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Wind energy development in Latin America and the Caribbean: Risk assessment for flying vertebrates

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ABSTRACT

Airspace fragmentation caused by human activity threatens wildlife. Wind turbines occupy a range of altitudes frequently used by many flying vertebrates, potentially leading to collisions and other adverse effects. Here, we review the impact of wind farms on birds and bats in Latin America and the Caribbean (LAC) and found that research is lacking, with just 22 available articles focusing on only six countries. Indirect effects, such as habitat fragmentation and barrier effects remain understudied, with most studies focusing on direct collision mortality. We identified more than 16,000 wind turbines in operation or being planned in LAC countries. Nearly half of the region's threatened bird and bat species inhabit areas with operating wind farms, including the densely wind farmed Isthmus of Tehuantepec in Mexico, the Guajira region in Colombia, and the Caribbean islands, among others. Passeriformes, followed by Psittaciformes, were the bird orders most frequently found in areas with wind turbines. Additionally, we found some migratory bat species, which are particularly prone to collision with wind turbines, were commonly associated with regions of high wind turbine density. Our results suggest that expansion of wind energy in Latin America and the Caribbean could affect several threatened species. Finally, we provide a map showing potential areas for future wind energy development and recommend conducting focused field studies on habitat use by local bird and bat species in these regions to avoid, minimize and mitigate impacts.

1. Introduction

In the current context of climate change, renewable energies, such as the wind energy industry, have emerged as a solution to progressively replace fossil fuels (GWEC, 2024; Haces-Fernandez et al., 2022; Ortega-Izquierdo and Río, 2020). Its rapid growth and expansion are expected to continue in the coming decades worldwide (GWEC, 2024). Despite the environmental benefits of wind energy, such as replacing energy sources such as fossil fuels that produce large quantities of greenhouse gases, it is also important to consider their impacts throughout its life cycle. These include the sourcing of materials, gas emissions and toxic emissions generated during the manufacture, transport and construction of components, particularly the turbines, as well as the treatment and disposal of waste at the end of the project's life (Arvesen and Hertwich, 2012). In addition, the construction and operation of wind farms can have adverse effects on the environment and biodiversity (Mello et al., 2020; Saidur et al., 2011). From an aeroecological perspective, wind farms can negatively impact the aerial habitat and the species that inhabit it (Drewitt and Langston, 2006; Kunz et al., 2007; Lambertucci et al., 2015; Thaxter et al., 2017). The most widespread modern onshore wind turbines typically have a hub height of approximately 80 m and a rotor diameter of about 120 m, with blades reaching 60 m in length (Lantz et al., 2019). However, in recent years there has been a trend towards increasing rotor size to improve wind capacity per turbine, with onshore turbines already reaching heights of up to 245 m (GWEC, 2024). Furthermore, distribution and transmission lines stand between 10 and 30 m high (Martín Martín et al., 2022). Consequently, the airspace between 10 and around 200 m, which represents the aerial domain with the highest concentration of flying vertebrates, is now extensively occupied by human infrastructure (Lambertucci et al., 2015). Wind

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energy main impacts on birds and bats is by direct collisions with turbine blades and towers (Arnett et al., 2008; de Lucas et al., 2007; Drewitt and Langston, 2006; Hein and Schirmacher, 2016; Marques et al., 2014); collisions and electrocutions caused by the associated infrastructure such as power lines are well documented (Bernardino et al., 2018; Loss et al., 2015; Loss et al., 2014; Manville, 2016; Rebolo-Ifrán et al., 2023). Other negative impacts include habitat loss, barrier effect (Drewitt and Langston, 2006; Lemaître and Lamarre, 2020; Sánchez-Zapata et al., 2016; Smith and Dwyer, 2016), and noise and visual pollution (Teff-Seker et al., 2022; Wang and Wang, 2015).

Bird and bat mortality due to collisions with wind turbines has been widely documented worldwide (Thaxter et al., 2017). This can have a negative impact on the demography and population dynamics of species exposed to these structures (Duriez et al., 2023; Rydell et al., 2010; Schaub, 2012). For instance, collision mortality poses a significant extinction risk for endangered species as the Egyptian vulture (*Neophron percnopterus*) (Sanz-Aguilar et al., 2015). The global lack of comprehensive population-level data for many bats species makes it difficult to fully assess the impact of wind turbines on their demography (Arnett and Baerwald, 2013; Arnett and May, 2016; O'Shea et al., 2016). Nevertheless, recent studies indicate that the mortality of the Hoary Bat (*Lasiurus cinereus*) due to collision with wind turbines has already caused a reduction in their population size, which would significantly elevate this species' risk of extinction (Frick et al., 2017; Friedenberg and Frick, 2021).

The impact of wind farms on flying fauna has been mainly studied in industrialized regions of the northern hemisphere (Thaxter et al., 2017), but much less is known about the Neotropical region (Agudelo et al., 2021). It is crucial to identify the most vulnerable areas where wind farms may affect threatened flying fauna. This would facilitate planning for the mitigation measures of existing wind farm threats and help to determine suitable areas for future wind farm industry, which would minimize or prevent adverse impacts.

To understand the impact of wind farms on birds and bats in the Latin America and the Caribbean (LAC) region, we first conducted a comprehensive review of studies that assessed any of the phases leading to wind farm establishment: pre-construction, construction, and short- and long-term operation. We also evaluated the risk currently represented by wind farms to the IUCN globally threatened birds and bats species. This assessment involved overlaying species distribution data with wind farm locations. Then, we identified the areas of potential overlap and species most vulnerable to wind farm impacts. Finally, we analyzed Wind Power Density (WPD), an indicator of available wind energy that considers air density and wind speed that is generally used to evaluate the feasibility of installing wind energy infrastructure, to predict potential future wind farm locations, aiming to identify areas where wind farm construction would affect birds and bats in the region, in particular threatened species.

2. Methods

2.1. Bibliographic search

We first conducted a literature review to obtain and assess information available on the impact of wind farms on LAC birds and bats by searching scientific articles in Scopus (https://www.scopus.com/) and Google Scholar (https://scholar.google.com/). For the literature search, we combined the words "wind farm", "wind energy", "turbine" or "renewable" with the terms related to the target impact, such as "bats" or "birds", combined with every LAC country name. The search was carried out in English and in the main local languages of most countries: Spanish and Portuguese. We selected scientific articles up to April 2024 evaluating the current or potential impact of wind energy development on birds and bats. We extracted information about the country and year analyzed, bird or bat species studied, type of impacts assessed (collision fatality/habitat loss/barrier effect/physiological impacts), and the phase of windfarm stage (pre-construction / construction / operation).

2.2. Wind turbine, wind power density and flying wildlife

2.2.1. Wind farm database

We made an exhaustive compilation of operating and planned wind power plants in all LAC countries. For this purpose, we created a database with information on the location of wind farms, the number of wind turbines in each, and the energy produced. Data was obtained from the global wind energy database: The Wind Power (https://www.thewindpower.net). The potential missing data was complemented with information from the websites of wind energy companies working in the area. We thus compiled an updated list of operating wind farms in LAC.

2.2.2. Threatened species database

To identify bird species that, due to their conservation status, could experience any negative impact as a result of wind farm infrastructure, we selected all the threatened LAC bird and bats species according to the IUCN criteria: Vulnerable (VU), Endangered (EN) or Critically Endangered (CR). For this purpose, we used the advanced search tool of the IUCN website (https://www.iucnredlist.org/search) with the following filters: Taxonomy (birds or bats), Red List Category (CR - Critically Endangered, EN - Endangered, VU - Vulnerable), Land Regions (Caribbean Islands, Mesoamerica, North America, South America) and Country Legends (Extant and Possibly Extant). We then eliminated all North American species that do not live in the Neotropics (e.g., species endemic to the USA and Canada). Finally, we eliminated orders of birds with low or no susceptibility to aerial impact (i.e., collision) with wind turbines, such as terrestrial or flightless bird orders (e.g., Struthioniformes, Sphenisciformes). Threatened bird and bat species distribution data were downloaded from the IUCN website (https://www.iucnredlist.org/es/search) in shapefile format. Although not all globally threatened species are necessarily susceptible to wind energy development, we decided to take a precautionary approach because the effects on these threatened species, if they occur, may have a disproportionate population impact. Therefore, their threatened status in combination with their overlap with areas of potential wind energy development could pose a concerning risk to them.

In the case of birds, we validated our analyses with distributions based on the records available through the eBird citizen science project. We did this because IUCN data provides a simple expert-based distribution polygon for each species (coarse grain data), whereas eBird provides curated records for the presence of each bird (fine-grain data). We downloaded presence records for each bird species in LAC (https://science.ebird.org/en/use-ebird-data/download-ebird-data-products, eBird, 2023). We found eBird records were available for 390 of the species. Species that were not recorded in eBird either inhabit inaccessible environments or are found in very low densities. In addition, some species might have more than one classification or scientific name, a problem which complicated comparison between the two datasets. Thus, when comparing IUCN and eBird derived richness, we restricted this comparative analysis to species present in both databases. We found that IUCN polygons present wider distribution ranges than eBird observations, particularly over the ocean and in inaccessible onshore areas where eBird records are scarce (Fig. S1). While eBird field records offer valuable information on species observed, they have some important limitations, particularly in terms of lack of data for inaccessible areas or regions with low bird watchers' presence. An underestimation of species distributions in these areas is predictable (e.g., marine, Andean and Amazonian species). However, preliminary information shows the similar results for both databases (Fig. S2). Therefore, given objective of the study, similar results between two databases, and that the IUCN database is the only available for bats, we used IUCN distribution polygons to assess a coarse-grained overlap between species distribution and wind turbines.

2.2.3. Wind power density (WPD)

Global wind speed and air density *geotiff* images were downloaded from Global Wind Atlas version 3.0 (https://globalwindatlas.info/). We used wind power density (WPD) at 50 m above ground level as a quantitative measure of available wind energy. We have selected this altitude as a conservative estimate of minimum wind potential and construction feasibility. This approach minimizes the risk of overestimating viable areas and allows the identification of regions with clear wind potential at lower altitudes and/or with low investment requirements.

WPD was calculated by using the equation:

$$WPD_{(x,y)} = 1/2 \text{ x } AD_{(x,y)} \text{ x } WS_{(x,y)}{}^{3}$$

where $AD_{(x,y)}$ represents the mean air density [kg/m^3] within a grid cell, and $WS_{(x,y)}$ the mean wind speed [m/s]. $WPD_{(x,y)}$ [Watts/m^2].

We calculated WPD classes (1–7), following the methodology of Elliott (1986). All pixels with WPD $<$ 50 were assigned to class 0, which represents a very low capacity to generate electricity with a wind speed annual average of less than 9 km/h. We identified the threatened bird and bat species that overlap their distribution with areas with WPD $>$ 1 where there are still no turbines (see Table S3 for the proportion of each species' distribution that overlaps with areas where WPD $>$ 1).

2.2.4. Spatial overlap analysis

All datasets were loaded in *python* environment version 3.7.8 (libraries *cartopy* 0.18.0, *geopandas* 0.10.2, *matplotlib* 3.5.1, *numpy* 1.21.2, *pandas* 1.4.1, *regionmask* 0.9.0, *xarray* 2022.3.0), and put into a 1° by 1° grid of LAC (latitude = [−57,34], longitude = [−119,-30]). All codes, raw figures and the general notebook workflow has been uploaded to a Github repository https://github.com/nlois/Latam_windfarms_birds_bats/

We generated maps based on a 1° by 1° analysis grid, within which we summarized each variable with *xarray* library (see Supplementary Code). First, threatened species richness was calculated by counting the number of species present within each grid cell in both the IUCN database and eBird records. Wind turbines and wind farms were also counted within each grid cell. Finally, WPD was averaged within each cell, which was then classified following the methodology by Elliot and collaborators (Elliott, 1986).

To investigate the potential impact of wind farms on avian and bat species in LAC, we created two maps: the first is an overlay map showing where threatened bird and bat species coincide with operating wind turbines; we took into account species richness and wind turbine density to quantify the extent of exposure to potential impacts of wind infrastructure. The second map illustrates WPD in regions where wind farms are currently absent; this helps identify areas of potential wind development and bird and bat species that could be negatively affected in the future by the ongoing energy transition. Species overlap with these areas was estimated and tabulated.

In short, the analytical workflow consisted in calculating WPD through Eq. 1 and obtaining for each grid a spatial mean for WPD, which was then classified into WPD classes (0–7). Species richness within each cell was then calculated for each dataset: IUCN presence polygons were rasterized to the 1°grid and eBird points by species were plotted within each cell and converted into a presence/absence (1/0) raster. Finally, wind farm and turbine sites compiled for this study were counted within each cell (see summary of workflow in Fig. 1). To overlap these raster layers, we normalized each variable by its maximum, thus obtaining an index for each variable within a range of 0–1, and multiplied the two normalized values in each cell. We finally normalized this overlap index to obtain a 0–1 range once again.

3. Results

3.1. Scientific information from Latin American and the Caribbean (LAC)

We found 22 scientific papers that evaluate the different impacts of wind farms on birds and bats in LAC (Table 1). Twelve of these were on bats, nine on birds, and one on both groups. Six LAC countries conducted research on this topic: twelve articles focused on Mexico, seven on South

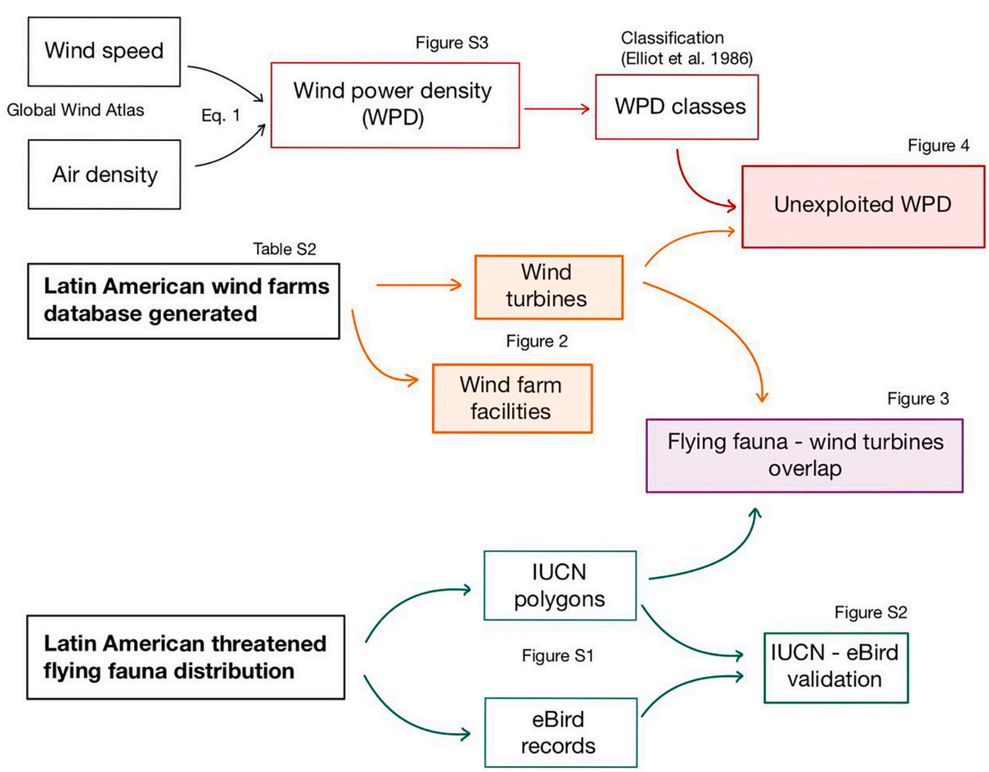

Fig. 1. Spatial analysis workflow to obtain figures for the study.

Table 1
List of scientific papers published up to April 2024 on the impact of wind farms on birds and bats in the Neotropics.

Reference	Taxa	Year_analyzed	Country	Phase
Barros et al. 2015 [1]	Bats	2004–2010	Brazil	Pre-construction/ Operational
Bolívar-Cimé et al., 2016 [2]	Bats	2009–2013	Mexico	Operational
Briones-Salas et al., 2017 [3]	Bats	2007–2014	Mexico	Pre-construction / Construction / Operational (short and long term)
Cabrera-Cruz and Villegas-Patraca, 2016 [4]	Birds	2009–2014	Mexico	Operational
Cabrera-Cruz et al. 2020 [5]	Both	2015	Mexico	Operational
Cabrera-Cruz et al. 2023 [6]	Bats	2021	Mexico	Operational
do Amaral et al., 2020 [7]	Bats	2014–2018	Brazil	Operational (short and long term)
Escobar et al. 2015 [8]	Bats	2010	Chile	Operational
Falavigna et al., 2020 [9]	Birds	2009–2015	Brazil	Pre-construction / Construction / Operational
García-Luis and Briones-Salas, 2017 [10]	Bats	2013–2014	Mexico	Operational
Herrera-Alsina et al. 2013 [11]	Birds	2010–2011	Mexico	Operational
Lemos et al., 2023 [12]	Birds	2009–2015	Brazil	Pre-construction
Medina-Cruz et al., 2020 [13]	Bats	2014	Mexico	Operational
Pedrana et al., 2023 [14]	Birds	2015–2018	Argentina	Operational
Rodríguez-Durán and Feliciano-Robles, 2015 [15]	Bats	2013–2014	Puerto Rico	Operational
Sauthier et al. 2023 [16]	Bats	2021	Argentina	Operational
Trujillo et al. 2020 [17]	Bats	2015–2016	Guatemala	Operational
Trujillo et al. 2021 [18]	Bats	2015	Guatemala	Operational
Uribe-Rivera et al. 2019 [19]	Birds	2015–2016	Mexico	Operational
Villegas-Patraca et al., 2012 b [20]	Birds	2008	Mexico	Operational
Villegas-Patraca et al., 2014 [21]	Birds	2011	Mexico	Operational
Villegas-Patraca & Herrera-Alsina 2015 [22]	Birds	2008, 2009 and 2011	Mexico	Operational

1. Barros MAS, De Magalhães RG, Rui AM. 2015 Species composition and mortality of bats at the Osório Wind Farm, southern Brazil. *Studies on Neotropical Fauna and Environment* **50**, 31–39. (doi:https://doi.org/10.1080/01650521.2014.1001595).

2. Bolívar-Cimé B, Bolívar-Cimé A, Cabrera-Cruz SA, Muñoz-Jiménez Ó, Villegas-Patraca R. 2016 Bats in a tropical wind farm: species composition and importance of the spatial attributes of vegetation cover on bat fatalities. *Journal of Mammalogy* **97**, 1197–1208. (doi:https://doi.org/10.1093/jmammal/gyw069).

3. Briones-Salas M, Lavariega MC, Moreno CE. 2017 Effects of a wind farm installation on the understory bat community of a highly biodiverse tropical region in Mexico. *PeerJ* **5**, e3424. (doi:https://doi.org/10.7717/peerj.3424).

4. Cabrera-Cruz SA, Villegas-Patraca R. 2016 Response of migrating raptors to an increasing number of wind farms. *J Appl Ecol* **53**, 1667–1675. (doi:https://doi.org/10.1111/1365-2664.12673).

5. Cabrera-Cruz SA, Cervantes-Pasqualli J, Franquesa-Soler M, Muñoz-Jiménez Ó, Rodríguez-Aguilar G, Villegas-Patraca R do Amaral et al., 2020 Estimates of aerial vertebrate mortality at wind farms in a bird migration corridor and bat diversity hotspot. *Global Ecology and Conservation* **22**, e00966. (doi:https://doi.org/10.1016/j.gecco.2020.e00966).

6. Cabrera-Cruz, S. A., Aguilar López, J. L., Aguilar-Rodríguez, P. A., Oropeza-Sánchez, M. T., Muñoz Jiménez, O., & Villegas Patraca, R. (2023). Changes in diversity and species composition in the assemblage of live and dead bats at wind farms in a highly diverse region. Environmental Monitoring and Assessment, 195(12), 1480.

7. do Amaral IS, Ramos Pereira MJ, Mader A, Ferraz MR, Bandeira Pereira J, Oliveira LR do Amaral et al., 2020 Wind farm bat fatalities in southern Brazil: temporal patterns and influence of environmental factors. *Hystrix, the Italian Journal of Mammalogy* **31**, 40–47.

8. Escobar LE, Juarez C, Medina-Vogel G, Gonzalez CM. 2015 First Report on Bat Mortalities on Wind Farms in Chile. *Gayana (Concepc.)* **79**, 11–17. (doi:https://doi.org/10.4067/S0717-65382015000100003).

9. Falavigna TJ, Pereira D, Rippel ML, Petry MV do Amaral et al., 2020 Changes in bird species composition after a wind farm installation: A case study in South America. *Environmental Impact Assessment Review* **83**, 106,387. (doi:https://doi.org/10.1016/j.eiar.2020.106387).

10. García-Luis M, Briones-Salas M. 2017 Composición y actividad de la comunidad de murciélagos artropodívoros en parques eólicos del trópico mexicano. *Revista Mexicana de Biodiversidad* **88**, 888–898. (doi:https://doi.org/10.1016/j.rmb.2017.10.018).

11. Herrera-Alsina L, Villegas-Patraca R, Eguiarte LE, Arita HT. 2013 Bird communities and wind farms: a phylogenetic and morphological approach. *Biodivers Conserv* **22**, 2821–2836. (doi:https://doi.org/10.1007/s10531-013-0557-6).

12. Lemos CA, Hernández M, Vilardo C, Phillips RA, Bugoni L, Sousa-Pinto I. 2023 Environmental assessment of proposed areas for offshore wind farms off southern Brazil based on ecological niche modeling and a species richness index for albatrosses and petrels. *Global Ecology and Conservation* **41**, e02360. (doi:https://doi.org/10.1016/j.gecco.2022.e02360).

13. Medina-Cruz GE, Salame-Méndez A, Briones-Salas M do Amaral et al., 2020 Glucocorticoid Profiles in Frugivorous Bats on Wind Farms in the Mexican Tropics. *Acta Chiropterologica* **22**, 147. (doi:https://doi.org/10.3161/15081109ACC2020.22.1.013).

14. Pedrana J, Gorosábel A, Pütz K, Bernad L. 2023 First assessment on the influence of wind farms and high-voltage networks on ruddy-headed goose *Chloephaga rubidiceps* migration in Patagonia, Argentina. *Polar Biol* **46**, 639–653. (doi:https://doi.org/10.1007/s00300-023-03153-5).

15. Rodríguez-Durán A, Feliciano-Robles W. 2015 Impact of Wind Facilities on Bats in the Neotropics. *Acta Chiropterologica* **17**, 365–370. (doi:https://doi.org/10.3161/15081109ACC2015.17.2.012).

16. Sauthier, D. E. U., Herrera, G. O., Formoso, A. E., & D'Agostino, R. L. (2023). Primer registro del murciélago escarchado grande Lasiurus villosissimus (E. Geoffroy Saint-Hilaire, 1806) en la porción oriental de la provincia del Chubut, República Argentina. Notas sobre Mamíferos Sudamericanos, 5.

17. Trujillo LA, Barahona Fong R, Pérez SG do Amaral et al., 2020 Filling gaps in the distribution of the four free-tailed bat species of the genus Nyctinomops Miller, 1902 (Mammalia, Chiroptera, Molossidae), with three new records for Guatemala. *CheckList* **16**, 1747–1754. (doi:10.15560/16.6.1747).

18. Trujillo LA, Barahona-Fong R, Kraker-Castañeda C, Medina-Fitoria A, Hernández J, Pérez SG. 2021 Noteworthy records of bats of the genus Eumops Miller, 1906 from Guatemala: first confirmed record of Underwood’s Bonneted Bat, *Eumops underwoodi* Goodwin, 1940 (Mammalia, Chiroptera, Molossidae), in the country. *CheckList* **17**, 1147–1154. (doi:10.15560/17.4.1147).

19. Uribe-Rivera MA, Guevara-Carrizales AA, Ruiz-Campos G. 2018 Mortalidad incidental de aves paseriformes en un parque eólico del noroeste de México. *Huitzil Rev. Mex. Ornitol.* **20**, 1–7. (doi:10.28947/hrmo.2019.20.1.377).

20. Villegas-Patraca R, MacGregor-Fors I, Ortiz-Martínez T, Pérez-Sánchez CE, Herrera-Alsina L, Muñoz-Robles C. 2012 Bird-Community Shifts in Relation to Wind Farms: A Case Study Comparing a Wind Farm, Croplands, and Secondary Forests in Southern Mexico. *The Condor* **114**, 711–719. (doi:https://doi.org/10.1525/cond.2012.110130).

21. Villegas-Patraca R, Cabrera-Cruz SA, Herrera-Alsina L. 2014 Soaring Migratory Birds Avoid Wind Farm in the Isthmus of Tehuantepec, Southern

Mexico. *PLoS ONE* **9**, e92462. (doi:https://doi.org/10.1371/journal.pone.0092462).
22. Villegas-Patraca R, Herrera-Alsina L. 2015 Migration of Franklin's Gull (*Leucophaeus pipixcan*) and its variable annual risk from wind power facilities across the Tehuantepec Isthmus. *Journal for Nature Conservation* **25**, 72–76. (doi: https://doi.org/10.1016/j.jnc.2015.03.006).

America, and three on Central America and the Caribbean islands (Table 1). The most frequently studied impact was collision fatality, with 58 bat species belonging to six families and 49 bird species from 26 families recorded affected by this threat (Table S1). Habitat reduction or loss was recorded by two bat studies conducted on the Isthmus of Tehuantepec, Mexico, where species composition was evaluated on different spatial and temporal scales (Briones-Salas et al., 2017; García-Luis and Briones-Salas, 2017). Two bird studies addressed habitat reduction or loss due to wind farms in Brazil and Mexico (Villegas-Patraca et al., 2012). The barrier effect was analyzed only for birds. Two studies, both on the Isthmus of Tehuantepec, Mexico, observed that soaring bird species of the families Cathartidae, Accipitridae and Laridae adjusted their flight paths during migration to avoid areas occupied by wind turbines (Cabrera-Cruz and Villegas-Patraca, 2016; Villegas-Patraca et al., 2014). The physiological consequences of wind turbines on bats were evaluated in one study. Although glucocorticoids concentration in four species of fruit bats were always higher at sites with turbines than at sites without them, differences were not conclusive (Medina-Cruz et al., 2020).

In terms of the global threat category of the species studied, we found that three species of bats categorized as threatened or near threatened according to the IUCN are affected by wind farms. Collision fatalities were recorded for the Vulnerable Minor Red Bat (*Lasiurus minor*), and the Near Threatened Red Fruit Bat (*Stenoderma rufum*), both on a wind farm in eastern Puerto Rico (Rodríguez-Durán and Feliciano-Robles, 2015). In addition, the Near Threatened Lesser Long-nosed Bat (*Leptonycteris yerbabuenae*) was recorded as a victim of both collisions and habitat reduction due to the installment of turbines on wind farms on the Isthmus of Tehuantepec in Mexico (Bolívar-Cimé et al., 2016; Briones-Salas et al., 2017). Among birds, collision fatalities were recorded for the Near Threatened Eastern Whip-poor-will (*Antrostomus vociferus*) and Northern Bobwhite (*Colinus virginianus*). In addition, the Near Threatened Olive-sided Flycatcher (*Contopus cooperi*) and the Vulnerable Orange-fronted Parakeet (*Aratinga canicularis*) were present in secondary forests and croplands in the vicinity of the wind farm, but they were not present within 200 m of the turbine location (Villegas-Patraca et al., 2012). The Vulnerable Ochre-breasted pipit (*Anthus nattereri*) was also present during the preconstruction phase of the wind farm but it was not recorded during the construction or operation phases of the wind farm (Falavigna et al., 2020). Finally, four species of Procellariiformes were suggested to be potentially affected by future offshore wind development in southern Brazil. They are the Great Shearwater (*Ardenna gravis*), the Vulnerable White-chinned Petrel (*Procellaria aequinoctialis*), and two Endangered species: the Atlantic Yellow-nosed Albatross (*Thalassarche chlororhynchos*) and the Atlantic Petrel (*Pterodroma incerta*) (Lemos et al., 2023).

