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RESEARCH ARTICLE

Sensitivity analysis of collision risk at wind turbines based on flight altitude of migratory waterbirds

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Abstract

1. A rapid increase in wind power generation has led to bird collisions becoming a serious problem worldwide. Developing useful sensitivity maps to select low-risk sites for birds is an urgent issue. For migratory birds, such as geese and swans, that visit different habitats throughout their life cycle, it is important to conduct risk assessments that take into account their behavioural characteristics in each habitat. Geese and swans fly and migrate at varying altitudes (above the ground) ranging from 10 to hundreds of metres. Accurate predictions of avian flight altitudes are essential in assessing the risks of collisions with human-made structures.
2. We first obtained location data for four species of geese and swans to identify their spring migratory routes within Japan (Bean Goose *Anser fabalis* and *Anser serrirostris*, Greater White-fronted Goose *Anser albifrons*, Tundra Swan *Cygnus columbianus bewickii* and Whooper Swan *Cygnus cygnus*). As all four species used the same roosts and overlapping foraging areas from winter to spring, a single migratory route was defined by integrating the location data of the four species.
3. Flight trajectories were tracked using an ornithodolite. The median flight height for these four species in all landscape types was 150 m or less. Then a LASSO regression model was created with flight altitude obtained as the response variable and topographic and landscape factors as explanatory variables. Trends in flight altitude with environmental differences were similar for the four species, indicating that topographical factors strongly influence flight altitude. Finally, a statistical model was used to predict flight altitudes along migration routes.
4. The sensitivity maps we generated showed that for all four species, most flight heights during spring were within the wind turbine range, suggesting that their risk of collision with wind turbines was greater along their migratory route. Sensitivity maps that accurately reflect avian flight characteristics help provide useful information when considering the location of further wind turbine construction.

KEYWORDS
flight altitude, geese, migration routes, ornithodolite, sensitivity map, swan, wind turbines

1 | INTRODUCTION

Global warming has become a major concern around the world. The Paris Agreement of 2015 (UNFCCC, 2015) mandates the reduction of CO_2 emissions in developed countries, and subsequently renewable energy sources that produce significantly fewer greenhouse gases, such as wind, solar and geothermal, have increased rapidly since the 2000s. The relatively low cost of construction and maintenance of wind power generators makes it a commonly used method of energy generation. The installed capacity of wind generation globally, as of 2017, was 20 times greater than that in 2001 (GWEC, 2017). However, there are concerns that the construction of wind farms leads to the degradation of landscapes and the natural environment. In particular, impacts on birds and bats, that is, collisions with wind turbines, increased detour costs due to avoidance of wind turbines, and habitat abandonment, are serious problems worldwide (Amorim et al., 2012; Erickson et al., 2014; Harrison et al., 2018; Marques et al., 2019; Masden et al., 2009; Smallwood, 2013). Smallwood (2013) estimated that 573,000 birds and 888,000 bats per year would be killed in installed wind energy capacity by 2012, in the United States, which represented 16.5% of the world's installed wind power (GWEC, 2017).

Bird collisions are influenced by the landscape, terrain and weather in which wind farms are constructed. They are often reported in ecologically sensitive locations such as along flight paths between roosting and foraging areas and on slopes over which the updrafts occur that are used by soaring birds (Drewitt & Langston, 2006; Johnson et al., 2002; Kitano & Shiraki, 2013; Murgatroyd et al., 2021; Peron et al., 2017).

Avoiding selecting areas for the construction of wind farms that are likely to have a strong impact on birds is part of efficient site selection. To this end, the development and introduction of sensitivity maps in advance of planning wind farms have been promoted mainly in Europe and the United States in order to prevent bird collisions (Bright et al., 2009; Garthe & Hüppop, 2004; McGuinness et al., 2015; Retief et al., 2010). Basic information that contributes to creating such sensitivity maps for birds includes major wintering areas and stopover sites, the main habitats of key species and key migration routes (Bright et al., 2009; Garthe & Hüppop, 2004; Retief et al., 2010). Previously proposed sensitivity maps were often based on two-dimensional information concerning the main habitats and distributions of target species (Bright et al., 2009; McGuinness et al., 2015; Retief et al., 2010). Recently, for large raptors, collision risk has been visualized by predicting the area where they fly below the height of the wind turbine based on spatial factors such as slope and distance from the nest (Murgatroyd et al., 2021). However, few research cases have reflected three-dimensional information such as flight altitude, which may vary depending on environmental characteristics, making it impossible to identify high-collision-risk areas.

Hokkaido and Tohoku regions in northern Japan have considerable potential for wind turbine installation due to favourable wind conditions (MOEJ, 2011). Currently, these two regions account for 47% of total wind power generation in Japan (MOETIJ, 2020). These regions have many wetlands, including rivers, lakes and marshes that serve as important stopover and wintering grounds for large, migratory waterfowl species such as geese and swans (Mikami et al., 2012), the populations of which number approximately 160,000 (MOEJ, 2021c). There have been no reports of geese and swans colliding with wind turbines in Japan (Ura, 2015), possibly because wind farm managers are not required to report collisions. However, collisions have been reported in Europe (Rees, 2012), where wind farms have been built since the 2000s (GWEC, 2017), and there are concerns about negative impacts such as bird collisions and habitat abandonment in the future (Ura et al., 2021). Therefore, the development of sensitivity maps for these species has become an urgent issue.

In this paper, we provide wind turbine sensitivity maps that focus flight altitudes on geese and swans. In particular, we use 3D trajectories to identify the influence of land use and topography on differences in flight altitude. Additionally, we extrapolate statistical models that predict flight altitudes to migratory routes to produce maps showing the risk of collisions.

2 | MATERIALS AND METHODS

2.1 | Target species and survey area

We focus on the four most abundant species of large waterfowl in Japan: Bean goose *Anser fabalis* and *Anser serrirostris* (BG), Greater white-fronted Goose *Anser albifrons* (GWG), Tundra swan *Cygnus columbianus bewickii* (TS) and Whooper swan *Cygnus cygnus* (WS). The data from interviews and 'monitoring site 1000' described below include cases where the two BG species were treated as one. Furthermore, in some cases, the distance between the object and the observer was so great in the field survey that it was difficult to distinguish the two species. Therefore, we grouped the data for the two species of BG.

The selection of field survey sites was based on annual point count surveys of geese and swans at approximately 9000 sites in Japan from October to April by Japan's Ministry of the Environment (MOEJ, 2021c). This survey has been conducted for geese, swans and ducks throughout Japan, but there are not as many survey sites in Hokkaido as on Honshu Island. Therefore, to complement the MOEJ's surveys, we decided to focus on Hokkaido as the main survey area and also on the Tohoku region, which is a major wintering ground for geese and swans. Field surveys were carried out in Hokkaido, Aomori, Akita, Yamagata, Niigata and Miyagi prefectures, which are home to 80% of the BG, 90% of the GWG, 66% of the TS and 67% of the WS during winter in Japan (MOEJ, 2021c).

Regarding offshore areas, although flights of geese and swans were confirmed offshore during this study, detailed location data could not be obtained because the distance from the shore was too great to be recorded; hence, we only targeted onshore areas.

Our fieldwork was conducted on public lands that did not require an application for a use licence.

2.2 | Collection of bird distribution

The foraging and resting flocks of swans and geese were located and recorded at the stopover sites and in the wintering areas by vehicle (Figure 1). A cumulative total of approximately 60,000 km^2 of farmland (including pastures, rice fields and cropland), in addition to bodies of water, including rivers, ponds and lakes was covered. The surveys were carried out for a total of 101 days: 9 days in Niigata Prefecture (from November 2018 to February 2019), 4 days in Yamagata Prefecture (in February 2019); 10 days in Akita Prefecture (in February and November 2017); 11 days in Akita Prefecture (in December 2018 and February 2019), 10 days in Aomori Prefecture (March 2018 and March 2019); 5 days in Miyagi Prefecture (in November 2017); and 52 days in Hokkaido (in March and April 2017, March and April 2018 and March 2019). The surveys were carried out in daylight between 08:00, after the birds left their roosts in the morning, and 16:00, before they roost in the evening. The approximate sunrise and sunset times during the study period were from 04:30 to 06:30 am and from 15:30 to 18:00 (NAOJ, 2021). During the surveys, species and flock sizes on the ground were recorded and locations were mapped. Birds in flight were recorded only when they passed directly above the researcher.

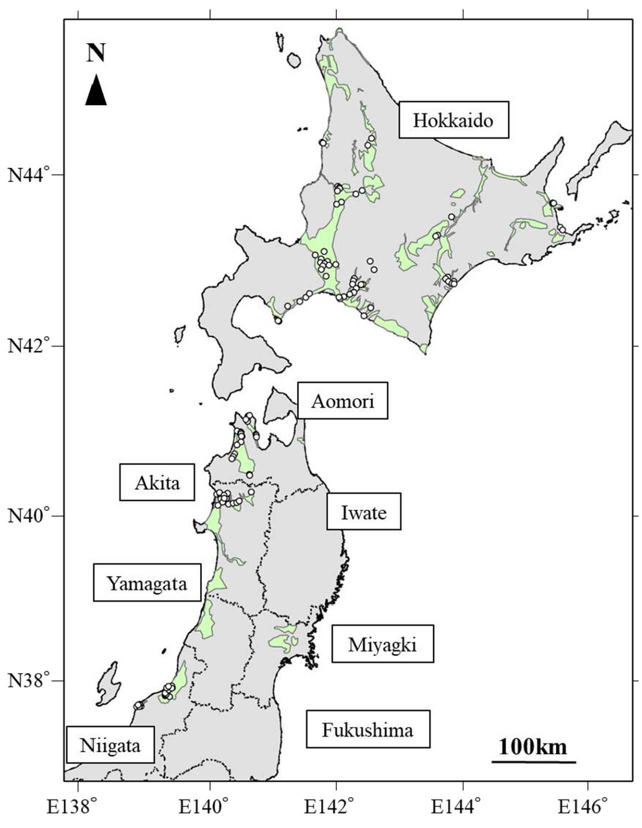

FIGURE 1 Survey sites for a collection of bird distribution and fixed-point observations. Green areas indicate where collections of bird distribution were conducted, white circles indicate where fixed-point observations were conducted.

2.3 | Fixed-point observation using an ornithodolite

We used ornithodolites (VECTOR21, VECTOR21 AERO and MOSKITO manufactured by SAFRAN Vectronix; 1σ distance error: ±5 m, 1σ elevation error: ±0.2°, 1σ azimuth: ±0.6°) capable of obtaining highly accurate three-dimensional location data. These devices accurately measure an object's azimuth, elevation and oblique

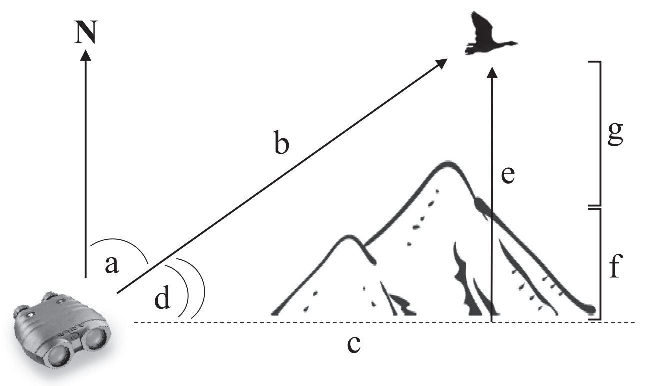

FIGURE 2 Tracking a flying bird with an ornithodolite. Ornithodolites were used to acquire flight altitudes with a laser and to measure: (a) azimuth, (b) oblique distance and (c) elevation angle, to calculate (d) the horizontal distance to obtain the location, to calculate (e) the altitude from the point of measurement, and subtract (f) the elevation at the measured position to obtain (g) the altitude of the target object above the ground.

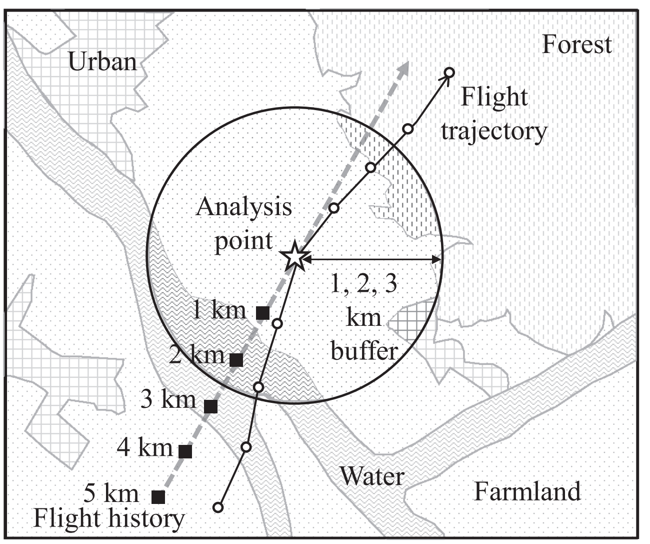

FIGURE 3 Extraction of environmental variables used in statistical modelling. The centre point (star) of the flight trajectory measured by the ornithodolite (white points) was used for the analysis. Farmland area, water area, urban area, forest area and elevation variation (standard deviations) within a 1–3 km radius buffers from the centre point were extracted as variables. As variables related to the terrain flow (flight history), the highest elevations within 1–5 km from the centre point in the direction opposite to the average flight direction (grey dotted arrow) were extracted.

distance and calculate the latitude, longitude and altitude using the built-in compass and infrared laser illuminator (Figure 2). When used for birds, the tracking data are acquired at 3–6-s intervals. The response of flight altitude to terrain and landscape can be understood. During March and April 2018 and February and March 2019, fixed-point ornithodolite surveys were conducted at 93 sites within the study area (Figure 1) to obtain location and flight altitude data. We measured flight altitudes in various environments, including farmland, water bodies, urban areas, forests and mountainous areas, to elucidate the effects of landscape and terrain factors on flight altitude. The maximum measurable range according to the device's specifications was 12 km for structures. However, for the target species of geese and swans, the measured range was approximately 2 km for individual birds and approximately 3 km for flocks.

TABLE 1 A list of variables used for LASSO regression. Twenty environmental variables were extracted to predict flight altitude by LASSO regression.

Variable	Summary of variables	Reference
Farmland area (km^2)	Total farmland area in 1–3 km buffer	JAXA (2018)
Water area (km^2)	Total water area in 1–3 km buffer	
Urban area (km^2)	Total Urban area in 1–3 km buffer	
Forest area (km^2)	Total forest area in 1–3 km buffer	
Topographic roughness	Standard deviation of elevation in 1–3 km buffer	MLIT (2011)
Flight history	Maximum elevation 1–5 km in flight history	

2.4 | Definition of a migratory route

The ranges of spring migration routes were defined using the outermost boundary method using location data obtained from

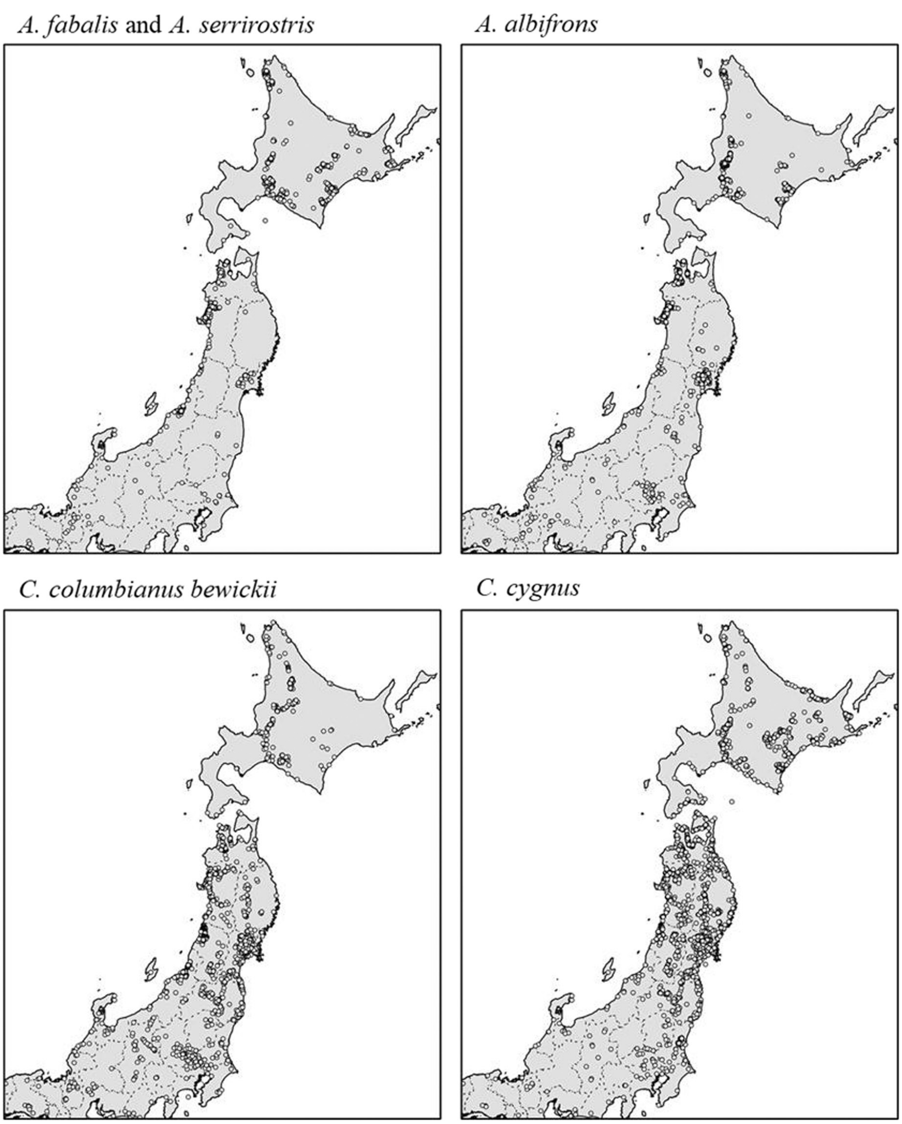

FIGURE 4 The distributions of Bean Goose, Greater White-fronted Goose, Tundra Swan and Whooper Swan in northern Japan. Location data were collected by adding public databases (MOEJ, 2021b, 2021c; YIO, 2021) to field surveys and interview data.

field surveys, interviews with the Wild Bird Society of Japan, and the Nationwide Census on Wild Geese, Ducks, and Swans (MOEJ, 2021c), Monitoring Sites 1000 (MOEJ, 2021b) and Bird Atlas data (YIO, 2021) as public databases. Furthermore, we showed the connectivity of habitats in areas lacking observational data by referring to satellite-tracked studies of geese and swans (Chen et al., 2016; Kurechi, 2006; MOEJ, 2018; Shimada et al., 2014; Ueta et al., 2018; YIO, 2010).

2.5 | Extraction of environmental factors

Esri Arc GIS Pro ver. 2.41 was used to create flight trajectories based on positional data and to extract landscape and topographical factors (JAXA, 2018; MLIT, 2011). To create a statistical model to predict flight altitude, flight trajectories were drawn from the continuous latitude and longitude data of the flock and the centre point of the trajectory was set as an analysis point, from which environmental factors were extracted. The flight altitude data of flocks that were confirmed to be landing was excluded from the analysis because their movements were judged to be local flights between roosts and foraging areas, not migratory flights.

For landscape factors related to land use, 1, 2, and 3 km buffers were generated from the analysis points, which allowed the acquisition of farmland areas, water areas, urban areas and forests. Farmland includes rice fields, vegetable fields and pastures that serve as foraging habitats, and bodies of water include lakes, marshes and rivers that serve as roosts and foraging habitats.

In the case of factors related to topography, buffers of 1, 2 and 3 km were generated from the analysis points. Standard deviations of elevation within each buffer area were calculated as values representing topographic roughness (Figure 3). While analysing factors that determine flight altitude, the characterization of flight behaviour in highly variable mountain forest areas was considered an important process to improve the explanatory power and predictability of statistical models; hence, changes in flight altitude along with changes in elevation were tracked. Additionally, considering that the history terrain (the terrain over which birds had recently flown) travelled to the analysis point affects the determination of flight altitude, lines of 1, 2, 3, 4 and 5 km were generated in the opposite direction of the mean flight direction (hereinafter, flight history), and the highest elevation on the line was obtained (Figure 3). For statistical modelling, a total of 20 factors were incorporated as explanatory variables (Table 1).

2.6 | Statistical analysis

To determine the autocorrelation of flight altitude, we performed ANOVA with trajectory ID as a factor. We performed the Kruskal–Wallis test and Steel–Dwass test to compare flight altitudes for each landscape.

Statistical models were created for each of the four species using R ver. 3.6.0. LASSO regression (a type of regularized linear regression analysis) of the R package GLMNET was applied (Friedman et al., 2010; R Core Team, 2022). Dimensional compression by the L1 norm and regularization by adjusting the coefficients were applied. It is possible to create a statistical model that is relatively easy to interpret while preventing overfitting (Ranstam & Cook, 2018). In our study, environmental variables were obtained at various spatial scales. Because the most influential spatial scale for each variable may differ, it is reasonable to apply modelling incorporating all variables. Therefore, we used the LASSO regression, which is considered less prone to overfitting, even when a large number of variables are involved. The flight altitude (masl) of analysis points was used as the response variable. Environmental factors standardized to have a mean of 0 and a standard deviation of 1 were used as explanatory variables. To optimize the value of λ, which determines the influence of the regularization term, a cross-validation was performed in which the data were divided into 10 sections. To avoid overfitting the final model, we used

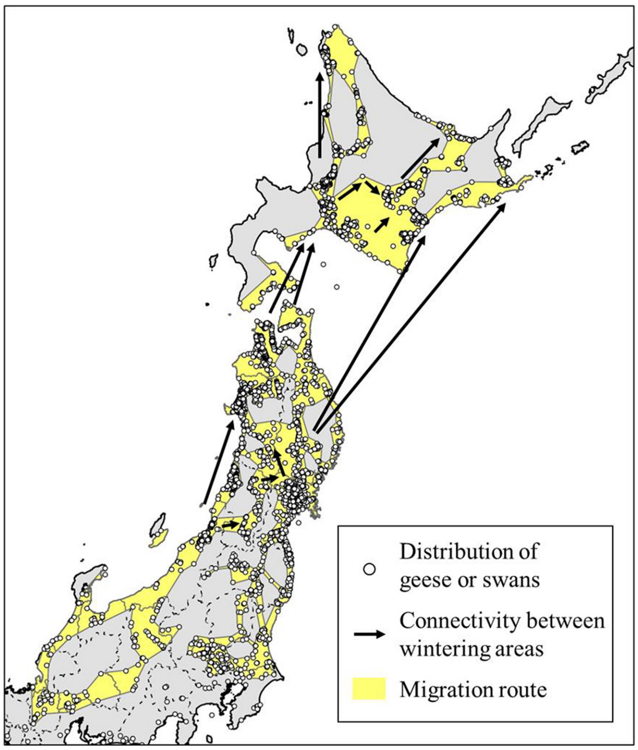

FIGURE 5 The migratory routes of geese and swans based on location data. White circles indicate the distribution of any of the four species. Arrows indicate connectivity between habitats, as revealed by transmitter tracking (Chen et al., 2016; Kurechi, 2006; MOEJ, 2018; Shimada et al., 2014; Takekawa et al., 2000; Ueta et al., 2018; YIO, 2010). Yellow areas indicate the migratory routes of geese and swans in northern Japan.

the maximum λ value that was within 1SE of the minimum cross-validation error. The R^2 values were calculated as the explanatory power of the final model.

2.7 | Extrapolation of the statistical model

A 250 m grid was created within the migratory route, which was the extrapolation area, and each of the variables used in the model was extracted. For the variables of flight history, the flight direction was defined from the connectivity of lakes and marshes as roost based on studies using transmitters. For each square, the nearest flight direction was referenced. The variables extracted from within the extrapolation area were standardized on the same scale as the model and used to predict flight altitude.

When used as a sensitivity map, the possibility of birds flying at the same height as the wind turbine built on the ground is an evaluation factor. Hence, the flight altitude relative to the ground was calculated by subtracting the average elevation within the square from the predicted flight altitude in each square. The predicted flight altitude was classified according to the risk of collision based on the height of wind turbine. In creating our sensitivity maps, we assumed that one of the largest wind turbines in Japan, with a rated output of 3200 kW (wind turbine height of 150 m, rotor diameter 103 m, hub height 98 m) (SEI, 2020), taking into account the recent increase in the size of wind turbines (JWEA, 2016). The predicted flight altitudes of the four geese and swan species were classified into three levels, low, medium and high. Medium (45–150 m) was within the range of rotating wind turbine blades and was considered to have the highest risk of collision, low (<45 m) was lower than most wind turbine blades and was considered to have a lower risk than medium; and high (>150 m),

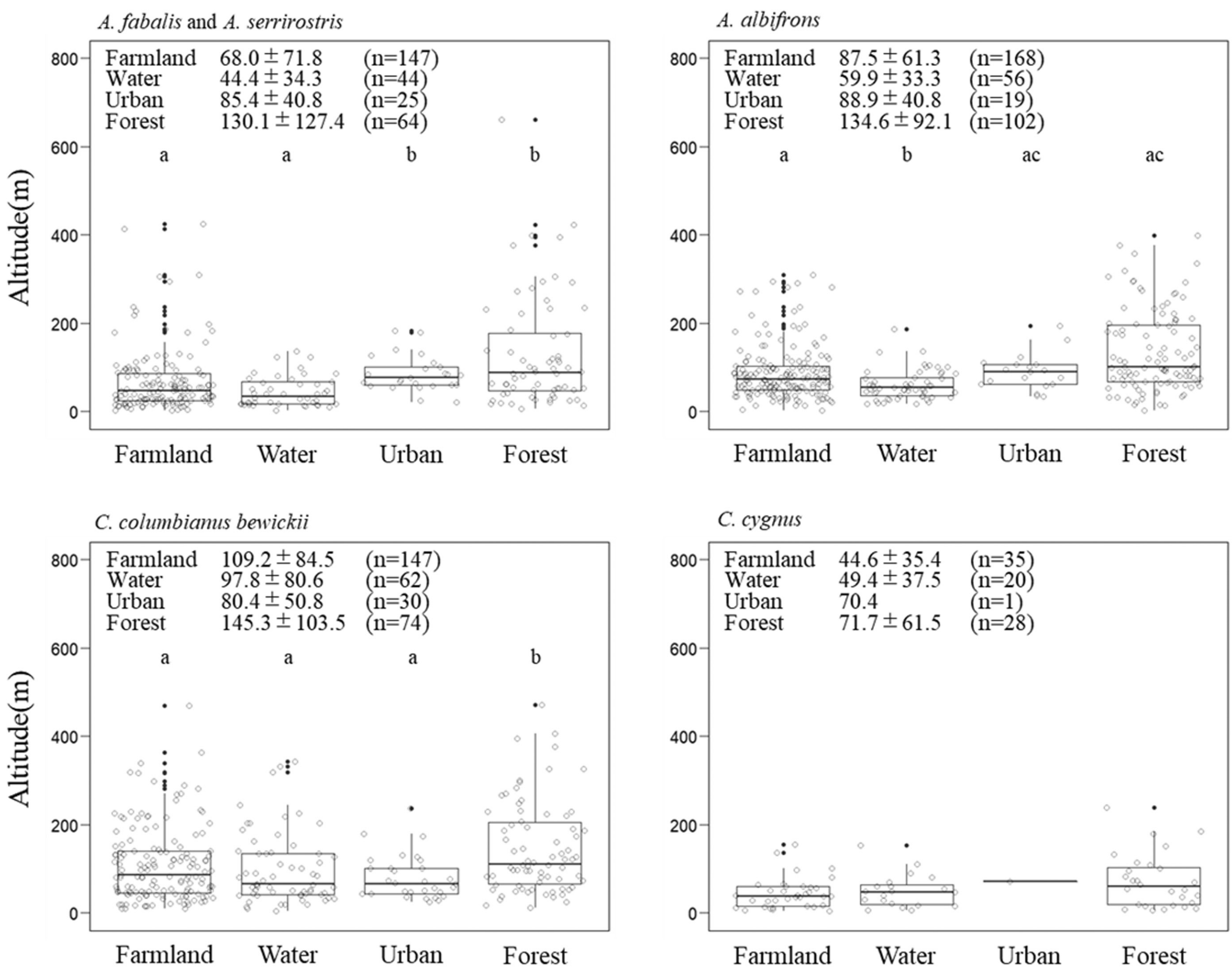

FIGURE 6 Flight altitude for each land use and landscape. Ground-level flight altitudes were plotted for four landscapes: farmland, water areas, urban areas and forests, by subtracting the lowest elevation from the sea level flight altitude measured using the ornithodolite. Boxes are quartiles, and the central black bar indicates the median. Mean values and SE and sample size are shown in the figure. The sample size (n) means the number of flocks (trajectories). Alphabets indicate statistical significance (Steel–Dwass test: $p < 0.05$).

which was higher than the height of the wind turbine, was considered to have zero risk of collision (Figure S1).

3 | RESULTS

3.1 | Migratory routes of geese and swans

Migratory routes were defined using 7168, 3229, 6366 and 10,929 location data of BG, GWG, TS and WS (Figure 4). Habitat connectivity has been shown between Niigata and Yamagata or Akita, Yamagata and Miyagi, Miyagi and Akita, Miyagi and eastern Hokkaido, Aomori and western Hokkaido, and western Hokkaido and northern or eastern Hokkaido by previous studies using satellite transmitters (Figure 5, Chen et al., 2016; Kurechi, 2006; MOEJ, 2018; Shimada et al., 2014; Takekawa et al., 2000; Ueta et al., 2018; YIO, 2010). To prevent an overestimation of the extent of migratory routes, regions with few observed cases were excluded, except where satellite tracking indicated connectivity. Since there have been reports of birds in southern Japan crossing to the Euroasiatic continent without passing through Tohoku and Hokkaido (YIO, 2010), the migratory route was defined only for northern Japan.

3.2 | Relationship between landscape and topographical factors and flight altitude

The number of trajectories obtained in ornithodolites was 185, 221, 170 and 51 for BG, GWG, TS and WS respectively. The highest frequency of tracking points per trajectory was 5 to 10 for all species (Figure S2). The size of the flock per trajectory was most frequently between 10 and 20 birds (Figure S3). Analysis of variance showed that the main factor of the change in altitude was between trajectories rather than within trajectories for all species (Table S1). The mean SD of height within a trajectory was 5.9, 7.7, 6.7 and 7.7 m for BG, GWG, TS and WS respectively (Figure S4).

For BG, the altitude was significantly higher in urban and forest than in farmland and water (Figure 6; Steel-Dwass test, $p < 0.01$). For GWG, the altitude was significantly lower in water than in other places and significantly higher in urban and forests than in farmland (Figure 6; Steel-Dwass test, $p < 0.05$). For TS, the altitude was significantly higher in forests than in farmlands, water and urban areas (Figure 6; Steel-Dwass test, $p < 0.01$). No significant differences were shown for WS, but higher altitudes were flown in urban areas (sample size = 1, though) and forests (Figure 6; Kruskal–Wallis test, $p = 0.29$). Furthermore, the median

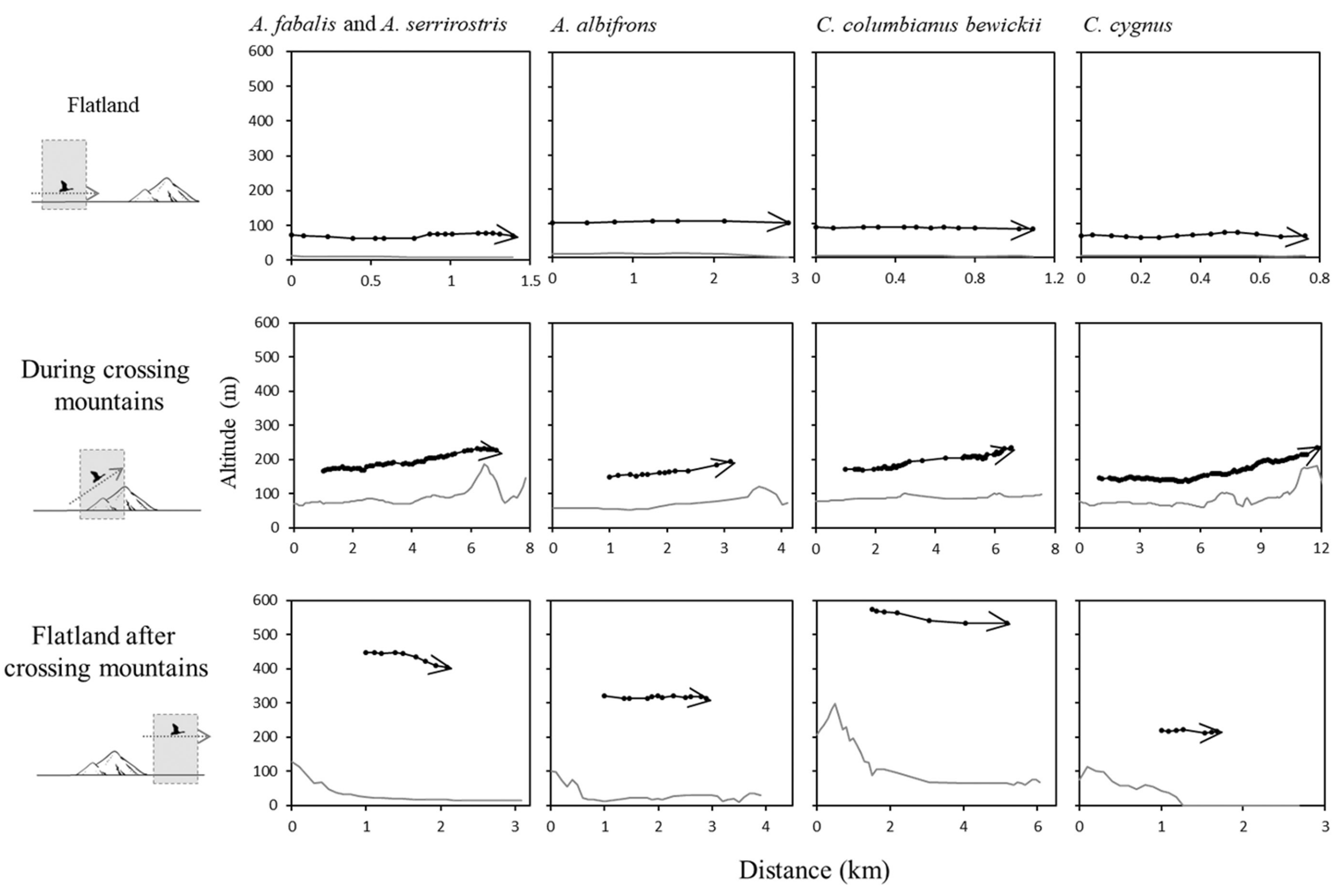

FIGURE 7 Relationship between topographic characteristics and flight altitude. The grey line indicates the land elevation beneath the flight path. Black dots indicate the flight altitude measured by ornithodolite.

height for all four species and in all landscapes was lower than the height (<150 m) of the wind turbine blades. All four species showed a great variation in flight altitudes in forests, including mountainous areas.

The flight trajectories of the four species differed between those over flatlands before and those after crossing mountains (Figure 7). No large altitude change was observed for any of the four species in their flight trajectories over flat terrain. In contrast, changes in flight altitude were observed in mountainous areas with large topographic roughness. Before crossing mountains, the flight altitude of the flocks increased with elevation. In particular, around the peaks of ground elevation, although flight altitudes above sea level were high, their flight altitudes over the ground level were low. They maintained their greater flight altitude for some distance after crossing mountains before descending, thus their flight altitude above the ground was higher after crossing mountains than at other times.

The R^2 values in the LASSO regression, which indicate the explanatory power of model, were 0.67 for the BG, 0.79 for the GWG, 0.57 for the TS and 0.76 for the WS of the model respectively (Table 2). For all four species, the most influential variables were those related to topography, with positive effects in environments with large roughness and areas of high elevation in flight history. For landscape, although the influence was smaller than for topography, the area around water on the 1 and 2 km scales had a negative effect, and the forest area on the 1 km scale had a positive effect. In particular, the most influential flight histories were the more recent ones. For all species, the previous 1 km of elevation had the largest coefficient, indicating that they continued to fly at greater altitudes after crossing higher mountain ranges.

TABLE 2 Relationship between flight altitude and landscape and topographic factors. The coefficients for each variable, R^2 value and λ estimated in the LASSO regression are shown. Blank columns indicate no coefficients.

	Scale size (km)	*Anser fabalis, Anser serrirostris*	*Anser albifrons*	*Cygnus columbianus bewickii*	*Cygnus cygnus*
Intercept		131.15	143.85	174.63	123.68
Farmland area	1				
	2				
	3				
Water area	1	−3.59		−5.22	
	2	−4.11	−2.39	−9.62	
	3				
Urban area	1				
	2				−1.26
	3				
Forest area	1	3.3	3.01	24.65	
	2				
	3				
Topographic roughness	1				
	2				
	3	25.79	27.95		3.06
Flight history	1	31.62	49.22	24.51	69.03
	2		7.13	16.46	11.25
	3				
	4				
	5	17.16		11.72	
R^2		0.67	0.79	0.57	0.76
Lambda.1SE		20.45	11.57	14.2	20.86

3.3 | Four types of sensitivity maps on the migratory route

The statistical model predicting flight altitude was extrapolated to create a sensitivity map for the migration route (Figure 8). Of the extrapolated range of predicted flight altitudes, the proportions of time spent in each of the low, medium and high zones were as follows: BG, low 27.7%, medium 60.7% and high 11.6%; GWG, low 23.9%, medium 64.3% and high 11.8%; TS, low 21.1%, medium 60.7% and high 18.2%; and WS, low 48.8%, medium 47.1% and high 4.2%. BG, GWG and TS were predicted to spend most flight time in the Medium zone, with the greatest risk of collision with wind turbines. WS were predicted to be in the low zone more often than the other three species.

4 | DISCUSSION

One of the advantages of our analysis is that the sensitivity map can be updated and used according to the standard strut height and a blade length of the wind turbine because it offers a numerical prediction of flight altitude. It is possible to accommodate wind turbines that are expected to become larger in the future.

Differences in factor scales in the statistical model may be due to differences in the decision-making process for flight altitude. The time and energy costs required for altitude changes in mountainous terrain, where flight altitude is higher, are likely to be greater than over water bodies, where flight altitude is lower. In mountainous areas, there may be a response to the environment using the information on a broader spatial scale and the performance of low-load flight by increasing altitude in advance.

A previous study using GPS transmitters has shown that the Bar-headed Goose *Anser indicus*, renowned for its trans-Himalayan flights, has shown that it typically flies along valleys, albeit at high altitudes (Hawkes et al., 2012). In general, oxygen availability is lower at high altitudes, and the energetic flight costs of are greater (Bishop et al., 2015; Butler, 2016; Hawkes et al., 2012). During winter, when food is scarce, and during spring migration before reproduction, birds may follow topographic variation and maintain their flight at low altitudes to minimize energy consumption. Therefore, when flying along ridges, the flight altitude above the ground is low, which means that there is a sufficiently high possibility of flying in the wind turbine zone.

Several issues were identified during this study. First, the density of the target species is not reflected in the migratory route. Geese and swans choose to fly at as low an altitude as possible to minimize energetic costs (Bishop et al., 2015; Hawkes et al., 2012; Klaassen

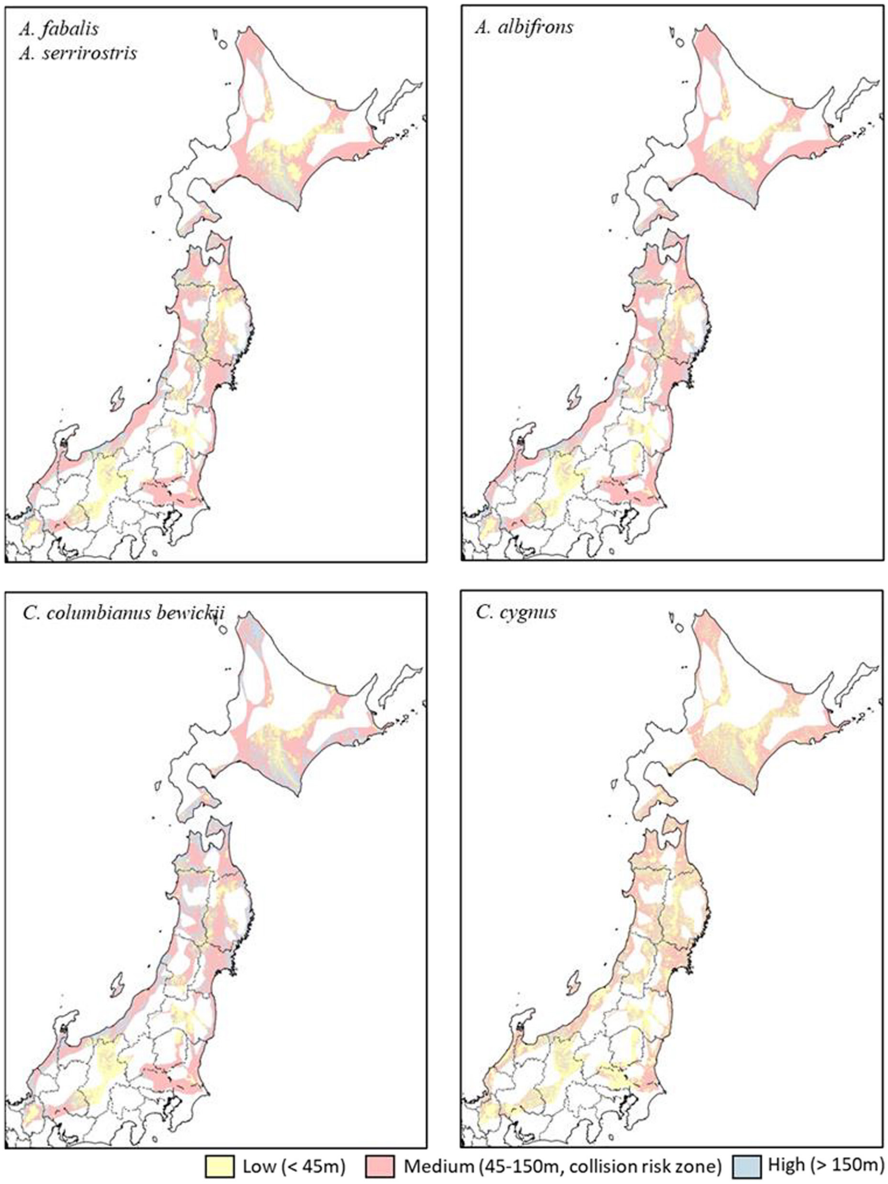

FIGURE 8 Predicted flight altitude on the migratory route for each of four target species. The flight heights (ground heights) were predicted from the LASSO regression for each of the four species and are shown as low (<45 m), medium (45–150 m; collision risk zone) and high (>150 m) zone.

et al., 2004). Assuming that it is possible to elucidate the environmental preferences involved in path selection during migration and to extract environments with high flight density, we will be able to evaluate collision risk with higher accuracy. Although this study focused on migratory routes in northern Japan, waterfowl populations wintering in Lake Shinji, in southern Japan, use uncharted migratory routes to the Eurasian continent rather than via northern Japan (YIO, 2010). In the future, migration routes between wintering areas and stopover sites in areas beyond the scope of the present study need to be identified and collision risks evaluated.

In this study, we were unable to analyse the position and altitude data at sea due to insufficient acquisition. There are many plans to introduce increasing wind power generation in Japan, both onshore and offshore. In particular, plans have been made to build some of Japan's largest offshore wind farms off the coasts of Akita and Aomori prefectures (MOETIJ, 2020). Wind turbines built offshore, 200 m or higher, are taller than those built on the land. Little information is available on the migratory routes of geese and swans over the sea in Japanese waters. The clarification of offshore flight characteristics and collision risk assessment for offshore wind turbines are important issues for the future.

MOEJ has developed a sensitivity map, which evaluates the collision risk of each grid square (10 km grid) at five levels based on the total risk score. This score is based on the distribution information of several rare bird species selected by the government and included in Japan's Red Data Book (MOEJ, 2020) and the information on wintering areas and stopover sites (MOEJ, 2021c). To further reduce the impact of wind turbines on the local environment, a risk assessment of rare species in each region and indicator species for the region are also necessary in addition to a multiple species risk assessment such as the MOEJ sensitivity map devised. The opinion of the MOEJ (MOEJ, 2014) is that the assessment should be particularly rigorous for rare species inhabiting the area or bird species for which the area is a breeding ground. In such cases, more accurate sensitivity maps reflecting the behavioural characteristics of the target species will be essential, such as in our study and previous studies of large raptors (Murgatroyd et al., 2021; Peron et al., 2017). The resolution of a sensitivity map is also important. A 10 km grid map, such as that provided by the MOEJ, can be used for selecting wind power project sites, but finer scale maps are necessary (we created a 250 m grid map) for environmental assessment (EIA) within a project site. Biological information from the MOEJ in EADAS (MOEJ, 2021a) will be linked to our sensitivity maps. