CONTRIBUTED PAPER

Conservation Science and Practice
A journal of the Society for Conservation Biology

WILEY

Assessing the spatial distribution of avian collision risks at wind turbine structures in Brandenburg, Germany

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Abstract

The risk of collision with wind turbines remains a critical issue for bird conservation. Undoubtedly, for the continued development of wind farms to increase the energy capacity, wind farm locations must be carefully chosen going forward. This can be achieved not only by avoiding areas with higher bird densities but also by avoiding installations at sensitive distances from their ecologically important land-use types. Through analyses of the Euclidean distances to the different land-use types, we utilized the random forest (RF) machine learning algorithm to model the distance-based impacts of wind turbine locations on detected bird collisions for the frequently-hit groups of birds at WTs. Although, the predicted areas with potential collision risk in total had a small but highly dispersed expanse of ~2,130 km^2 across the vast 29,479 km^2 area of the federal state. Our results further segregated these assessed areas based on their different probabilities of collision thresholds (between 0 and 1) to only detect the areas with collision probabilities <.05, which were interpreted as the actual "no risk areas". These "no risk areas" summed to a total of merely 754 km^2 of the land space in Brandenburg, suggesting that any further planned additions of wind energy farms in the state that is, the proposed wind turbines, to be suitably positioned only in these safer areas. Additionally, the study also enabled the identification of any existing wind turbines already installed in the remaining less safe 28,725 km^2 area of the state. These areas are also essential to be include in the collision detection surveys and bird population dynamic studies. This would further our understanding regarding the deleterious consequences of collisions at the population levels of birds, eventually helping in the formulation of adequate mitigation measures.

KEYWORDS
bird collisions, Euclidean distance, land-use types, random forest, wind energy structures

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Anushika Bose and Tobias Dürr contributed equally to this work.

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1 | INTRODUCTION

Climate change phenomena has promoted high investments in "renewable" energies (Kaldellis & Zafirakis, 2011), for example, wind power. Along with the development of wind power, avian collisions have also developed as a rather escalating source of unnatural mortality among birds, bats and other flying animals, such as insects (Corten & Veldkamp, 2001). As the number of these power structures rapidly grows (Valença & Bernard, 2015; Wang & Wang, 2015), concerns have been raised in relation to the collision risks posed, especially for birds and bats (Bellebaum, Korner-Nievergelt, Dürr, & Mammen, 2013; Schuster, Bulling, & Köppel, 2015; Voigt, Lehnert, Petersons, Adorf, & Bach, 2015), putting their populations under increasing unsustainable pressure (Jenkins et al. 2000).

Currently, there are more than 25,000 onshore wind turbines installed in Germany (May, Andrew, Köppel, Langston, & Reichenbach, 2017), with federal states further aiming to provide up to 1.5% of their land areas for the same, resulting in more than doubling their currently installed capacities. As a result, the pressure on birds will continually grow, and less problematic locations for installations will become increasingly rare. This would make it challenging to propose new wind farm locations (May et al., 2017).

The most simplistic solution is to avoid areas with higher bird densities, making the general assumption of a link between higher abundance and higher rates of mortality (Atienza, Martín Fierro, Infante, & Valls, 2008; Carrete, Sanchez-Zapata, Benitez, Lobon, & Donázar, 2011). But researchers found contradictions between the preinstallation bird abundance and the detected bird mortality from collisions once operations commenced (Carrete et al., 2011; De Lucas, Janss, Whitfield, & Ferrer, 2008; Ferrer et al., 2012).

Generally, carcass search operation-based studies underestimate or overestimate the actual number of individuals being killed; likely due to spatial incompleteness, temporal incompleteness and detection incompleteness of the surveys (Erickson, Wolfe, Bay, Johnson, & Gehring, 2014).

However, many studies have accounted for some of these shortcomings by correcting detection biases (Bellebaum et al., 2013, Nievergelt et al. 2013); by comparing searcher efficiencies and carcass persistence times by trials using surrogate carcasses (Erickson et al., 2014). Other studies have addressed the need to resolve these contradictions to correctly guide the installation of future wind turbines with the techniques of species distribution modeling (SDM) (Bose et al., 2018; Santos, Rodrigues, Jones, & Rebelo, 2013).

SDMs generally describe the relationship between the occurrence of species and a set of predictor variables that quantify the habitat and other limiting variables (Anderson, Lew, & Peterson, 2003; Guisan & Zimmermann, 2000; Magness, Huettmann, & Morton, 2008; Santos et al., 2013). As collisions differ among wind farms (Smallwood & Thelander, 2004, De Lucas et al., 2008, Hull and Muir 2013), the occurrence of collisions can also be thought to be related to the specific ecological conditions that are associated with the location of the wind farm and to that of the specific habitat requirements of the species that collide (Santos et al., 2013). Therefore, collision data when used as a proxy for species presence against the environmental conditions in SDMs, enables the prediction of bird collision risk areas.

Some previous studies have also analyzed the impacts of turbines on birds using the same module and evaluated the accuracy of collision predictions of birds by assessing the success of future detections at the predicted locations (Bellebaum et al., 2013; Dürr, 2011; Eichhorn, Johst, Seppelt, & Drechsler, 2012; Grünkorn et al., 2009; Grünkorn et al., 2016; Hötker et al., 2013; Illner, 2012; Langgemach & Dürr, 2015; Rasran & Dürr, 2013; Rasran & Thomsen, 2013; Schreiber, 2014; Weitekamp et al., 2015).

We focused our module ONLY on landscape features around the locations of the WTs, that is, distances of WTs to different landscape features to predict collisions. Other influencing factors, for example, seasonality, turbine specifications were ignored. Our choice to focus on sensitive distances to edges of landscape elements was because policymakers are concerned with distance effects when making decisions ensuring safe deployment of WTs. Moreover, with continuous advancements in turbine specifications to generate more energy, along with no possible control on meteorological conditions or ornithological behavior, the best step forward would be to focus on delineating ecologically sensitive distances for taxa toward habitat elements and avoiding these distances to reduce wildlife risks with turbine installations (TIs).

To uncover these mechanisms, we used random forest (RF) algorithms analyzing the turbines with carcass detections in relation to the local landscape. This ascertained special combinations of distances to different land-use types, leading to a higher risk of bird collisions, to ultimately develop collision distribution models. We specifically made these evaluations for the frequently-hit bird taxa in our sample (buntings, crows, larks, pigeons, and raptors).

With respect to collisions at wind turbines, raptors already have been the subject of maximum attention, because these birds generally have low reproductive rate, and any minor increase in mortality can have considerable consequences on their populations (Bellebaum et al., 2013; De Lucas, Ferrer, Bechard, & Muñoz, 2012;

Eichhorn et al., 2012; Ferrer et al., 2012; Schaub, 2012). Although, the large birds being reported unproportionally often, due to their larger body sizes with greater carcass persistence times. The smaller birds largely go undetected, due to their smaller body sizes and shorter carcass persistence times (Erickson et al., 2014). Therefore, our study chose to focus on all the frequently-hit taxa from the same benchmark of conservation concern.

2 | MATERIALS AND METHODS

2.1 | Study area

The study area was the federal state of Brandenburg, Germany (Figure 1), with an area of ~29,500 km^2. Half of the area of the state is used for agriculture and livestock production, and roughly another one-third of the region is covered by forests (Kamp, Bock, & Hölzl, 2004). Over the past two decades, wind turbine structures have contributed substantially to the disturbance of the landscape structure in Brandenburg, rapidly proliferating across the entire landscape (Bose et al., 2018; Dürr, 2014).

2.2 | Carcass search data

This study is based on a database registering counts and locations of birds found dead as a consequence of collision with WTs in the Federal State of Brandenburg; provided by the Brandenburg State Agency for Environment. Accessible at: http://www.lugv.brandenburg.de/cms/media.php/lbm1.a.3310.de/meldebogen_anflugopfer.xls. The database is hosted by the State Agency, which is deputized in this study by one of the authors (Tobias Dürr). More information about the sampling can be retrieved from: http://www.lugv.brandenburg.de/cms/detail.php/bb1.c.312579.de.