Regarding the temporal scale of the studies, most of them were conducted exclusively during the wind farm operation phase ($n = 18$). Three studies included preliminary evaluations that were used to compare with the post-construction phase (Table 1). The only study that exclusively evaluated the pre-construction phase found that four species of Procellariformes are potentially susceptible to the installation of offshore wind farms in Brazil (Lemos et al., 2023). In addition, only two studies provided short and long-term results during the operational phase (Table 1). In Mexico, the bat community was studied during the construction and operation at the La Venta wind farm. In this study, species richness and both functional and phylogenetic diversity declined during the construction and the first phase of operation; then, it increased over the years, but it did not recover to the values before the construction of the wind farm (Briones-Salas et al., 2017). Something similar occurred in the Palmares wind farm (Brazil) where the richness and abundance of birds decreased significantly after the beginning of the wind farm operation and then seemed to remain relatively similar during the following four years (Falavigna et al., 2020). Finally, most bat collision deaths at the Santa Vitória do Palmar wind farm (Brazil) occurred in the first year, with significantly lower mortality in the following three years of sampling (do Amaral et al., 2020).

3.2. Latin American wind farms

We found 857 wind farms (86 % in operation) with more than 16,000 wind turbines distributed in 20 LAC countries by September 2022 (Fig. 2). We created a database with information on each wind farm and its location (Table S2). Brazil stands out as the region's leader in wind turbine deployment, with over 7900 turbines; Mexico follows with more than 3000 turbines, whereas Chile and Argentina both have around 1000 wind turbines.

3.3. Latin America's threatened birds and bats

We identified 456 LAC threatened bird species (IUCN) that could be susceptible to the impact of wind turbines (Table S3). The highest richness of threatened birds was on the northwestern coasts of South America, including the northern part of Peru, Ecuador and Colombia, and on the southern coast of Brazil (Fig. 3a).

We identified 34 threatened LAC bat species (Table S3). The highest richness was found in Mexico, Caribbean islands and South American countries such as Venezuela, Colombia, Ecuador and Peru (Fig. 3c).

3.4. Wind turbines and flying fauna overlap

We obtained a map of the overlap between threatened bird and bat species richness and wind turbines for each 1° x 1° cell in LAC (Fig. 3b, d). Wind turbines currently overlap with the distribution of threatened bird species in several Central American and Caribbean countries; in Mexico and areas in northeastern Brazil, the southern coast of Brazil and Uruguay, central Chile, and central Argentina (Fig. 3b). The bat overlap map highlights Mexico, the Caribbean Islands and small areas in Chile, Ecuador and Peru as potential high-risk locations for this group (Fig. 3d). Of the 456 threatened bird species in the region, 50 % ($n = 228$) are distributed in areas currently occupied by operating wind farms (ranging from 0.1 to 178 turbine density per pixel). Of these, 14 are distributed in areas with a density of more than 50 turbines per 1° x 1° pixel, an area of approximately 10,000 km2 (Table S3). Of these, three species are Critically Endangered, the Yellow-naped Amazon (*Amazona auropalliata*), the Guanacaste Hummingbird (*Amazilia alfaroana*) and the Alagoas Tyrannulet (*Phylloscartes ceciliae*). In addition, four are classified as Endangered. Among the latter is the Leari's macaw (*Anodorhynchus leari*), Bahia Tyrannulet (*Phylloscartes beckeri*), Diamantina Tapaculo (*Scytalopus diamantinensis*) and Bare-necked Umbrellabird (*Cephalopterus glabricollis*).

We found that 16 bat species had varying degrees of overlap in their current distribution with wind turbines (range 0.1 to 52.8 turbines per 1° x 1° pixel, Table S3). The five bat species with the highest proportion of overlap with wind turbines were the Flat-headed Myotis (*Myotis planiceps*), the Greater Long-nosed Bat (*Leptonycteris nivalis*), Paraguana moustached Bat (*Pteronotus paraguanensis*), Thomas's Sac-winged Bat (*Balantiopteryx io*) and Eastern Pipistrelle (*Perimyotis subflavus*).

3.5. Wind power density (WPD)

From the spatial distribution of WPD at 50 m above ground level (Fig. S3), we obtained a map of WPD in areas where no wind farms currently exist (Fig. 4). Our map highlights some areas with favorable wind conditions, i.e. WPD > 1, but still without wind farms, that would

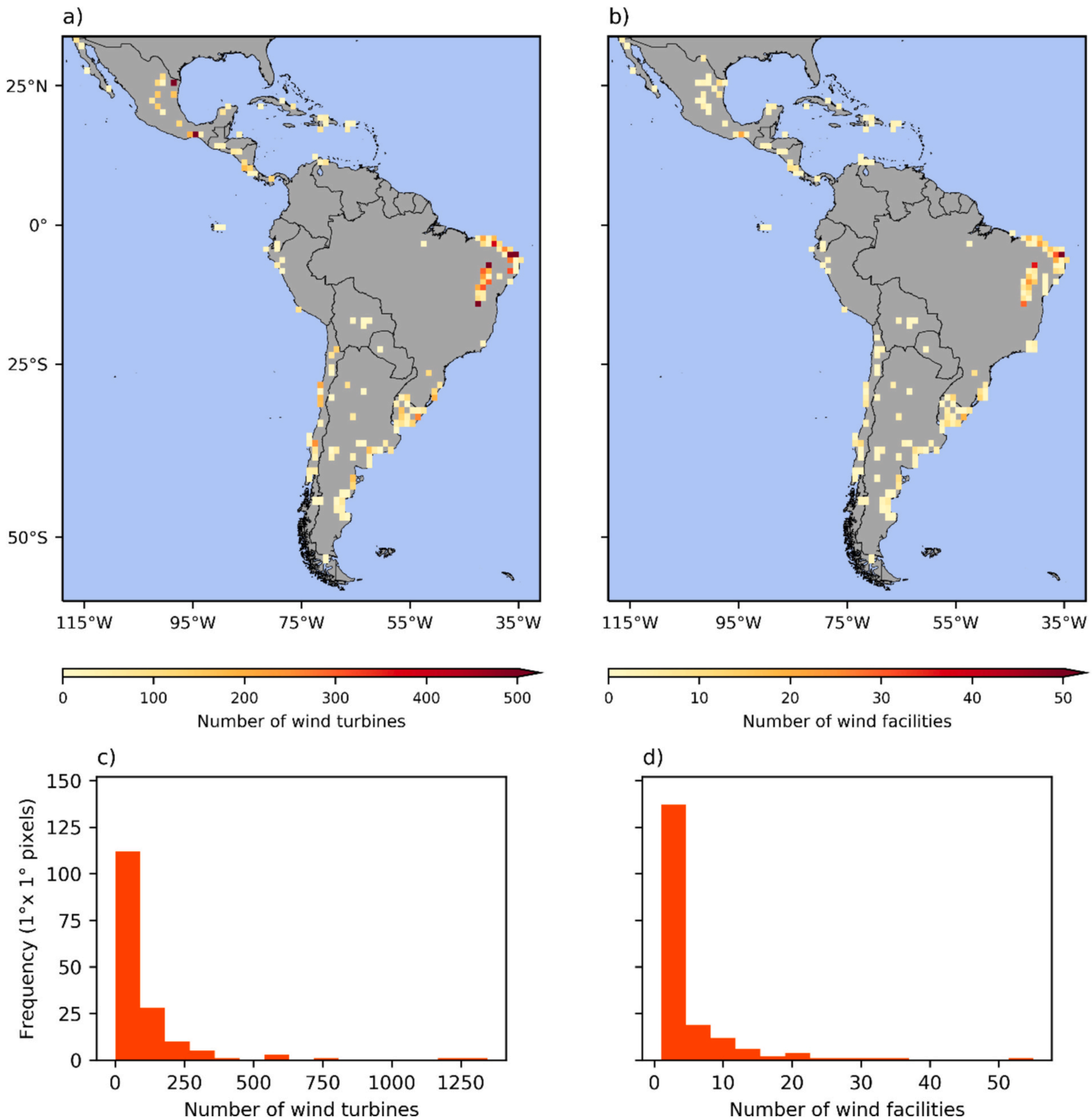

Fig. 2. Number of wind turbines (a) and the number of wind farms (b) within the 1° x 1° analysis grid in Latin American and the Caribbean. The color scale indicates the density of wind energy infrastructure, with darker colors representing higher densities. The high density per facility in Brazil and Mexico is evident from the difference between the maps. Panels (c) and (d) show histograms of pixel values corresponding to Fig. 2a and b, respectively, summarizing the distribution of density values.

