the location of vultures at the moment of observation and allow including this uncertainty in the statistical analysis. Another consequence of the yielded polygonal visualization is the distortion of the total number of records; the sum of W_{birds} in all grid cells and H_{birds} estimated for types of landscapes are much higher than the actual number of all recorded birds. This happened because the point objects
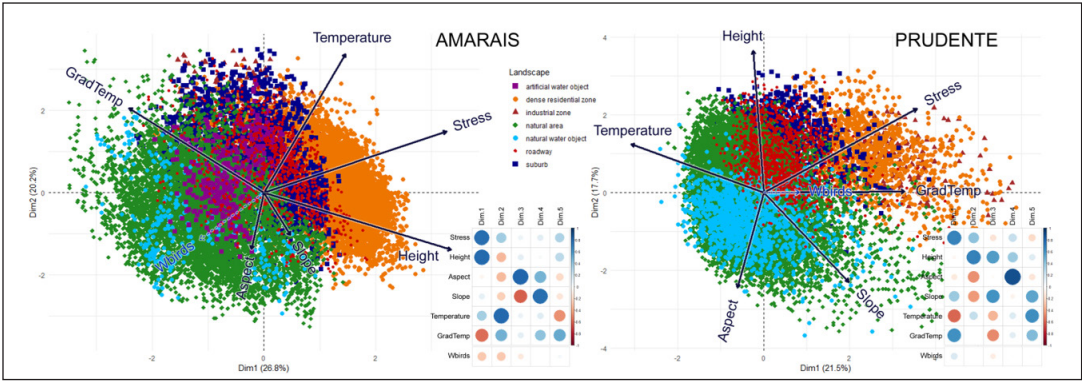
Figure 4. The principal component analysis of superficial characteristics and soaring activity (W_{birds}) of black vultures (*Coragyps atratus*) within 20-km Airport Safety Area of the Amarais Airport and Presidente Prudente Airport in southeast Brazil, September 2012 to August 2013. The factor maps reveal that vultures preferred to soar over less heated lands with greater gradients in surface temperature (GradTemp). Natural area and natural water objects attracted more birds in the Amarais site, whereas near Presidente Prudente Airport they chose anthropogenic landscapes.
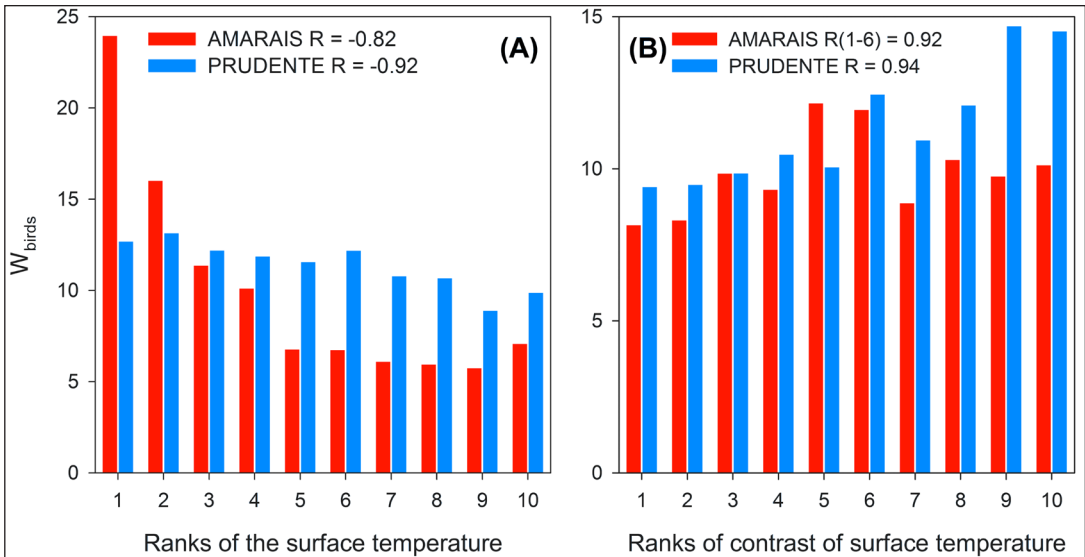