The detections were spatially limited and available from 69 of the 3,811 currently functional wind farms (mean of five functional turbines per wind farm, excluding the dismantled wind farms and wind turbines).
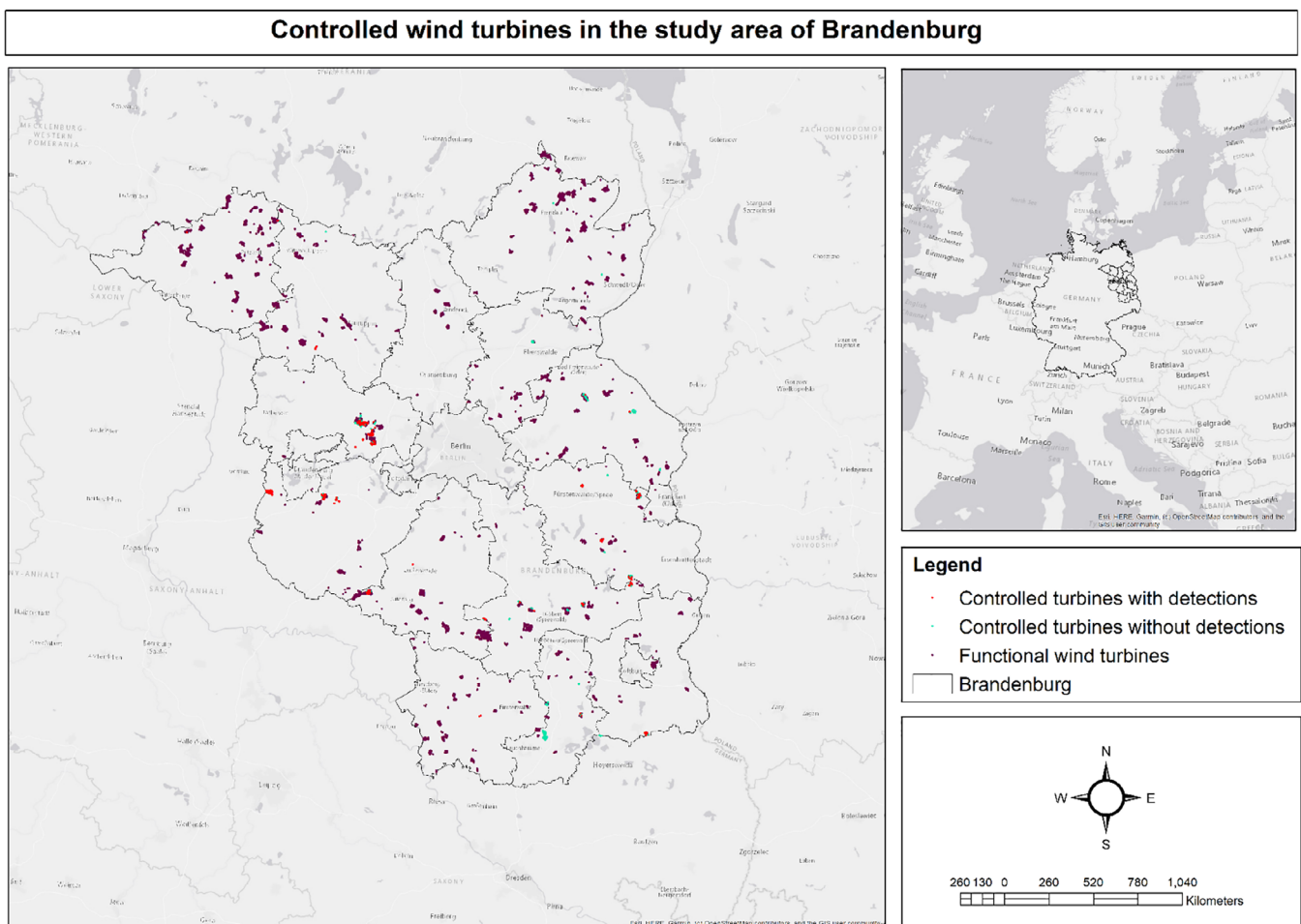

FIGURE 1 Study area showing the spatial locations of all the functional wind turbines (surveyed with carcass detections and without carcass detections)
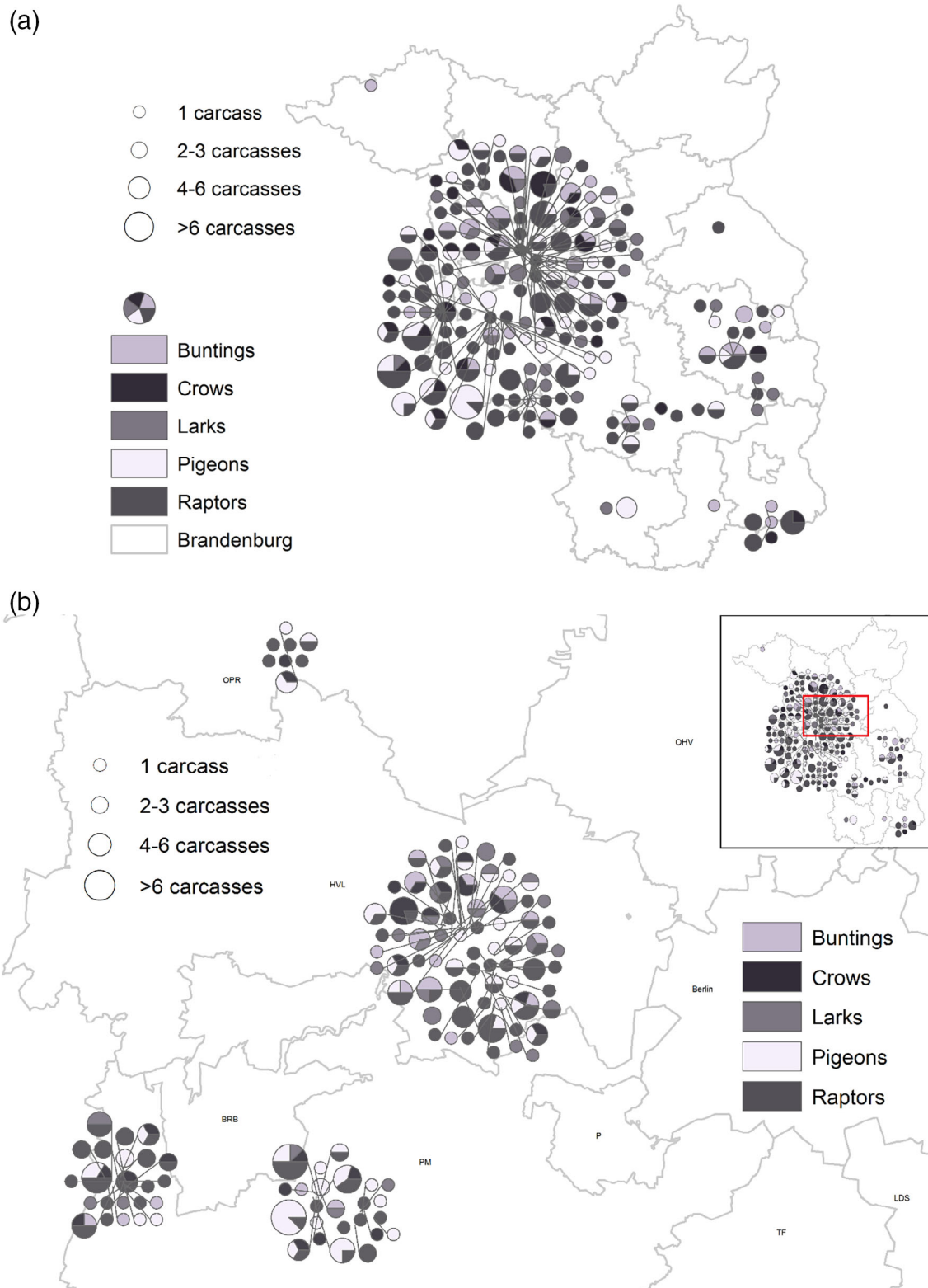
FIGURE 2 (a) Relative abundance of the members of the frequently-hit bird-groups at the carcass detected functional wind turbines in the study area. With pies showing results of bird-group identifications expressed as relative frequencies (shading inside the pie), and total number of carcasses detected (size of the pie) from each wind turbine *(from Bose et al., 2018)* (b) Relative abundance of the members of the frequently-hit bird-groups within the carcasses detected at wind turbines in a sector of the study area. With pies showing results of bird-group identifications expressed as relative frequencies (shading inside the pie), and total number of carcasses detected (size of the pie) from each wind turbine

The turbines were primarily concentrated toward the western and southern districts of the federal state (Figure 2). A total of 617 turbines were controlled: with rotor diameters varying from 40 to 100 m and nacelle heights varying from 41.5 to 160 m, with a power generation capacity between 1 and 6 MW. A total of 7,428 carcass search operations were conducted between 2000 and 2011, with ~1–31 (mean 8.1) turbines controlled per search operation, out of which only 450 searches detected bird carcasses in total. The time interval between these search operations (searching the same turbine) varied between 1 and 188 days, with a median of 2 days (mean 5.3 days) (Bellebaum et al., 2013; Bose et al., 2018).

Although, we are aware of the spatiotemporal inconsistencies related to carcass detected studies, it is not only difficult but also sometimes impossible to account for multiple influencing factors to standardize the available data. For example, not all the birds injured by the strong turbulences or direct collisions (causing muscle ruptures, wing luxation, or bone fractures) die and fall in the immediate vicinity of the turbine they collide with. An unknown proportion will still pass this situation and fly larger distances, with suffering from severe/minimal injuries and die later because of starvation, predation, or other reasons directly related to the collision event. This way, it is impossible to estimate the proportion of birds actually hit, because each of these events would have to be detected, the type and the severity of the injury has to be registered, and the fate of the still alive, that is, escaped bird to be monitored.

The second group of victims are those, that can be found in the near vicinity of the turbines post the collision event. This is the proportion of birds that suffered serious injuries due to the collision or turbulence and either lost their ability to fly or died immediately. However, even from this group only a smaller proportion cannot be found because of inconsistencies related to species-specific carcass persistence times, searcher efficiencies, and substratum or vegetation cover present (Erickson et al., 2014). Ignoring these factors can cause serious bias in estimates of collision probabilities. However, the conceptual model behind the proposed factor estimates are still absent or incomplete, resulting in a constrained estimation method in the sense that the available procedures are not applicable under general circumstances either (Korner-Nievergelt et al., 2011). Enhancing this problem with very often or not, is the no information about the boundary conditions of the detected carcass data set. Especially in our case, where the underlying material is an opportunistic set of data collected from systematic surveys of different intensity and duration, as well as accidentally found and reported carcasses.

TABLE 1   Distance to edge-based land-use variables (DELVs) used as predictors in the federal state of Brandenburg, Germany

Variable	Description	Coverage (~%)	Variable acronym
Bushlands	Deciduous bushes, field bushes, tree-lined roads, tree groups, and riparian woods	0.8	B
Fields	Plow lands, arable lands and other farmlands	35	F
Forests_forestry	Forests and commercial forests	35	FF
Flowing_watercourses	Streaming waters, springs, small flowing rivers, and channels	0.40	FW
Green_areas_settlements	Biotopes of green areas and open spaces including parks, gardens and village greens	2	GS
Grass_forbs	Meadows, pastures, grasslands, lawns, and forb areas	16	GF
Ruderal_areas	Anthropogenic raw soil sites and ruderal areas with or without very few vegetation	0.26	RA
Shrublands	Dwarf shrubs, heathlands, and conifer bushes	0.35	S
Special_biotas	Special biotopes including valleys, plantations, commercial gardens, and tree nurseries	0.87	SB
Settlements_structures	Buildings, roads, paths, traffic and industrial areas, railroads, and village like developments	6	SS
Still_watercourses	Still waters, lakes, small waterbodies, reservoirs, ponds, and mine waters	2	SW
Wetlands	Mosses, swamps, sedges, and peat cutting sites	1	W

Therefore, we used a conservative approach of the detection and non-detection to assess the combination of predictors that created an increased risk of bird collisions on TIs. We solely utilized the respective spatial information, neglecting the detailed but often very biased associated information.

For our study, we used a subset of carcass detections from the following taxa only: buntings ($n = 29$), crows ($n = 30$), larks ($n = 37$), pigeons ($n = 55$), and raptors ($n = 128$). We also analyzed the surveys where the following taxa were absent: buntings ($n = 491$), crows ($n = 490$), larks ($n = 483$), pigeons ($n = 465$), and raptors ($n = 392$) (Figure 2a; Bose et al., 2018, Figure 2b). This taxonomical stratification criteria were chosen because of shared similar morphology and ecology within each category; the goal was to have enough individuals in each of the subsamples for statistical testing. Such stratifications were based on linkages, primarily between the taxonomic and functional diversities defined by similar species morphologies that determine their habitat preferences (Moore, 2001), which also influences their likelihood of colliding with WT structures (Bose et al., 2018).

2.3 | Data preparation

2.3.1 | Distance to edge-based land-use variables

The detailed land-use database provided by the biotope type and land use mapping project of the state of Brandenburg from 2011 (BTLNK, 2011) was processed to create predictor variables for the 12 major land-use classes. Individual features were preprocessed to measure the Euclidean distances at a 100 m grid cell resolution with ArcGIS version 10.1 (ESRI, 2012). The resolution of 100 m was chosen to compromise between the accuracy and size of the raster maps and the available hardware processing time, in addition to being suitable for providing recommendations to policymakers for TI purposes. The Euclidean distances were prefixed with a negative or a positive sign; denoting distances inside the feature of the particular land-use class or distances outside the feature of the particular land-use class, respectively (Bose et al., 2018) (Table 1; Figure S1).

2.4 | Data analysis

To develop models that allow the prediction of the potential collision risks areas, we used random forest (RF) algorithms (Breiman, 2001; Evans, Murphy, Holden, & Cushman, 2011) to quantify the relationship between carcass detection and

TABLE 2 RF and AUCRF output for the frequently-hit bird-group at WTs in the federal state of Brandenburg, Germany

Bird-group	OOB error rate (%)	Presence class error	Presence classified incorrectly (FP)	Presence classified correctly (TP)	Pseudo-absence class error	Pseudo-absence classified correctly (TN)	Pseudo-absence classified incorrectly (FN)	n presence	Kopt[a]	OOB-AUCopt	AUC CV
Buntings	4.43	0.79	23	6	<0.001	490	0	29	7	0.82	1
Crows	5.73	0.96	29	1	<0.001	476	0	30	9	0.82	1
Larks	6.3	0.86	32	5	<0.001	471	0	37	3	0.65	1
Pigeons	7.92	0.7	39	16	0.002	449	1	55	9	0.83	1
Raptors	8.61	0.37	48	80	0.008	472	4	128	9	0.92	1

[a]Number of selected variables.

the land-use types. We used individual turbines (presence: with carcasses; pseudo-absence: without carcasses) as the sampling points restricted to the surveyed and already existing turbines in the landscape. The detection of at least one carcass at one wind turbine within a grid cell was given the value of 1, and grid cells where no carcasses were
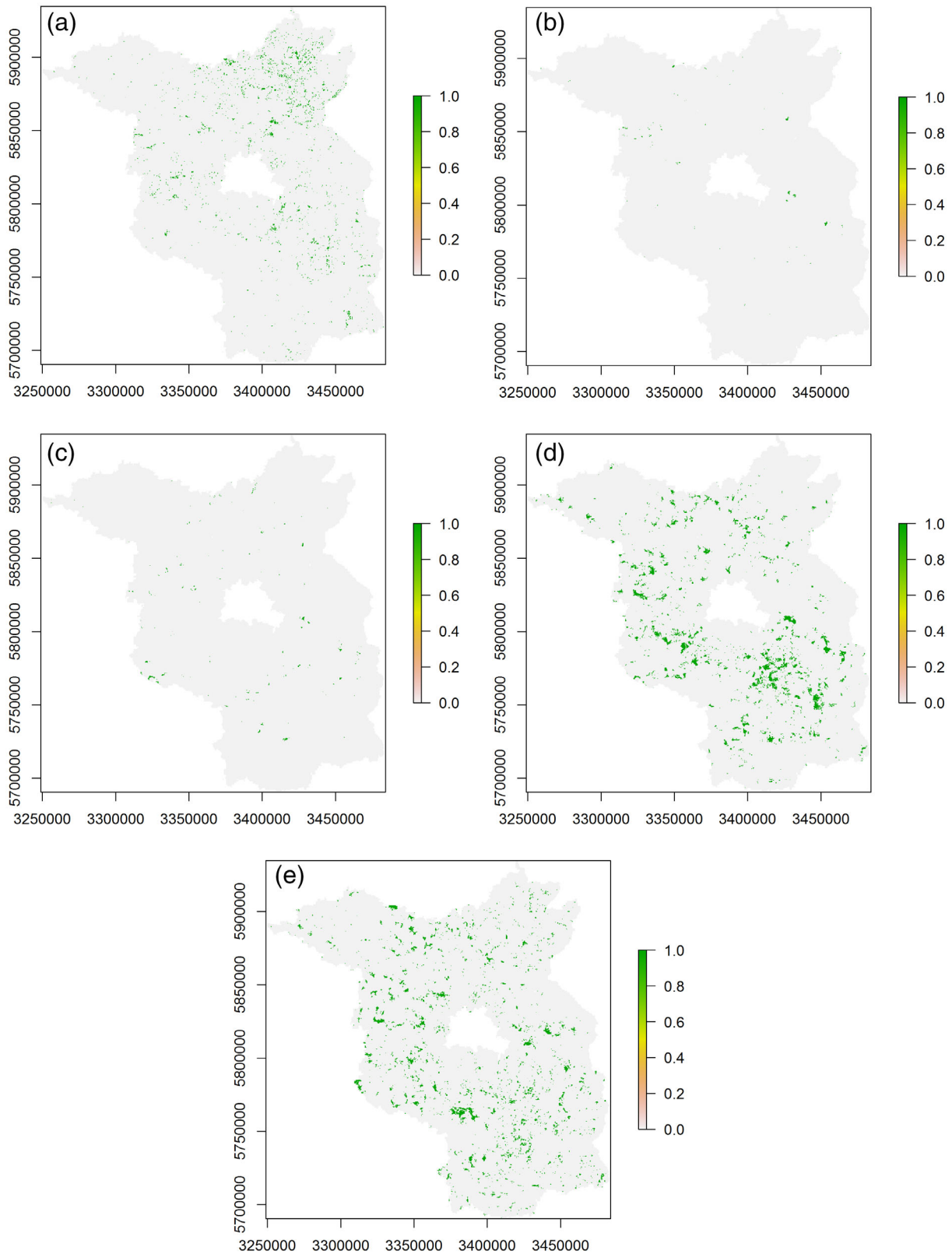

FIGURE 3 Predicted collision risk areas for each of the frequently-hit bird-groups at WTs in the federal state of Brandenburg (a) Buntings (b) Crows (c) Larks (d) Pigeons (e) Raptors

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TABLE 3 Expanse of the predicted collision risk areas (in km^2) for each of the frequently-hit bird-groups at WTs in the federal state of Brandenburg

Bird-group	Collision risk area (~in km^2)	Collision risk area (~%)
Raptors	747	35
Pigeons	1,037	49
Larks	125	6
Crows	36	2
Buntings	184	9

TABLE 4 Expanse of the overlaps between the predicted collision risk areas (*in km^2*); between the frequently-hit bird-groups at WTs in the federal state of Brandenburg

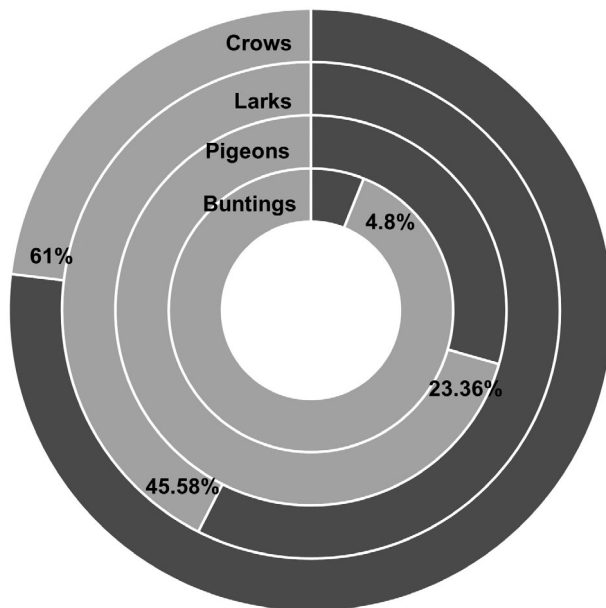|	Overlaps	Overlapping collision risk area (~*in km^2*)
Bird-groups	None	19,189
	2 bird-groups	10,038
	3 bird-groups	255
	4 bird-groups	0.02
	All	0

FIGURE 4 The predicted collision risk areas overlaps between the Raptor collision risk space and that of the other frequently-hit bird-groups at WTs in the federal state of Brandenburg

detected at a turbine were given values of 0. The relationship of the responses to the 12 distance to edge-based land-use variables (DELVs) were determined through classification and regression; partial dependence plots were constructed with the randomForest package in R (Liaw & Wiener, 2002, R Development Core Team, 2013) with the default reported number of trees in the forest (500) and with 3 DELVs sampled at each split. The influence of the DELVs were further exemplified by the RF classifier along with examination of the response across the DELVs with conditional density plots. Apart from the RF model, we also applied another R package, AUCRF (Calle & Urrea, 2014; Calle, Urrea, Boulesteix, & Malats, 2011; Development Core Team, 2013), as a supplementary test of the accuracy of the RF calibrations. The model performance was evaluated with the cross-

validation of a random data set using 70% of the sampled points for training and 30% to test the model.

3 | RESULTS

The results from the RF models for each of the frequently-hit groups of birds at the WTs (for the classification, between 0 and 1) provided comparative model fits with good overall out-of-bag (OOB) error rates. The OOB error for the raptor collision model was ~9%, with the classification error unequally balanced between the presence and pseudo-absence classes due to the imbalances in the input response data. For model evaluation, back-prediction to the k-fold cross-validated data set demonstrated a perfect fit with an AUC of 1, and that using the AUC-RF approach was also 0.92 with an 8% error rate. The models for pigeons, larks, crows and buntings followed this trend, exhibiting ~8, 6, 6, and 4% OOB errors, respectively. The back-prediction for these groups to the k-fold cross-validated data also provided an AUC of 1, but with the AUC-RF approach; the provided AUC values of 0.83, 0.65, 0.82, and 0.82, respectively, along with error rates of 17, 35, 8, and 8% (Table 2), respectively.

The RF models further simulated the group-wise potential areas with or without any collisions (i.e., binary response of 1 or 0, respectively) and with the different probabilities of collision (between 0 and 1). The areas with collisions (binary response = 1) had an overall expanse of ~2,130 km^2 across the 29,479 km^2 area of the state (Figure 3; Table 3). Raptors, pigeons, larks, crows and buntings contributing ~35, 48, 6, 2, and 9%, respectively, to the total (Table 3). The raptor collision data showed broad coverage across the total collision space and also showed significant overlaps with the collision spaces of the other bird groups; the pigeons, larks, crows, and buntings (shared ~23, 45, 61, and 5% of their respective collision space; Figure 4). However, when the composite values were averaged across all groups to find areas where the collision probability = 0 (which suggested that it was very
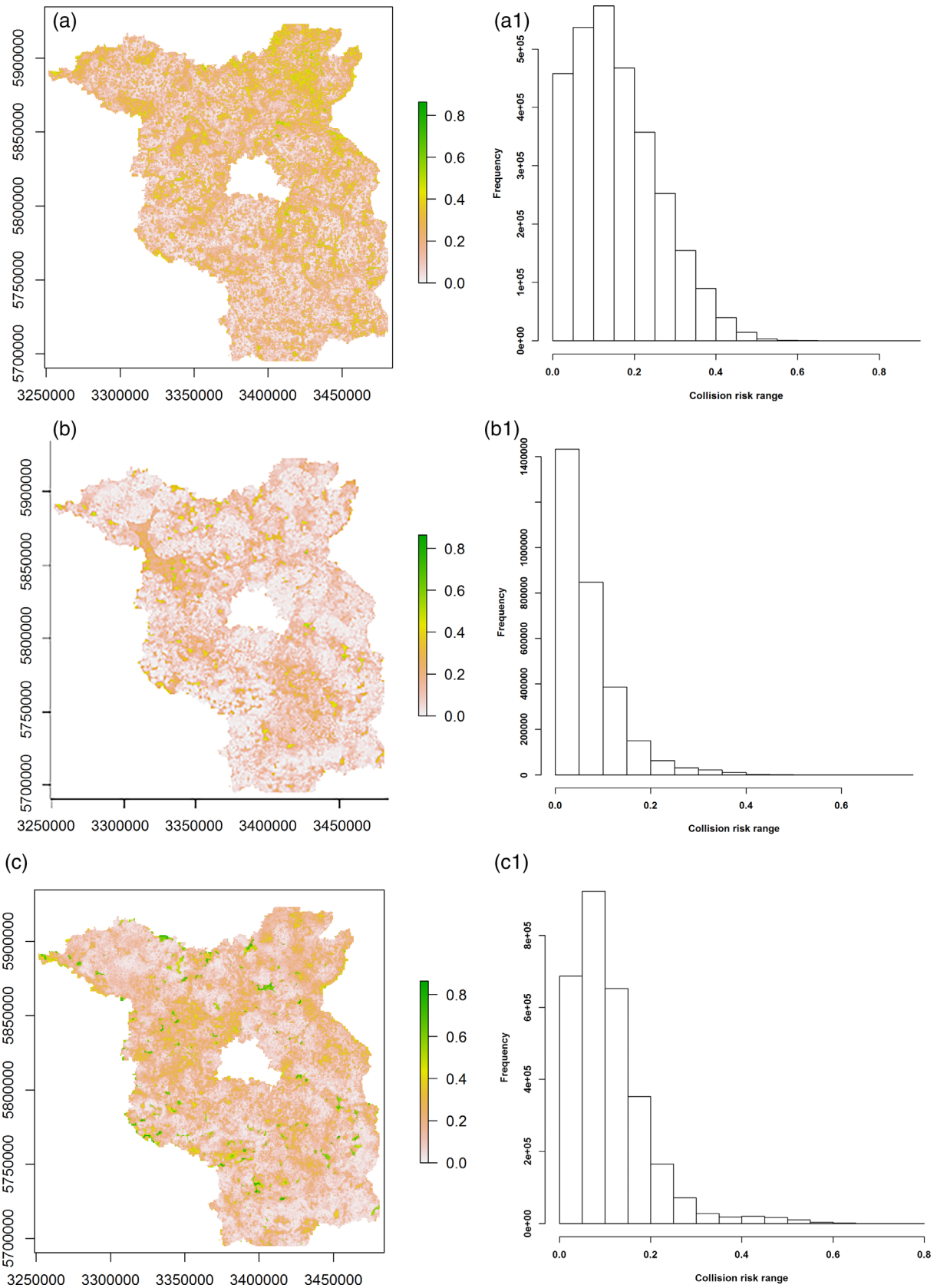
FIGURE 5 Collision risk areas at WTs in the federal state of Brandenburg, for the frequently-hit bird-groups along their entire collision risk range. (a) Buntings (a1) (b) Crows (b1) (c) Larks (c1) (d) Pigeons (d1) (e) Raptors (e1)
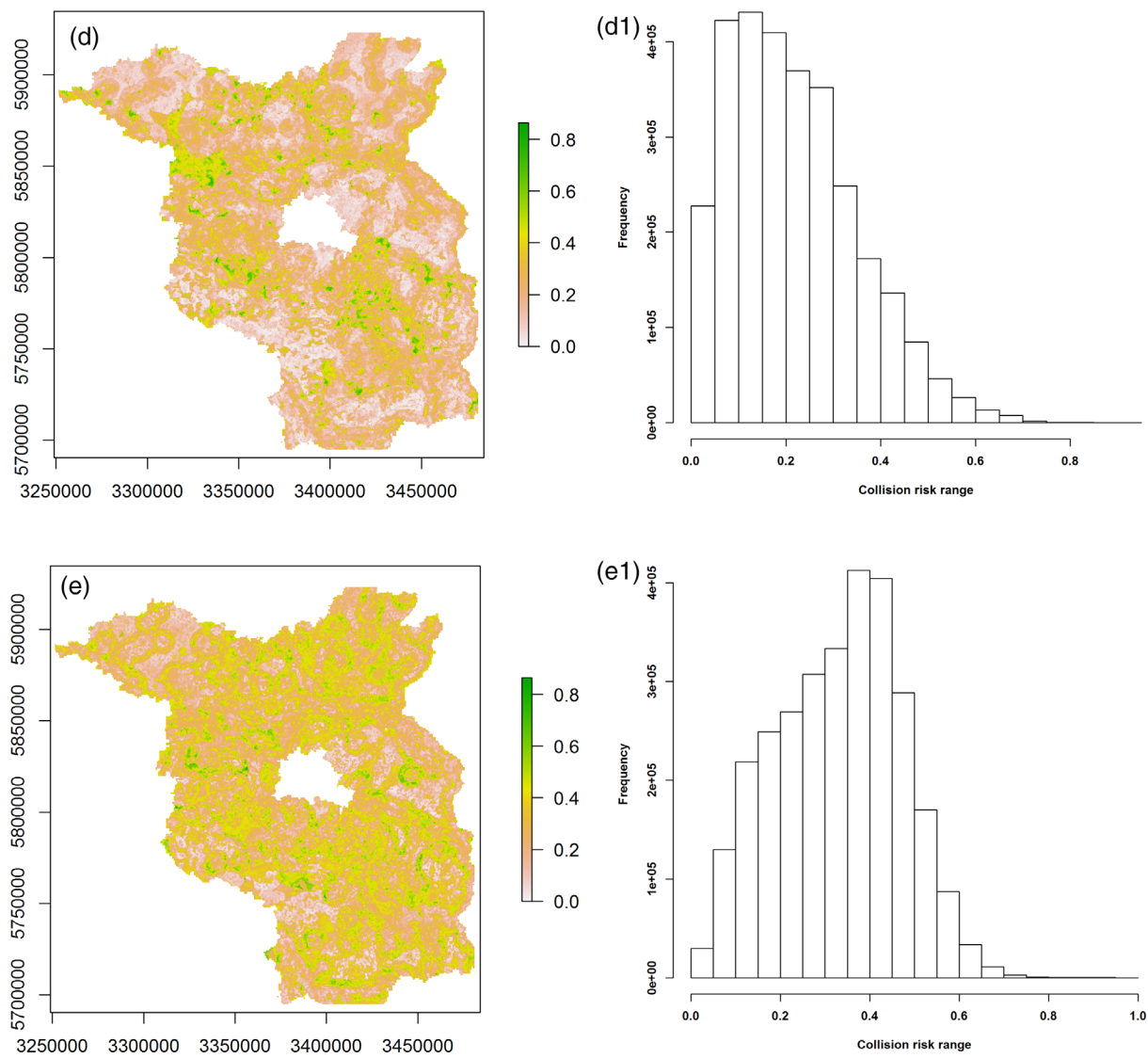
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FIGURE 5 (Continued)

unlikely that a bird belonging to any of the groups would collide on TI ~19,189 km^2), whereas when the collision probability = 1 (suggesting all the bird groups had a high probability of collision on TI ~0 km^2). Higher values indicated higher collision probabilities for some, if not all, of the five groups, while lower values indicated that at least one species had a very low collision probability in this grid cell. For the threshold cut-off values; 2, 3, and 4, the expanses were approximately 10,038, 255, and 0.02 km^2, respectively (Table 4).

Similarly, (Figure 5) the different probabilities of collisions (between 0 and 1) showed that the areas with probabilities of collision (with threshold; cutoff value >0.5) also had a small expanse (Table 5), especially in the cases of crows, buntings and larks, ~0.5 km^2 (0.9%), 39 km^2 (0.13%), and 150 km^2 (0.50%), respectively. The Raptors again showed the broadest coverage across the total collision

space for this threshold; with ~3,054 km^2 (~10%) and were followed by pigeons; with 945 km^2 (~3%).

However, for the further probabilities (with threshold; cutoff value <0.5) the collision risks assessed in the region were relatively much higher, that is, raptors, pigeons, larks, crows, and buntings; contributed ~26,429 km^2 (~90%), 28,536 km^2 (~97%), 29,329 km^2 (~99%), 29,305 km^2 (~99%), and 29,419 km^2 (~99%) across the state, respectively (Table 5). Out of these areas, only the areas (with threshold; cutoff values <0.05) could be categorized as areas with significantly lower probabilities of collision, that is, with raptors, pigeons, larks, crows and buntings; contributing ~298 km^2 (~1%), 2,273 km^2 (~8%), 6,864 km^2 (~23%), 14,149 km^2 (~48%), and 4,555 km^2 (~15%), respectively (Table 5).

Moreover, the composite analyses for all the bird groups together and with each group paired with the

raptors (Figures 6 and 7, respectively) also identified areas with lower probabilities of collision (with threshold; cutoff value >0.5) on TIs in the state. These were averaged across all groups and still showed only a small

TABLE 5 Expanse of the predicted collision risk areas (in km²) for different collision risk ranges for the frequently-hit bird-groups at WTs in the federal state of Brandenburg

Bird-group	Collision risk range	Composite collision risk area (~in km²)
Buntings	0–0.05	4,555
	0–0.5	29,419
	0.5–1	39
Crows	0–0.05	14,149
	0–0.5	29,305
	0.5–1	0.43
Larks	0–0.05	6,864
	0–0.5	29,329
	0.5–1	150
Pigeons	0–0.05	2,273
	0–0.5	28,536
	0.5–1	945
Raptors	0–0.05	297
	0–0.5	26,429
	0.5–1	3,055

expanse of 754 km², that is, ~2% of the area of the federal state (Tables 6 and 7, respectively).

Simultaneously, the RF algorithm also provided group-wise metrics of variable importance for the considered predictor DELVs, based on the descending in classification accuracy (Table 6). The distances to the edges of the flowing watercourses and the distances to the edges of green and open areas outside human settlements were the parameters with the largest importance in predicting the possibility of collision by raptors on TIs. Their observed carcasses were detected at turbines situated from 2,500 m onwards from the edges of the flowing watercourses and between 750 and 1,900 m from the edges of green and open areas outside of human settlements. The collision probability for crows also showed sensitivity to the distance from the edges of green and open areas outside the human settlements, with higher carcass detections at turbines closer to their borders; detections were primarily observed at turbines situated between 1,000 m and up to 1,500 m to these borders. The distances to the edges of the shrub lands and grasslands were also major determinants of bunting and lark collisions, respectively. The carcasses were detected near the wind turbines primarily situated at ~2,500 m from the edges of the shrub lands and between 250 and 750 m from the edges of the grasslands and open areas, respectively. The distances to the edges of the flowing watercourses were also of very high importance for the prediction of the collision probability of pigeons, with
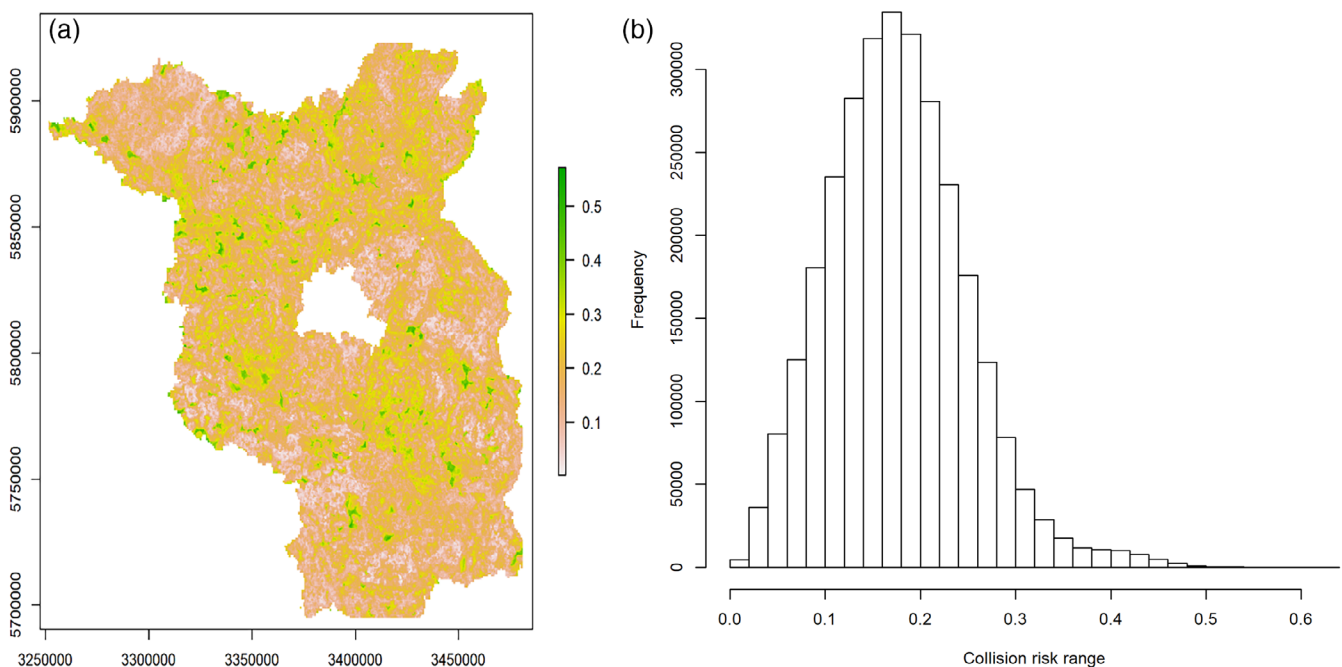

FIGURE 6 Composite collision risk areas at WTs in the federal state of Brandenburg, for the frequently-hit bird-groups along their entire collision risk range
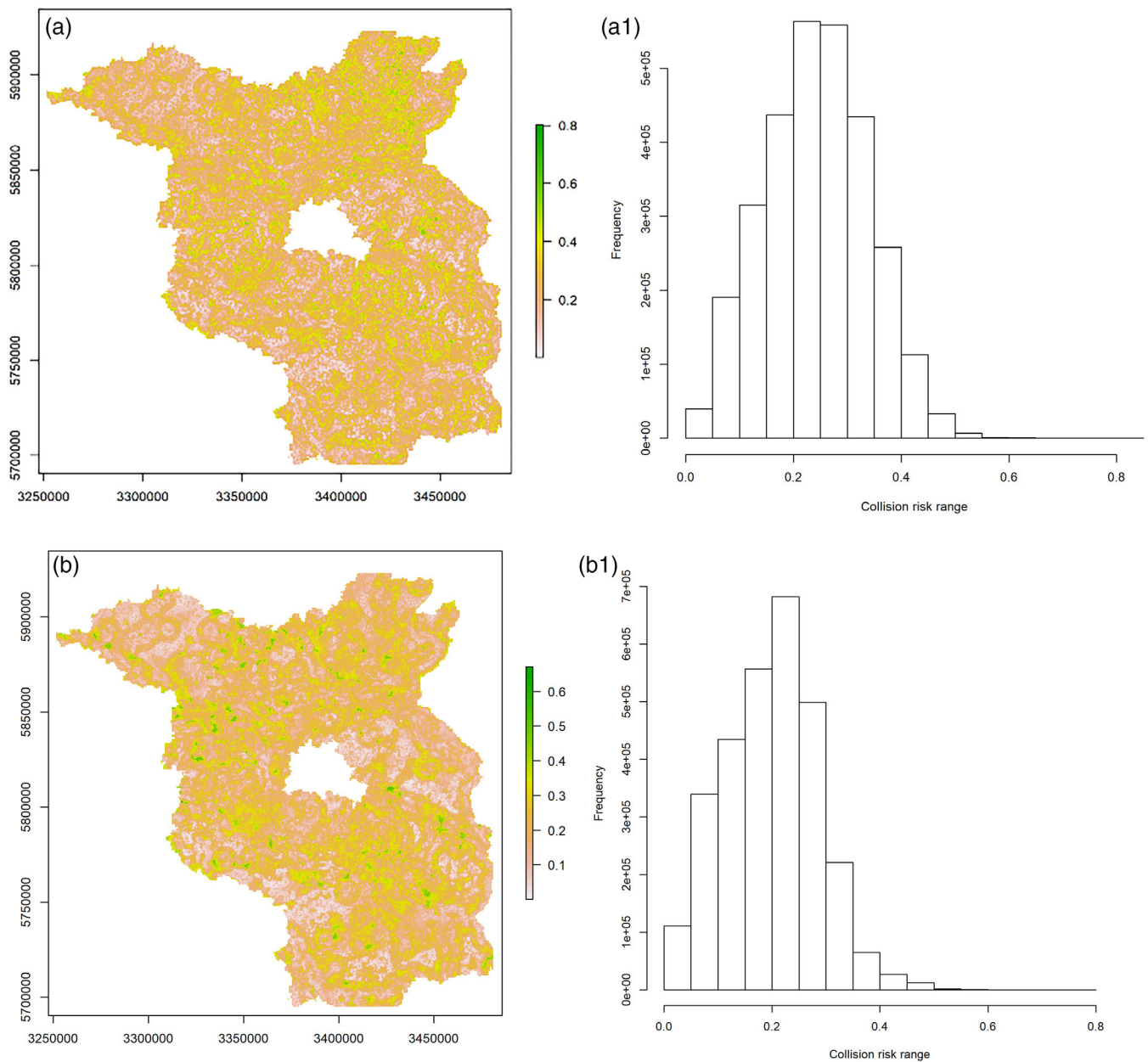
FIGURE 7 Expanse of the composite collision risk areas; between Raptors and other frequently-hit bird-groups at WTs in the federal state of Brandenburg, showing overlaps along their entire collision risk range (a) Buntings-a1 (b) Crows-b1 (c) Larks-c1 (d) Pigeons-d1

their carcass detections at turbines situated from 2,500 m onwards from the edges of flowing watercourses and at turbines between 100 and 1,000 m from the edges of the forests and forested areas, (Table 8; Figure S2).

These mechanistic relationships between the collision probabilities for the bird groups and the key sensitive distances from these particular land-use types can also be visualized according to the conditional density estimate plots with the discrete data (Falkowski, Evans, Martinuzzi, Gessler, & Hudak, 2009) and the partial dependence plots (Friedman, 2001) after RF analyses, respectively (Figures S3–S7).

4 | DISCUSSIONS

Our study demonstrates the benefits of incorporating species collision data sets at WTs as a proxy for species presence into SDM. This process was performed using RF; a machine learning algorithm that has increasingly wide usage in the environmental and nature conservation fields, such as climate change (Gaal, Moriondo, & Bindi, 2012), ecology (Cutler et al., 2007; Evans et al., 2011), forestry (Falkowski et al., 2009) and environmental remote sensing (Rodriguez-Galiano et al. 2011, Adelabu, Mutanga, Adams, & Sebego, 2014). Our approach of using the available collision
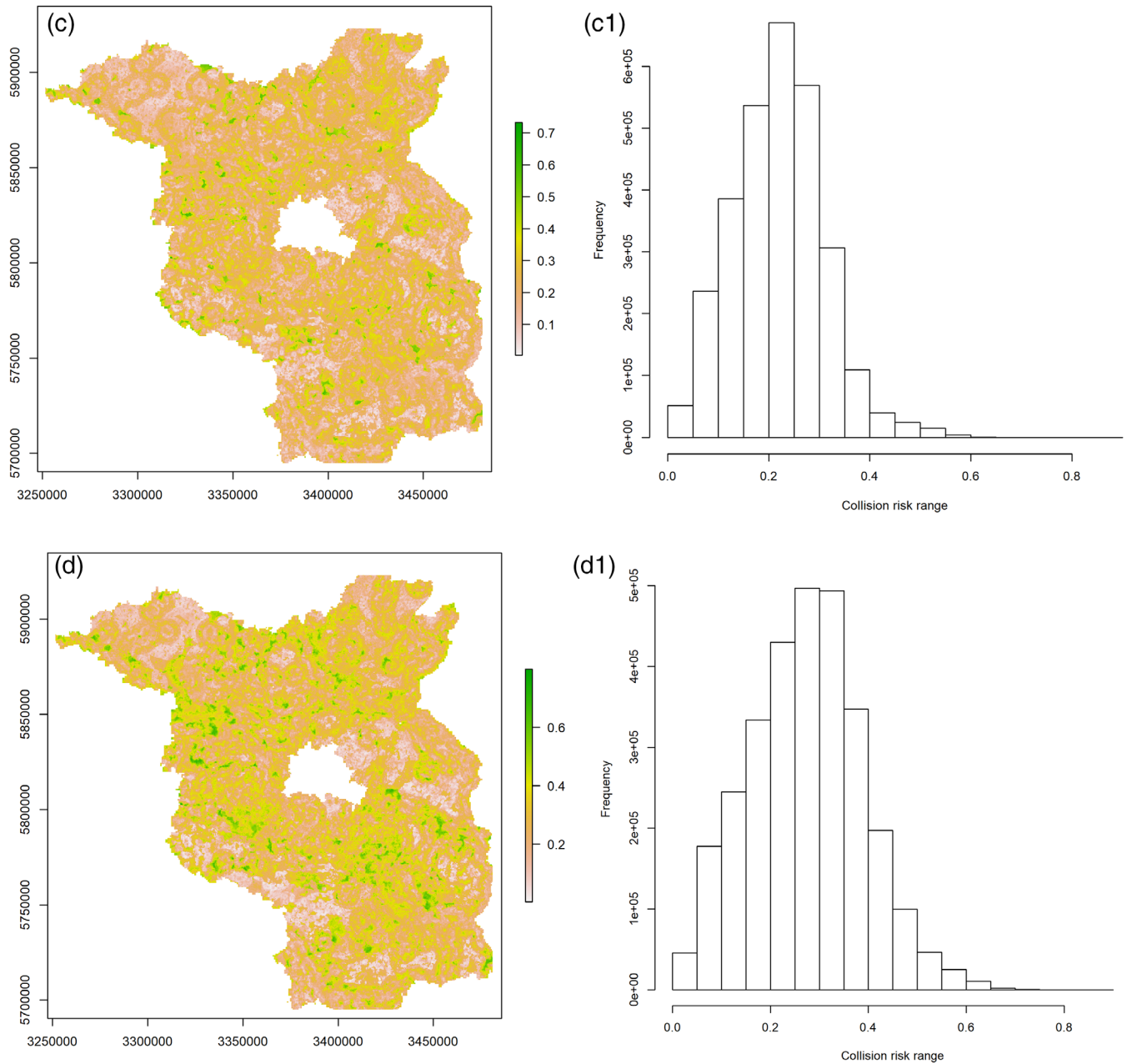
FIGURE 7 (Continued)

TABLE 6 Expanse of the predicted composite collision risk areas (in km²) for different collision risk ranges of the frequently-hit bird-groups (together) at the WTs in the federal state of Brandenburg

Composite collision risk range	Composite collision risk area (~in km²)
0–0.2	14,925
0.2–0.4	10,038
0.4–0.6	255
0.6–0.8	0.02
0.8–1	0

response (0–1) data from WTs allowed the identification of potential areas with collision risks (Figure 3; Table 3). Since the data in our study were not collected systematically, the compilation only provided a rough indication for the birds killed most frequently.

Our approach also checked for subsequent overlaps, if any, between the bird-groups (Figure 4; Table 4). This was essential given the large birds were reported unproportionally often, likewise, the smaller birds went undetected often. Necessary overlaps could ensure the extension of conservation efforts across taxa. For example, raptors have already been the subject of maximum attention w.r.t collisions at wind

TABLE 7 Expanse of the predicted composite collision risk areas (in km²) for different collision risk ranges; between Raptors and other frequently-hit bird-groups at WTs in the federal state of Brandenburg

	Bird-group	Composite collision risk range	Composite collision risk area (~in km²)
Raptors	Buntings	0–0.2	7,521
		0.2–0.4	18,136
		0.4–0.6	1,526
		0.6–0.8	0.57
		0.8–1	0.02
	Crows	0–0.2	9,915
		0.2–0.4	14,665
		0.4–0.6	405
		0.6–0.8	0.56
		0.8–1	0
	Larks	0–0.2	9,223
		0.2–0.4	16,550
		0.4–0.6	830
		0.6–0.8	4
		0.8–1	0.03
	Pigeons	0–0.2	5,785
		0.2–0.4	17,670
		0.4–0.6	3,674
		0.6–0.8	124
		0.8–1	0.11

TABLE 8 Variable importance based on the mean decrease in accuracy for the cases of detected collisions at WTs for each of the frequently-hit bird-groups

DELV[a]	Buntings	Crows	Larks	Pigeons	Raptors
B	15.7	17.6	16.2	20.8	24
F	13.7	12.2	14.5	15.3	23
FW	12.1	17.2	18.5	30.6	29
FF	17.5	14.5	18.5	23.6	21
GF	13.4	15.1	20.4	17.5	21.5
GAS	15.8	19.3	17.1	14.6	28
RA	15	16.9	18.5	18.3	23.5
SS	14.3	15.8	18.5	17.6	27
S	21.9	17.0	18.3	21	24
SB	18.4	14.5	17.7	18.8	22.5
SW	12	13.3	17.5	20.	22
W	13.8	13.9	17.2	18.4	24

Note: Higher values of mean decrease in accuracy indicate variables that are more important to the classification.
[a]Acronyms corresponding to the predictor variables are described in Table 1.

turbines (Bellebaum et al., 2013; De Lucas et al., 2012; Eichhorn et al., 2012; Ferrer et al., 2012; Schaub, 2012). They are also already known to play important roles as flagship/umbrella species (Donazar et al., 2016) for evaluating and managing mitigation measures (Pérez-García et al., 2011, 2016) in a prospectively changing landscape due to human interests (Donazar et al., 2016). Therefore, with raptors already showing the greatest overlaps with the collision space of all the other frequently-hit bird groups, most likely due to their broad range covering the parameter space of the reference area, as well as their appreciably greater probability to be hit by the turbine structures and be detected afterward owing to their bigger body sizes that have greater persistence times and are easier to detect (Bose et al., 2018; Table 3). Therefore, as an umbrella species, the raptor conservation should very well be given the highest priority, as nontarget taxa would also benefits from these efforts.