allow for future wind development in the region. Among the areas with the highest WPD values, the Patagonian region of Argentina and Chile ranks first, with an average WPD class of 5. The Caribbean islands and Central America show high and variable WPD values, mainly concentrated in the offshore and coastal regions. In addition, both the Pacific and Atlantic coasts of South America show favorable areas for wind development, with WPD values of 1, 2, and 3. Finally, there is a large area in central South America characterized by a WPD class 1, indicating sufficient and consistent potential for wind energy development.

We found 122 bird species, belonging to 13 orders, whose distributions do not currently overlap with wind turbines, but occupy areas favorable to wind development. In particular, 24 of these bird species are classified as critically endangered, which makes considering them particularly important for the future development of wind energy infrastructure in these areas. Seabirds (mainly of the order Procellariiformes) are present in coastal areas with a high WPD, making them especially exposed to potential offshore wind farm development (Fig. 4). In the case of bats, our results show that two species that currently do not overlap their distribution with wind turbines could do so in the future. They are the Cuban Greater Funnel-eared Bat (*Natalus primus*), a species with a very restricted distribution on the island of Cuba, and the Choco Broad-nosed Bat (*Platyrrhinus chocoensis*), a species distributed in Ecuador and Colombia, both considered as Vulnerable.

4. Discussion

Airspace is essential for the survival, movement, feeding, reproduction, and general well-being of many wildlife species, especially for flying fauna such as birds and bats (Davy et al., 2017; Lambertucci et al., 2015). We evaluated if wind farm development can be an emergent

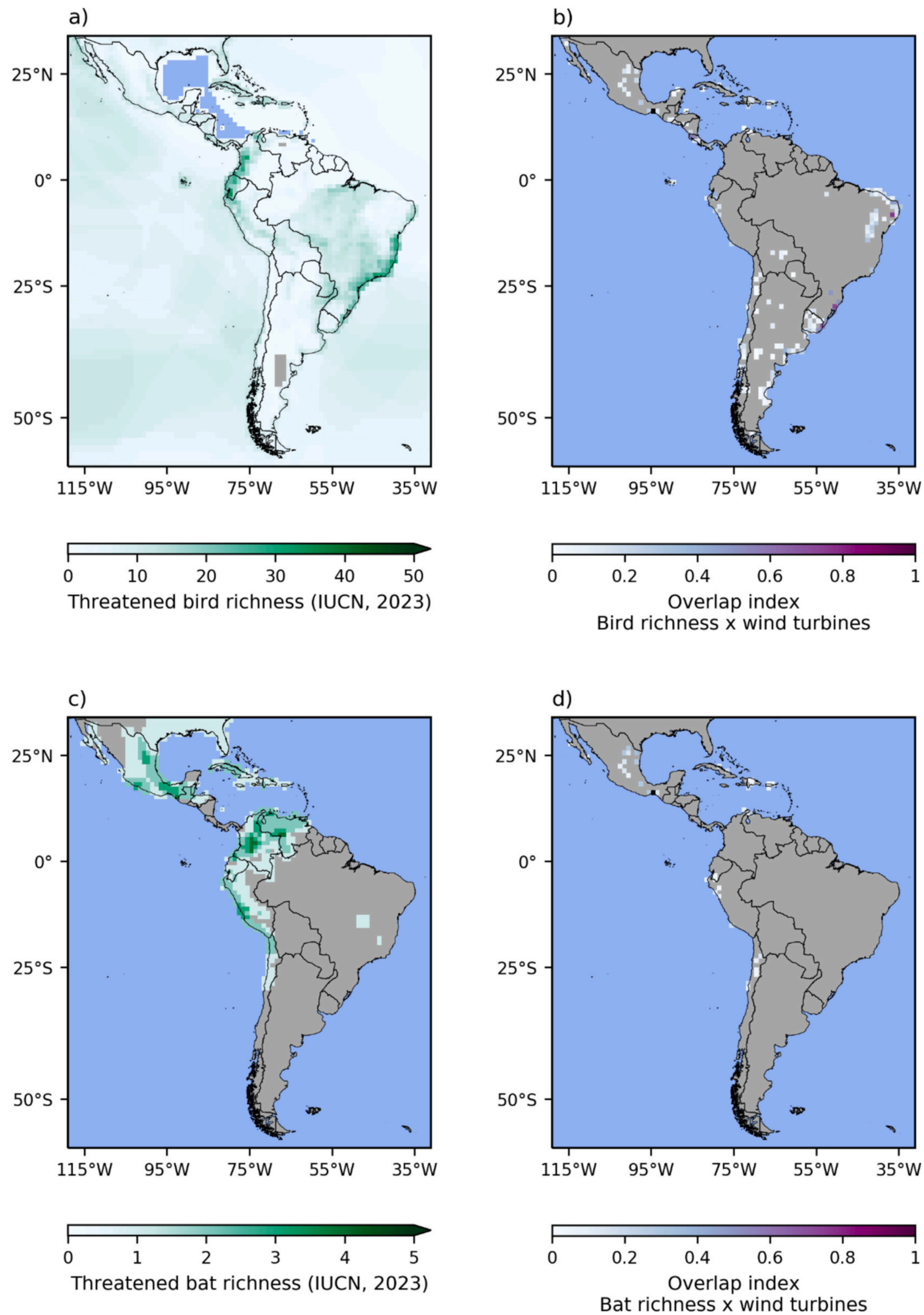

Fig. 3. Map of Latin America and the Caribbean showing the 1°x 1° analysis grid for a) richness of globally threatened bird species, b) overlap index for globally threatened bird species richness and wind turbines, c) richness of globally threatened bat species, and d) overlap index for globally threatened bat species richness and wind turbines.

threat for flying fauna in Latin America and the Caribbean region. First, our literature review reveals a general vacuum of scientific information on wind farm impacts for most LAC countries. Additionally, our review shows that wind farms already impact flying fauna in LAC countries, producing collisions and behavioral changes. In addition, we described how several threatened LAC species overlap with existing wind farms, and identify hotspot of their coexistence. Finally, we tackle the potential intensification of LAC's wind energy infrastructure development and report species and areas of concern. We aim to highlight the urgency of studying critical areas of airspace used by these species as a crucial step towards designing effective conservation strategies for flying threatened species. In addition, there is a need to focus studies on existing