Figure 5. The correlation of the soaring activity (W_{birds}) of black vultures (*Coragyps atratus*) versus (A) surface temperature, and (B) contrast of surface temperature within 20-km Airport Safety Area of the Amarais Airport and Presidente Prudente Airport in southeast Brazil, September 2012 to August 2013. Each rank in temperature or temperature contrast corresponds to 10% of all W_{birds}. For the Amarais site, the Spearman's rank correlation coefficient (R) between W_{birds} and temperature contrast was calculated for the first 6 ranks.

were "stretched" to the polygon. Therefore, the W_{birds} and H_{birds} are not the number of individuals attributed to some territory. Those indices can be considered as relative measures of the density of soaring vultures.

The superficial characteristics derived from satellite imagery AST_08 and ASTER GDEM v2 with different spatial resolutions. In order to compare those data with bird records, various averaging procedures have been employed. The temperature parameters obtained from the AST_08 raster with resolution of 90 m were

transformed to the grid with a cell size of 30 m. Besides, all used satellite products tied to specific shooting dates and do not show the variation of parameters in time.

Results
Dependence on relief, surface temperature, and anthropogenic pressure

The PCA revealed that surface temperatures correlated negatively versus the relative density of soaring birds (W_{birds}; Figure 4). This

Table 2. The soaring activity of black vultures (*Coragyps atratus*) over the different landscape types within 20-km Airport Safety Area of the Amarais Airport and Presidente Prudente Airport in southeast Brazil, September 2012 to August 2013. S – the area of each landscape type (ha); $\dot{S}$ – its portion (%); ΣH_{birds} – a sum of all records made during the year of observations above each landscape type; $\Sigma \dot{H}_{birds}$ – its portion (%); ρ – a density of bird records (birds ha^{-1}); $\hat{\rho}$ – a deviation from the mean density (%) corresponding to the relative attractiveness of landscapes.

Landscape type	Amarais Airport						Presidente Prudente Airport					
	S	$\dot{S}$	ΣH_{birds}	$\Sigma \dot{H}_{birds}$	ρ	$\hat{\rho}$	S	$\dot{S}$	ΣH_{birds}	$\Sigma \dot{H}_{birds}$	ρ	$\hat{\rho}$
Natural area	784.58	40	23,718	40	30.23	1	1,551.18	78	52,533	58	33.87	-26
Natural water object	39.12	2	4,011	7	102.52	244	112.56	6	13,737	15	122.04	168
Suburb	215.32	11	7,350	12	34.13	14	88.36	4	12,612	14	142.74	213
Artificial water object	39.27	2	1,824	3	46.44	56						
Roadway	122.08	6	6,024	10	49.34	65	90.60	5	7,641	8	84.33	85
Dense residential zone	611.20	31	10,590	18	17.33	-42	129.57	7	2,004	2	15.47	-66
Industrial zone	171.74	9	5,670	10	33.01	11	20.20	1	2,313	3	114.48	151