Apart from this, our approach also enabled the simulation of areas with different collision probabilities (between 0 and 1; Figure 5; Table 5), that is, areas from very low to very high chances of collisions. Additionally, the effects of the different land-use types on the collision sensitivity were also cataloged in the detected areas, which particularly highlighted the sensitive distances to these land-use types - that need to be avoided. In cases where turbines have already been installed at these ascertained distances, assessments of bird collisions become inevitable for further understanding the deleterious population-level consequences of collisions that need to be the focus of mitigation measures.

The calibrated RF models were considered robust and logical because of the minimal OOB errors, in combination with the higher classification errors for the minority classes and the negligible classification errors for the dominant classes (Evans et al., 2011). This resulted in the overrepresentation of the dominant class, while leading to the underestimation of the minority class, primarily due to the bootstrapping procedures used in the RF models. Therefore, the resulting RF models considered the presence (minority) class and intends to attenuate the overall rate, thereby resulting in very good prediction accuracy (Gaal et al., 2012).

The analyses for the relative importance of the considered DELVs on the group-wise collision response indicated that the distances to the edges of the flowing watercourses was the most important indicators in the classification process for raptors (Figure S7). The partial plots showed that there was a higher risk of collision at
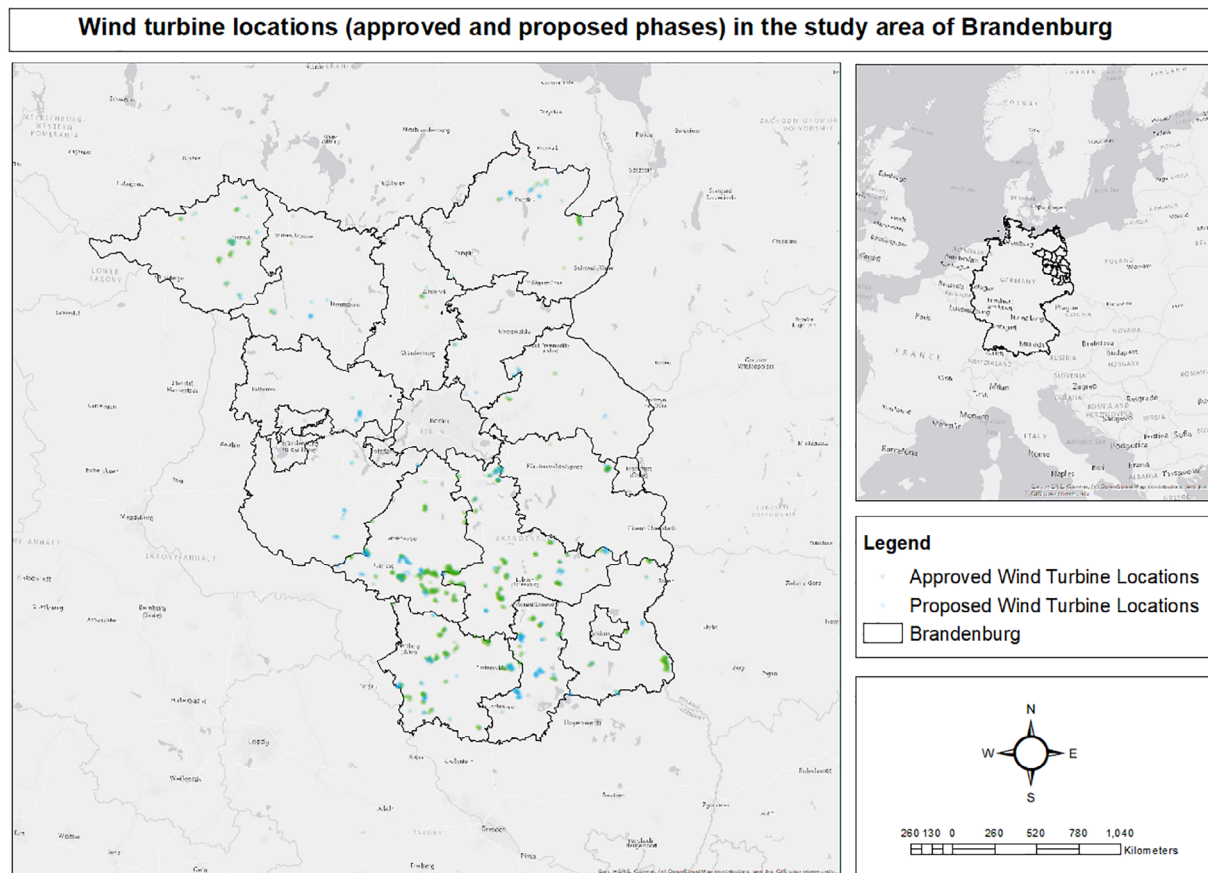
FIGURE 8   Study area showing the spatial locations of all the approved and proposed wind turbines (to be installed phase)

distances farther than 2,500 m from the edges of the flowing watercourses and at shorter distances the risk was much lower because thermal convection generally does not develop over large bodies of water, which typically makes raptors detour around large bodies of water (Alerstam, 2001; Bildstein, 2006; Meyburg, Matthes, & Meyburg, 2002; Meyer, Spaar, & Bruderer, 2000). Furthermore, the distances to the settlements and structures and to the green and open areas around these structures proved to be important in the classification process of raptors and crows as well (Figures S4, S7). This aligned with their respective affinities for the urban environments, because raptors and crows are highly abundant in open areas at the fringes of infrastructures and settlement zones (Benitez-Lopez, Alkemade, & Verweij, 2010), due to the availability of adequate hunting options (Dean & Milton, 2003) of especially many human-commensal small mammals (Mannan & Boal, 2000; Millsap & Bear, 2000; Ranazzi, Manganaro, & Salvati, 2000) and the availability of roadkill carrion (Lambertucci, Speziale, Rogers, & Morales, 2009). They have also been observed using the features of the urban landscape, such as trees, fences and buildings adjacent to open areas around settlements particularly, as perches and nesting substrates,

shelter from the wind and domestic predators and as concealment for ambush attacks on their prey (Chace & Walsh, 2006; Hogg & Nilon, 2015; Roth, Vetter, & Lima, 2008; Rutz, 2006). Corvids specifically nest within 1 km of settlements, ultimately increasing their reproduction and survivorship (Marzluff & Neatherlin, 2006). The partial plots showed that the risk of collision increased with increasing distances (>1,000 m) but decreased at distances farther than 1,500 m. Similarly, pigeons (Figures S6) also abundant in the built-up environments have adapted their nesting requirements and foraging habits to be conducive to urban lifestyles (Harris, de Crom, & Wilson, 2016). Especially in urban areas surrounded by forest/water landscape types (Hetmański, Bocheski, Tryjanowski, & Skórka, 2011). Their partial plot showed a higher risk of collision at distances closer than 1 km from the edges of forests and forestry areas than at greater distances.

Likewise, the distances to shrub-lands and grasslands were the major determinants for the collision risk of the buntings and larks, respectively (Figures S3, S5). The partial plots for Buntings exhibiting higher collision risks at approximately 2,500 m distances from shrub-lands. Buntings being shrub-land birds, prefer large intact stands
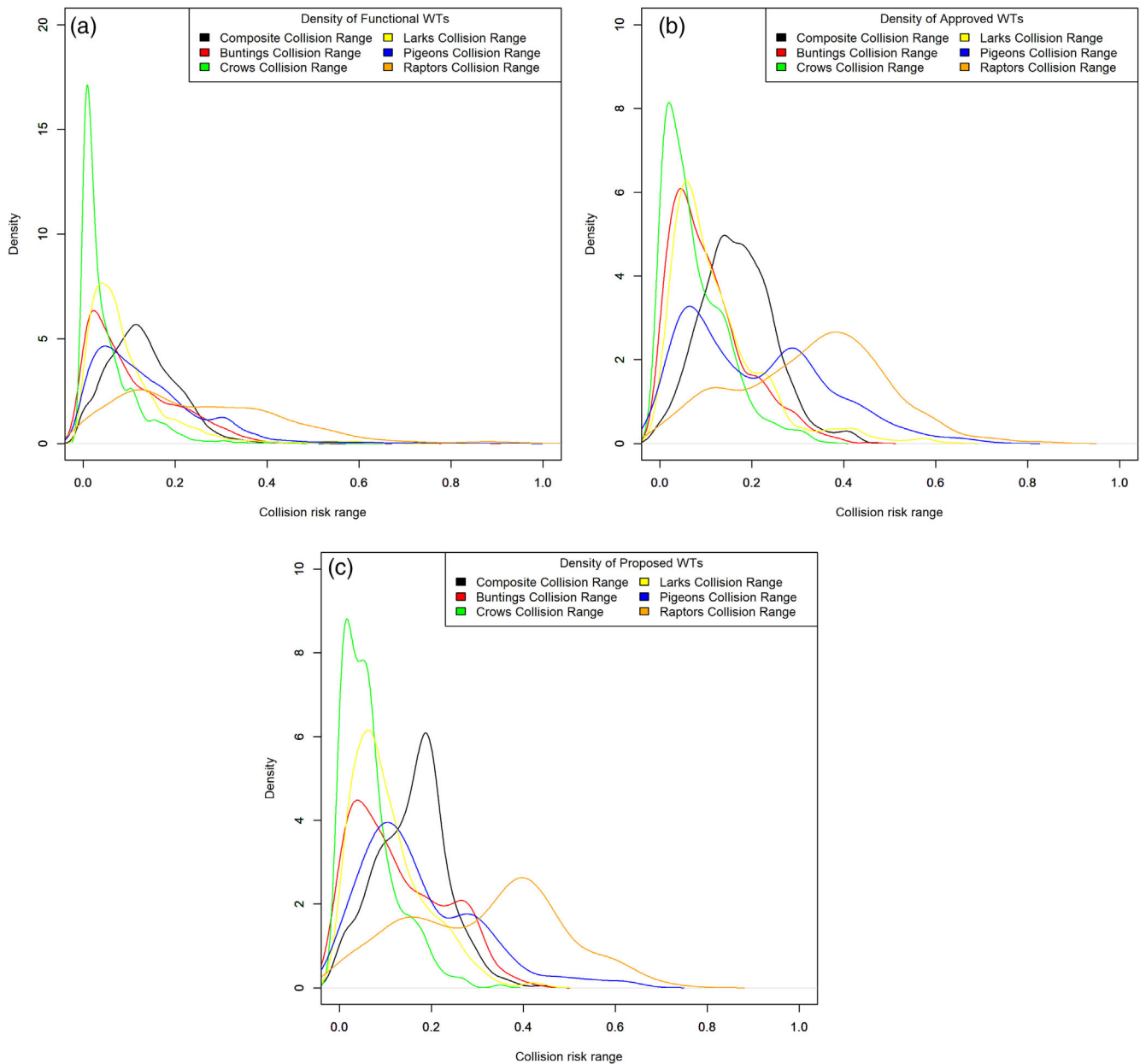
FIGURE 9 Density distribution of the functional wind turbines (existing), approved and proposed wind turbines (to be installed) along the entire predicted collision risk range of the frequently-hit bird-groups in the federal state of Brandenburg (individually and composite)

over small stands with larger habitat-edge ratios (Rodewald & Vitz, 2005; Rudnicky & Hunter, 1993). Larks on the contrary show affinities to pastures, grasslands, and open landscapes (Donald, Evans, Buckingham, Muirhead, & Wilson, 2001; Eraud & Boutin, 2002; Morris, Holland, Smith, & Jones, 2004). Their partial plots showed higher chances of collision between 250 and 750 m from the edges of the grasslands and open areas.

The predicted potential collision risk areas (Figure 3; Table 3) in total had a negligible but dispersed expanse of merely 2,130 km^2. Raptors contributed ~35% to the total while other bird groups shared appreciable proportions

(Figure 4). However, when values were averaged, the areas where birds belonging to any of the five groups would collide comprised of ~19,189 km^2, whereas there was no scenario where all five groups would have a high probability of collision together (0 km^2). Scenarios: 2 bird groups, 3 bird groups, and 4 bird groups, respectively had an expanse of ~10,038, 255, and 0.02 km^2 across the federal state (Table 4).

Similarly, different probabilities of collisions (between 0 and 1) showed that the areas with higher probabilities (threshold >0.5) also had a negligible expanse (Table 3). Raptors still showed the broadest coverage under this

threshold, with ~3,054 km^2, followed by pigeons; 945 km^2. However, for the lower probabilities (threshold <0.5) the associated collision risk areas were relatively higher; with raptors, pigeons, larks, crows, and buntings contributing ~26,429 km^2 (~90%), 28,536 km^2 (~97%), 29,329 km^2 (~99%), 29,305 km^2 (~99%), and 29,419 km^2 (~99%) across the state, respectively. Out of these areas, only the areas with collision probabilities below 0.05 (threshold <0.05) could be assessed as the actual "no risk areas". Of these areas, raptors, pigeons, larks, crows, and buntings contribute ~297 km^2 (~1%), 2,273 km^2 (~8%), 6,864 km^2 (~23%), 14149 km^2 (~48%), and 4,555 km^2 (~15%), respectively. But if the probability of collisions were above the 0.05 threshold, there was some risk of collision, even if the risk was low (Figure 5; Table 5).

Some of the existing turbines were already distributed in the predicted collision risk areas; where the risk was below the threshold of 0.5 for each of the bird groups, along with some wind turbines in the approved and proposed phases of construction also planned in these areas (Ministry of Environment, Health and Consumer Protection for the state of Brandenburg; LUGV, 2014). The areas where these turbines were distributed narrowly approached the collision risk areas with higher probabilities of collision (threshold >0.5), especially for pigeons and raptors (Figures 8 and 9). The expansion has already led to and will continue to lead to further increase of risks, although under particular thresholds. The turbines in areas with fairly lower collision probabilities could also lead to nonnegligible numbers of collisions, but only the areas with collision probabilities <0.05 can be interpreted as the actual "no risk areas", and all other probability thresholds do have some risk or at least a residual risk of collision.

Our results illustrated that the wind-based renewable energy targets set for the federal state of Brandenburg could be achieved by suitably positioning the wind turbines with utmost vigilance.

Our findings are particularly relevant for planners and policy-makers. The differential response of the reported birds suggest that it is possible to also locate wind farms and to plan changes in land use in accordance with conservation interests. Depending on regional conservation priorities, it may be possible to locate suitable wind turbine sites that might only affect species of lower conservation concern or specifically benefit those in need of conservation action or extended protection across nontarget species by extending suitable conservation actions to only the umbrella species.

Therefore, the authors would still like to clearly and understandably state that despite the usefulness of their study for regional planning processes, the assessed collision distributions are not a substitute for detailed population level monitoring nor for site-specific Environmental Impact Assessments Studies (EIAs) in the course of project planning. The best approach is not to expect our models to be an ultimate endpoint but instead to follow it as a guide for consultation within limited resources and should not be used as a sole decision-making tool for the selection of suitable wind turbine sites in the federal state.

AUTHOR CONTRIBUTIONS
Tobias Dürr was responsible for the sampling design and data collection. Anushika Bose was responsible for the subsequent analyses to which Reinhard Klenke gave advice and support. Anushika Bose wrote the main manuscript text and prepared all the figures. All authors reviewed the manuscript.

ETHICS STATEMENT
The material for this study is based on a database registering counts and locations of birds found dead as a consequence of collision with WTs in the area of the Federal State of Brandenburg and (with a lesser intensity) whole Germany. This database only contains information of counts and carcasses registered in a special data sheet provided by the Brandenburg State Agency for Environment (Brandenburg State Bird Conservation Centre, Unit N3, Buckower Dorfstraße 34, 14715 Nennhausen/OT Buckow, Germany).

Access: http://www.lugv.brandenburg.de/cms/media.php/lbm1.a.3310.de/meldebogen_anflugopfer.xls. More information about the sampling, the availability, and the results of analyses can be found at: http://www.lugv.brandenburg.de/cms/detail.php/bb1.c.312579.de. The data were collected either in special monitoring surveys following the construction of a wind park (i.e., carcass search operations) as requested by the Ministry of Environment, Health and Consumer Protection for the state of Brandenburg; responsible for permissions to construct wind parks according to the German nature conservation standards and planning laws. Mostly, the data provided to this

database was based on single sampling actions, for example, either by the state agency mentioned above or from accidental findings of collision victims by private people during a walk or other leisure activities on their own property or on public land. No living animal was caught or killed especially for this study. All animals collected and registered in this database were killed by collision with WTs independent of the sampling process and before the sampling was performed. The database contains data about protected and endangered species. However, these species were not killed or manipulated for this study, they were either found dead or seriously injured after the collision, registered and provided to the authority responsible for their registration and, if still possible, overhanded for appropriate health treatment and release. There was either no permission necessary for the registration and collection of the carcasses on public land or the collection was performed in accordance with the requested monitoring or a special permission given by the hunter (if the species was game), or the land owner or the nature conservation authority. All permissions followed the respective legislation at the federal and state levels. No illegal information is stored in this database. The database is hosted by the State Agency, which is deputized in this study by one of the authors (Tobias Dürr). A detailed description of the content and availability of the databases is given in: Dürr, T. (accepted): Bewertung und Nutzung der Schlagopferdatei als Hilfsmittel zur Analyse anlagebedingter Mortalität von Vögeln an Windenergieanlagen. (Assessment and use of data sets of bird strikes for the analysis of bird mortality at WTs). In Derschke, V., Bernotat, D. & Grunewald, R.: "Bestimmung der Erheblichkeit und Beachtung von Kumulationswirkungen in der FFH-Verträglichkeitsprüfung". BfN-Skripten, and will be available soon from the Internet pages of the Federal Agency for Nature Conservation: https://www.bfn.de/0306_eingriffsregelung-literatur.html/ https://www.bfn.de/0502_skripten+M52087573ab0.html

DATA AVAILABILITY STATEMENT

All data files are available from the Dryad Digital Repository (DOI: http://dx.doi.org/10.5061/dryad.j1h2v).

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.