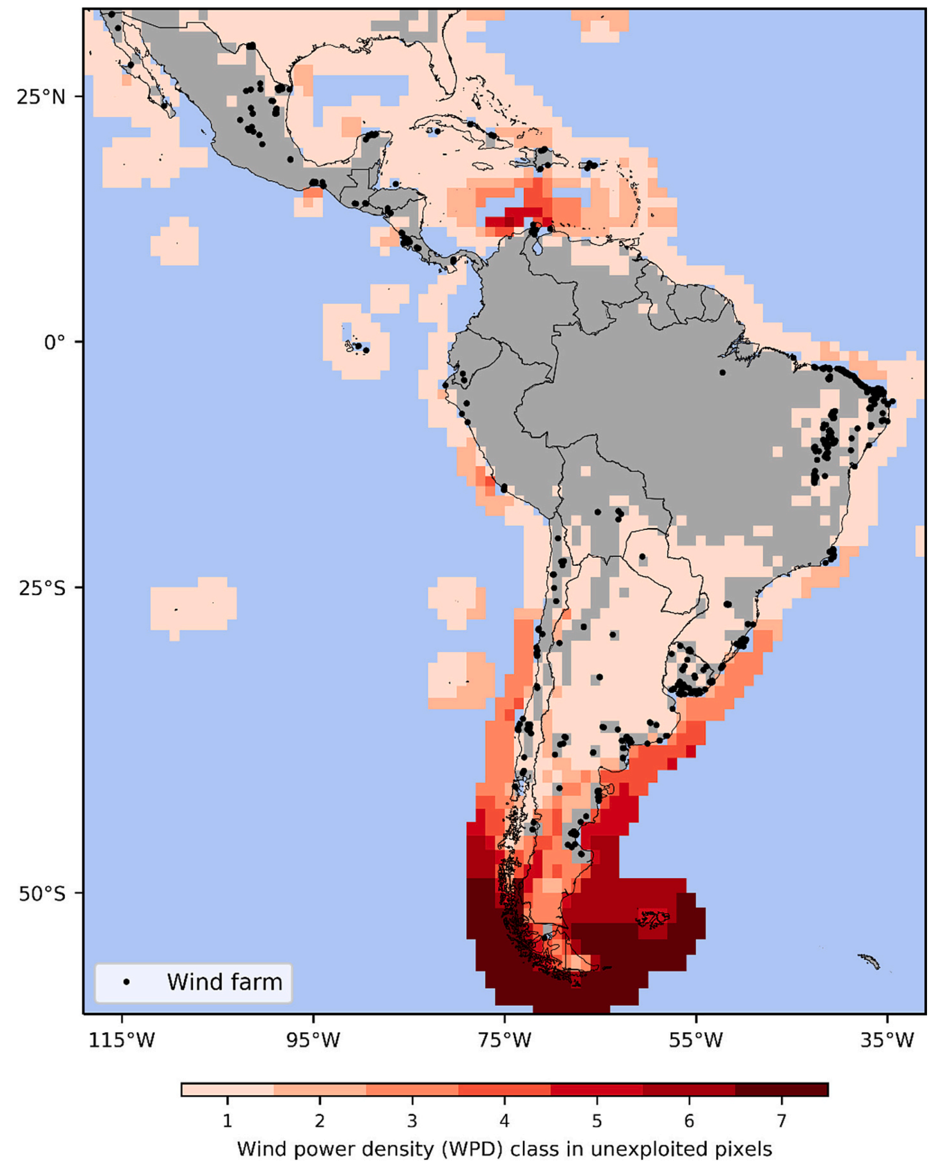

Fig. 4. Wind Power Density (WPD) in 1° x 1° grids not currently used for wind energy development in the Neotropics (i.e., where there are currently no wind farms).

operational wind farms to understand better which species are affected, which characteristics make a species from LAC more susceptible, and to develop and implement mitigation measures.

4.1. Review of the impact of wind farms on flying fauna

We provide an overview of existing research on the impact of wind farms on birds and bats in Latin America and the Caribbean. There is still very limited information on the impact of wind farms on the flying fauna of the region. A recent article identified ten studies focused on post-construction impacts of wind farms by 2020 (Agudelo et al., 2021). Four years later, and after broadening our focus to include potential impacts in all phases of wind projects, the number of studies increased to 22, suggesting a recent but growing scientific interest on this topic. Brazil and Mexico had the largest installed wind power capacity in LAC by the end of 2023 (GWEC, 2024; IRENA, 2023), however, these countries have few studies on the impact on flying vertebrates. Scientific information is also scarce or non-existent in most LAC countries where wind farms are currently operating.

Collision mortality was the predominant impact studied. This may be because it is a direct, visible and easy to assess impact on species compared with others (Allison et al., 2019). In contrast, analyzing indirect effects such as barrier effects, fragmentation or habitat loss often requires behavioral studies, satellite tracking devices or demographic models, which usually require long-term monitoring (Drewitt and Langston, 2006). This implies a large logistical and financial investment, which is not always available in LAC countries (Soares et al., 2023).

Only four of the 22 reviewed studies were conducted before wind farms started operation, and only two of them compared the results with the long-term operational phase (Table 1). Long-term studies are very important, as they provide valuable information on the cumulative effects of wind farms on wildlife, such as alterations in migration routes (Masden et al., 2009; Plonczkier and Simms, 2012; Skarin et al., 2015) or displacement of certain species from their habitats (Dohm et al., 2019). This is important in a region like Latin America, where there is a great diversity of birds (i.e., different movement patterns), but also an important corridor for many species of short- and long-distance migrants (Jahn et al., 2020). In addition, pre-construction studies of wind farms are crucial to minimize impacts on wildlife, as they not only help to identify optimal locations for wind farms, but also the optimal location of turbines within wind farms (Bevanger et al., 2010; Saidur et al., 2011). These studies are frequently included in Environmental Impact

Assessments (EIA) and are often mandatory, but this information remains scarce in published scientific research (Conkling et al., 2022). Finally, published data suggest that a minimum of 58 bat and 49 bird species in LAC have been already affected by collisions with wind turbines. Given the high richness of both bats and birds in this region and the limited available data, the actual number of species affected by this type of impact is almost certainly underestimated.

4.2. Flying fauna and current wind turbines distribution

Considering the underestimation on species affected we provide the overlap between the richness of flying fauna and existing wind turbines in LAC, to highlight the current and potential impact of wind farms on threatened fauna. For example, our findings revealed an overlap between threatened bird species and wind turbines mainly in Mexico, Caribbean islands, northeastern Brazil and the southernmost countries of Chile, Uruguay and Argentina. In addition, the overlap index for bats and turbines identifies potential hotspots for interaction with wind farms in Mexico, the Caribbean islands, northern Venezuela and Colombia, and some areas of Ecuador, Peru and Chile. In Mexico, there is a high degree of overlap in the Isthmus of Tehuantepec, an area with the highest density of wind turbines and one of the most studied in the region, accounting for 11 of the 22 articles reviewed.