finding was also confirmed by the SRCA, which showed the strong inverse correlation between W_{birds} and surface temperatures for both populations (Figure 5A). Also, PCA defined a positive correlation between gradient of surface temperatures (GradTemp) and W_{birds}. In Amarais, the SRCA did not detect a relationship between W_{birds} and the full range of contrasts of surface temperatures. However, first 6 ranks of this superficial characteristic demonstrated the high positive correlation ($R = 0.92$; Figure 5B). In the case of Prudente population, SRCA showed the strong correlation between W_{birds} and contrasts of surface temperatures at all ranges of collected data (Figure 5B). The correlation of soaring activity versus the extent of anthropogenic stress showed the opposite trends in 2 studied sites: a negative relationship in Amarais and positive in Prudente (Figure 4). Also, the higher anthropogenic stress corresponded to the higher surface temperature in the Amarais site, while an inverse link was found in Prudente. Other considered variables (aspect, height, slope) showed no remarkable patterns.
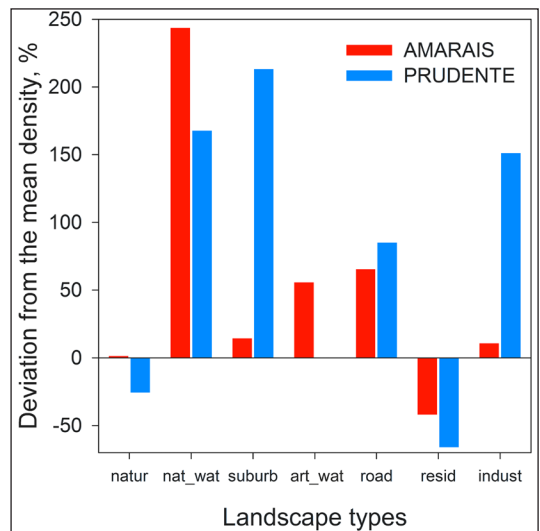

Figure 6. The percent deviation from the mean density of black vultures (*Coragyps atratus*) soaring above all landscape types ($\hat{\rho}$, %) within 20-km Airport Safety Area of the Amarais Airport and Presidente Prudente Airport in southeast Brazil, September 2012 to August 2013. Landscape types: natur – natural area, nat_wat – natural water object, suburb – soft urbanized lands, art_wat – artificial water object, road – roadway, resid – dense residential zone, indust – industrial zone.
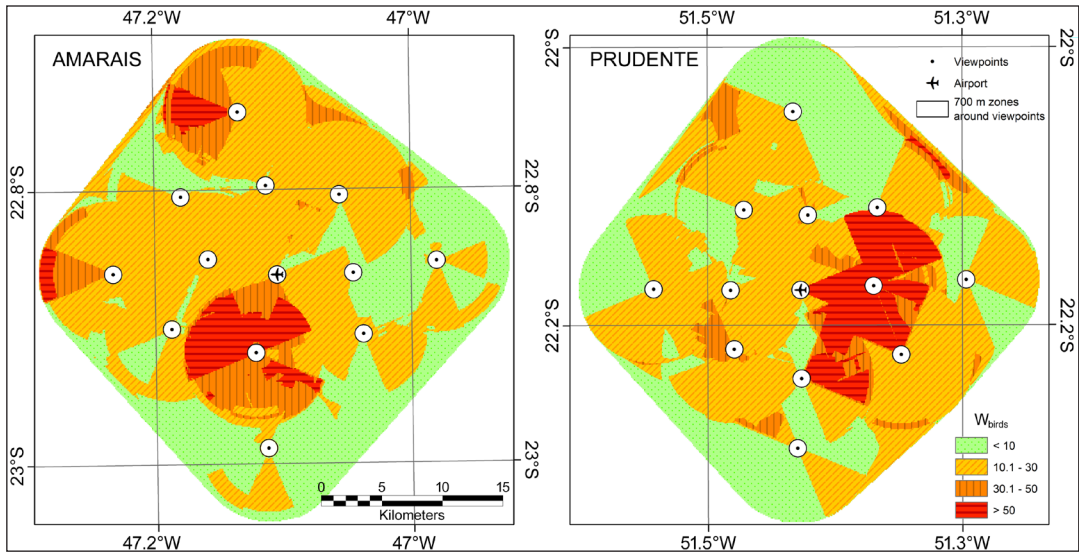
Figure 7. The risk assessment maps of aircraft collisions with black vultures (*Coragyps atratus*) within 20-km Airport Safety Area around the Amarais Airport and Presidente Prudente Airport in southeast Brazil, September 2012 to August 2013.

Dependence on the landscape type

The mean relative density ($\bar{\rho}$) found for the Amarais vicinity is 30 birds ha^{-1} and for Prudente, 46 birds ha^{-1}. The density of soaring vultures is about equal in both Amarais and Prudente above natural areas, natural water objects, and dense residential zones, but very different above suburbs, roadways, and industrial zones (Table 2; Figure 6). In comparing the types of landscapes, the dense residential zones were the least favorable territories around both airports. Vultures tended to avoid them. Natural areas provided the neutral attractiveness in the Amarais site and the negative attractiveness in Prudente. Natural landscapes dominated in the Prudente surroundings and the majority of vultures were recorded above them. However, although these places are the typical vulture habitats, they do not establish the special conditions for increased concentration of birds. Suburbs and industrial zones are about indifferent for vultures living near the Amarais Airport, but they are highly attractive for the Prudente population. The area of suburbs and industrial zones in the Prudente site is only 5% and, by contrasts to natural surroundings, they can provide strong technogenic thermals. The roadways together with artificial and especially natural water reservoirs (with shorelines) are the most attractive objects in both investigated areas.

Risk of collision with black vultures over the study sites

Two types of risk assessment maps were designed to illustrate the distribution of soaring black vultures in the vicinity of airports. The maps showing the 20-km zone around each airport (Figure 7) provided an overall estimation of the hazard of bird-strike events and identify the most dangerous areas for aircraft take-offs and landings. Whereas the threat of bird-strike events was much higher around Presidente Prudente Airport, the percent of territory with minimum risk of collision ($W_{birds} < 10$) in each site is about 30%. In the Amarais surroundings, birds concentrated to the south and southwest of the airport. The east and northwest are the safest regions. At Presidente Prudente Airport, the east, northeast, and southeast directions were the most at risk for bird strikes. The safest areas are located in the west.

The second type of risk assessment maps was built for the circular zone of a 700-m radius around the viewpoints and has a higher accuracy than the maps built for the entire area (e.g., the map built for the viewpoint no. 7 [airport] of the Amarais site [Figure 8D]). The risk assessment map is given in combination with the Digital-Globe image and the raster maps of surface temperature, contrast of surface temperature, and landscape characteristics constructed using the satellite imagery (Figure 8A–C).
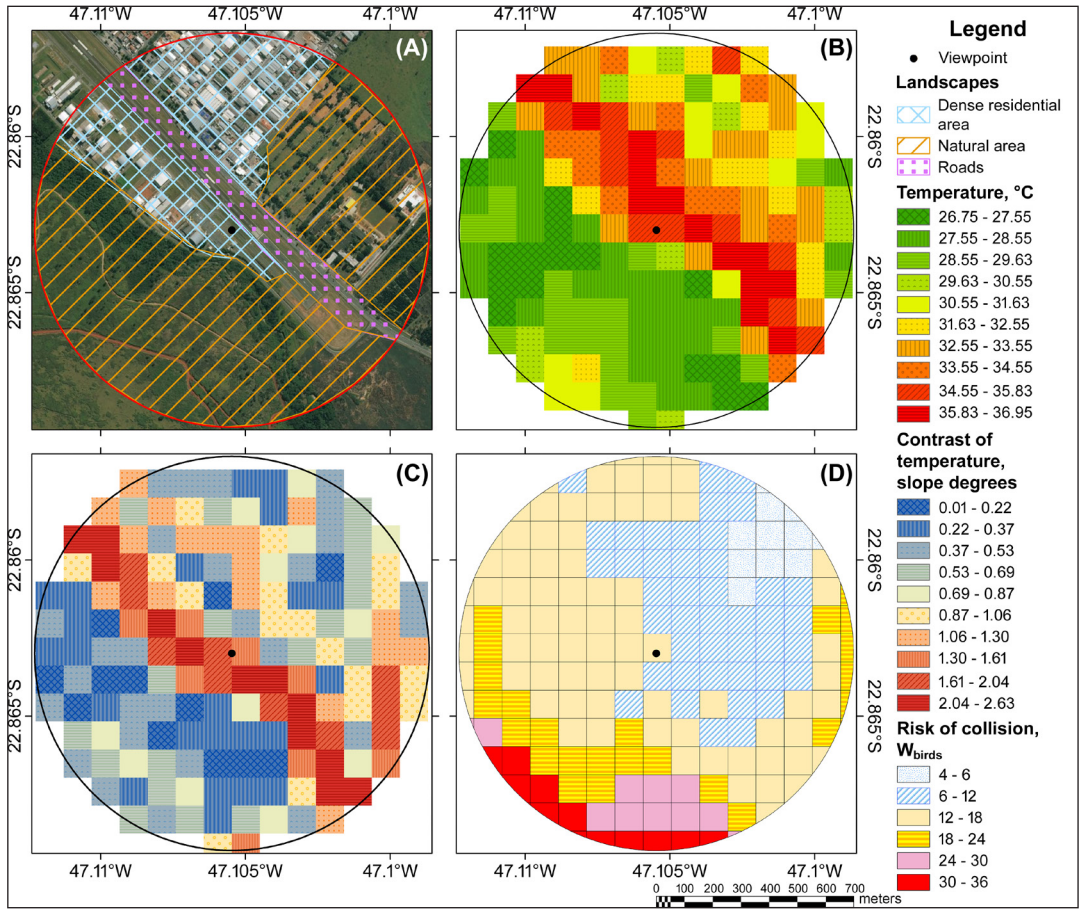
Figure 8. The risk assessment map designed for a 700-m zone around viewpoint no. 7 of Amarais Airport Safety Area, southeast Brazil, September 2012 to August 2013, combined with satellite data representation and landscape classification: (A) the true-color band composition of high-resolution imagery and landscape types, (B) surface temperature, (C) contrast of surface temperature, and (D) risk assessment map.

The visual analysis of risk assessment maps together with superficial characteristics indicated that: (1) the concentration of flying birds over the rural and natural lands was higher than over the urban territories; (2) the surface temperatures of urban areas were higher than in rural and natural lands, which is a clear cartographic confirmation of the well-known effect of the hotspots forming over cities; and (3) the strongest temperature contrast formed above roadways and at the boundary of natural or agricultural lands and urban districts.

Discussion

The contrast of surface temperatures, surface temperature, and level of anthropogenic pressure influenced the number of black vultures over the soaring terrain (i.e., W_{birds} parameter).

Those factors can be linked with thermal circulation in the atmospheric boundary layer. The contrast in surface temperatures causes the forming of thermals above hotspots, or areas heated more than the surrounded lands. The stronger temperature contrast provides the more powerful thermals (Stull 1988). Hence, considering the positive relationship observed between W_{birds} and temperature contrast, we can conclude that the number of soaring vultures depends on the strength of thermals. In other words, vultures choose the strongest thermals in their surroundings. This behavioral trait of black vultures is also typical for most avian scavengers and can be explained by adaptation to minimize the energy loss in flight (Schoener 1971, Ruxton and Houston 2002). Many researchers argued the importance of thermals for

soaring flight of black vultures and its related species, the turkey vulture (*Cathartes aura*; Newman 1958; Parrott 1970; Pennycuick 1971, 1983; Coleman and Fraser 1989; Thompson et al. 1990; Mandel and Bildstein 2007; Akos et al. 2010; Freire et al. 2015; Mallon et al. 2016). Both species use thermals for lift and continuous soaring during daylight. The soaring activity coincides accurately with hours of thermals rising; it starts after the local sunrise and finishes before the local sunset. Turkey vultures can even continue to soar after sunset using strong artificial thermals with illumination (Mandel and Bildstein 2007, Novaes and Cintra 2013, Freire et al. 2015). Besides, vultures often locate their roosts near the structures generating thermals (Thompson et al. 1990). During cold weather, the lack of strong and steady-state thermals can keep turkey vultures on the ground for several days or more (Mandel and Bildstein 2007). Both species use the flapping flight very rarely and mainly at low altitudes (about 10 m over the ground).

The activity of vultures correlated with contrast of superficial temperature linked with strength of thermals. However, the estimated confidence level of this relationship could be diminished by several factors. If the territory does not have strong triggers producing thermals, they will also be formed, but at variable positions (Stull 1988). In this case, methods analyzing the contrast in surface temperatures may not detect correctly the locality of thermals. There may be a threshold value for thermal strength that is able to impose vulture behavior. Vultures may not prefer the strongest thermal if it is only a bit stronger than its counterparts. Thermals attract soaring vultures, but this is not the only factor governing their behavior. Whereas highly urbanized vast lands of the Amarais site provide the strongest thermals, vultures avoid them because of their unfavorable environmental conditions. Open areas like pastures and fields are preferred for their foraging (Coleman and Fraser 1989).

There was a strong positive link between W_{birds} and the entire range of temperature contrast in the Prudente site. In the case of Amarais, this relationship was detected only for the first 6 ranks of this superficial characteristic. The areas with the highest contrast in surface temperatures differed for vultures living in the Amarais ASA zone. This finding can be explained by the stronger anthropogenic pressure in this site. There were more industrial and dense urbanized zones generating the artificial heating in the Amarais surroundings than near Presidente Prudente Airport (Table 2). The PCA analysis revealed a positive link between anthropogenic pressure and surface temperature for the Amarais records. Also, the performed tests showed the inverse correlation between surface temperature and W_{birds} in both sites. Therefore, areas exposed to strong anthropogenic impact, despite strong thermals forming over them, may be less attractive for black vultures than small urbanized areas surrounded by natural or rural environments. This may occur because of unfavorable conditions, such as the noise emitted by people and vehicles, the lack of high trees for perching and potable water, and scarce food resources. In addition, there were no large food dumps in the study sites, and all carcasses are usually quickly removed from the ground.

Most of the birds, 40% and 58% in Amarais and Presidente Prudente ASA zones, respectively, were recorded above natural and rural landscapes. However, those lands were characterized by the near-neutral attractiveness. They did not provide the conditions to foster huge aggregations of soaring birds in comparison with other types of landscapes. One possible explanation is that natural landscapes represent usual vulture habitats (Coleman and Fraser 1989).

The heterogeneous fragmented environments showed the elevated birds' densities in 2 study sites. The natural landscapes ("natural area" in Table 2) were more attractive for soaring vultures in Amarais than in Prudente. In contrast, the urbanized lands ("suburb" and "industrial zone" in Table 2) in Amarais were less attractive for vultures than those landscapes in Prudente. This observation can be explained by the different level of negative impact on the environment of highly urbanized lands in both study areas. Unlike the vicinities of the Amarais Airport, which are subjected to intensive human impact, the highly modified landscapes in the Presidente Prudente ASA zone consist mostly of small urban settlements surrounded by natural and agricultural areas. Therefore, those areas do not provide the strong deterrent

effect and, at the same time, can produce the increased air heating. As a result, vultures from the neighboring natural lands can be attracted to thermals rising over those lands. In contrast, despite strong thermals, birds prefer not to fly over vast uninterrupted urban areas (~20 % of the entire territory) in the Amarais site, possibly due to a stronger negative impact of the city environment. The small natural fragments of the Amarais site may attract vultures from more urbanized surroundings. This is probably a common behavioral trait of vultures inhabiting large cities (Novaes and Cintra 2013). Small natural fragments attract birds by thermals generated because of heating contrast between urban and natural lands and by other factors, such as high trees and quiet, natural places convenient for their roost as well as clean water for drinking. According to our observations in the city of Campinas, vultures need water for drinking. They drink water sitting on the ground even from a small puddle with a diameter of 1 m. In other words, heterogeneous habitats provide more diverse resources on a smaller area, and black vultures do not need to leave them. This remarkably fits the conclusion made by Tucker et al. (2019). They found that many bird species travel more intensively in homogeneous territories compared with areas of high resource variability. Also, the statistical analysis of data on bird strikes around U.S. airports reveals increased incident rates above heterogeneous landscapes with both natural and anthropogenic fragments and water bodies (Pfeiffer et al. 2018). Vultures use various environments and prefer areas combining feeding opportunity and safe roosting locals (DeVault et al. 2004).