Based on the overlap of distributions, we also identified 228 bird species and 16 threatened bats that may currently be affected by wind turbines. Among the orders identified, Passeriformes stood out as the most represented (Table S3). This is expected, considering the great diversity, abundance and wide distribution of this group. However, we consider it to be particularly important to conduct additional studies on the potential impact of wind farms on this taxon, as their numbers are often underestimated in mortality studies (Erickson et al., 2014; Gómez-Catasús et al., 2018). In addition, Psittaciformes were the second most represented group and we detected several species of the order Procellariiformes that overlap with wind turbines. The Procellariiformes order encompasses seabirds (albatrosses, petrels, and shearwaters) which rely heavily on oceanic and coastal habitats for their survival. It is important to consider that this study included globally threatened species, but other species may have serious conservation problems at the national level that should also be included in national conservation programs. Such is the case of the Ruddy-headed Goose, a Critically Endangered species in Argentina and of Least Concern worldwide. This species has recently been identified as a species susceptible to collision with wind turbines and power lines along its migratory route in Patagonia, Argentina (Pedrana et al., 2023).

Finally, migratory bat species are well-documented as highly prone to collision with wind turbines (Frick et al., 2017; Thaxter et al., 2017). We found that two of the five species found in areas with the highest wind turbine densities are migratory: the Greater Long-nosed Bat and the Eastern Pipistrelle (also known as Tricolored Bat). The latter already have records of collision mortality in other areas of its distribution (Fraser et al., 2012). It is important to note that due to the scale of our approach we cannot confirm that the highlighted species are impacted by the wind energy developments. Our results help to prioritize species and areas to be studied, as they provide a broad picture of the issue at a regional scale.

We note that not all threatened bird and bat species that are exposed to wind development will be at risk of impacts from wind energy - and likewise, some non-threatened species that are exposed will be at risk, though they were not examined in this study. Given the lack of knowledge about species affected by wind energy, we have adopted a conservation status-led approach, based on global threat status, prioritizing flying threatened species due to their potential vulnerability to additional threats, including wind energy development, which may increase existing pressures on their populations. We call for future research to conduct fine-scale studies to assess impacts on local species, considering their behaviour, habitat use and susceptibility to wind turbines.

4.3. Flying fauna and potential wind energy infrastructure development

We assessed wind power density (WPD) in areas where wind farms have not yet been established. This enabled us to identify regions with good potential for wind energy development. Interestingly, the WPD map shows that countries with the most developed wind industry are not necessarily those with the best wind resources, a trend also observed in other regions (Zwarteveen and Angus, 2022). For example, Brazil and Mexico have the highest installed wind power capacity in LAC, but they do not possess optimal WPD for wind power generation compared to regions like Patagonia in the southern tip of South America. Argentina and Chile have an intermediate level of investment in wind energy, but the highest wind resource index for the region. This discrepancy may be attributed to the dominance of economic and political factors over wind resource quality in the development of wind energy projects, particularly in developing countries (Zwarteveen et al., 2021). Moreover, although the WPD is critical to identify optimal regions for wind energy development, it is essential to consider other limiting factors such as the availability of the electricity grid to transport the energy. In the case of Patagonia Argentina, where WPD values were the highest in the region, although the current electricity grid is not sufficient to support accelerated wind growth, there are already specific investment plans to expand this infrastructure in the coming years in order to contribute to the objectives of the National Energy Transition Plan (2003).

We highlight the potential future implications for areas with high WPD values, as wind energy development could expand rapidly when favorable economic and political conditions come into play. Such is the case of Argentinean and Chilean Patagonia, where little wind energy infrastructure has yet been installed despite possessing the highest WPD values in the region. Local field studies are therefore necessary to determine fine-scale species' habitat use, abundance, and behavioral responses to infrastructure in these areas. Early guidance can then be given on the appropriate location of wind farms by identifying the most sensitive areas to avoid, which seems to be so far the most effective strategy to reduce the impact of wind farms on birds (Balotari-Chiebao et al., 2023). A recent study on the consequences of offshore wind farms in Brazil has identified several species of pelagic birds (Procellariiformes), also highlighted in our study, as potentially affected by the future development of these facilities (Lemos et al., 2023). We also identified two bat species with extremely restricted distributions, the Choco Broad-nosed Bat (*Platyrrhinus chocoensis*) between Ecuador and Colombia and the Cuban Greater Funnel-eared Bat (*Natalus primus*) in Cuba. Their distributions do not currently overlap with wind turbines, but do overlap with areas of high WPD. To effectively address the impact of wind energy on wildlife, priority should be given to prevention of the development of wind farms in habitats of high richness of endemic and threatened species. This proactive approach has proved the most effective strategy in mitigating potential adverse effects of wind energy on wildlife populations (Arnett and May, 2016; Drewitt and Langston, 2008).

4.4. Conclusion and final remarks

Wind farms and their associated structures can negatively impact species that inhabit airspace. They are increasing, or have the possibility to increase very fast in some regions of the world as in Latin America and the Caribbean. We found a clear need for more comprehensive studies on the impact of wind farms on flying fauna in Latin America and the Caribbean region. Even so, the scarce literature reveals that wind farms already cause impacts, such as collisions and behavioral changes, in several species of birds and bats in the region. In addition, we identified areas of high overlap between wind turbines and threatened bird and bat species which need to be considered and evaluated more in detail. Some of them, such as the Isthmus of Tehuantepec in Mexico, the Caribbean islands and northern Venezuela and Colombia, stand out for their high rates of overlap between operating turbines and the number of threatened bird and bat species. We show how several threatened bird and bat species overlap their current distributions with operating wind turbines, a trend that tends to intensify due to the growing wind industry in the region. Among them, some bird species stand out for their high indices of overlap with turbines in their distributions, such as the Yellow-naped Amazon (*Amazona auropalliata*) in Central America and the Leari's Macaw (*Anodorhynchus leari*) in Brazil and the migratory bat species, Greater Long-nosed Bat (*Leptonycteris yerbabuenae*) and the Eastern Pipistrelle (*Perimyotis subflavus*), among others. Therefore, it is vital to include the airspace habitat in the management plans of conservation frameworks (Lambertucci and Speziale, 2021). In this sense, our study identified areas suitable for future wind development and their overlap with threatened species of birds and bats, indicating potential future impact.

Avoiding the installation of wind farms in areas important for the conservation of threatened species may be the best strategy to minimize ecological impacts. On a large scale, Ecuador, Colombia and the southern coast of Brazil have the greatest richness of bird species, while Mexico and the countries of northwestern South America are relevant for endangered bat species. However, this is a large-scale approximation, so fine-scale field studies are needed to see if there is a current impact between wind development and threatened species in the highlighted areas. Airspace is essential for the survival, movement, feeding, and reproduction of many wildlife species of flying fauna such as birds and bats (Davy et al., 2017; Lambertucci et al., 2015). Because most impacts occur when the species are flying, there is a need for detailed evaluation of species flight altitude and behaviour (Péron et al., 2017). In this regard, we encourage studies evaluating the three dimensions of animal movement. The future of energy production is phasing out fossil fuels but looking for well-designed alternatives that reduce the impact on the environment as a whole. In this sense, it is crucial that wind farms meet these requirements, especially in regions where their development is quite recent and where they can have a major negative impact on biodiversity.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Codes and datasets have been added as suplementary materials and can also be found in the github repostitory https://github.com/nlois/Latam_windfarms_birds_bats.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.eiar.2024.107798.

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