In both study areas, the automobile roads and landscapes with banks of water bodies ("roadway," "natural water object," and "artificial water object" in Table 2) showed the high level of attractiveness for soaring vultures. This attractiveness of roadways is most likely due to 2 reasons. First, scavengers can find road kills there. Second, the dark asphalt pavement provides a high contrast in temperature in comparison to adjacent lands and generates the thermals.

The areas in ASA zones with small rivers and ponds were identified as the most attractive landscape for soaring vultures. The riparian area of artificial water reservoirs also draws birds, but to a lesser extent. This apparently contradicts the report of Mallon et al. (2016), which concluded that black vultures soar more frequently over field cover than shoreline or roads. According to our field observations, black vultures often preferred to soar above the narrow strips of vegetation fragments adjacent to water bodies, wetlands, ponds, and rivers, although there were no birds in the sky above nearby agricultural fields and suburbs. This behavioral trait can be explained by the increased contrast in superficial temperatures forming in daily hours between cold water bodies and heated dry lands. The resulted strong thermals can attract vultures from adjacent areas. Also, the fragments of vegetation often surrounding the water objects can provide perching and roosting sites. Moreover, vultures can find natural food and water in those landscapes.

Our data corroborate the reports that vultures soar above all types of natural and urbanized environments (Buckley 1999, Bastos 2001, Mandel and Bildstein 2007, Novaes and Cintra 2013). Heterogeneous landscapes combining natural, rural, and urban fragments are more attractive for them. Vultures tend to concentrate above hotspots, areas with a strong contrast in surface temperature, generating thermals.

The elaborated technique to design the risk assessment maps is an important result of this research. This approach allows predicting the dangerous objects in ASA zones of airports. The built examples (Figures 7 and 8) depict with color the degree of collision risk with black vultures. Unlike most of the previous GIS approaches applied to visualize the spatial distribution of flying birds at vast territories (Leshem et al. 1998, Buurma 1999, Anagnostopoulos 2000, Gray 2003, Kelly 2005, Gard et al. 2007), the present technique allows predicting the hazard from black vultures or other birds over any small area. As a result, the potentially dangerous zones can be found and the routes for safe landing and take-off operations can be tracked for airplanes in any airport surroundings. Using the relationships between soaring activity of vultures, thermal strength (or contrast of surface temperatures), types of landscapes, and anthropogenic stress, those maps can be built with high accuracy.

We expect this methodology can be adequately used to assess the risk of collision with other avian species all over the world.

Management implications

The areas generating strong and steady-state thermals attract soaring vultures and pose the major danger for aircraft flights. Natural thermals are triggered by the boundaries between different types of surface covering, producing high contrast in surface temperatures (e.g., the isolated constructions made of concrete, asphalt, and metal; the coastline of lakes, rivers, and ponds; the forest and plowed field margins; and the borders between hill slopes of different exposure). The technogenic thermals generated by industrial heating like power stations or factory pipes can be the most threatening for airplane flights since they can draw an extremely high concentration of birds. The illuminated technogenic thermals may be dangerous also at night hours. In this research, we detected the artificial and natural water bodies and their shorelines, automobile roads, and natural enclaves in urban ambient or suburbs surrounded by natural and rural landscapes as the most attractive objects for soaring vultures. All areas producing the high risk of collision with birds should be plotted on risk assessment maps visualizing the large ASA zones around airports. The mapping as a part of management strategy harmless to vultures' populations can identify the safe aircraft take-off and landing routes.

Acknowledgments

Supplementary materials

Supplementary Datasets including all data collected in field and processed with GIS are deposited at https://data.mendeley.com/datasets/8s3fps4vvb/.

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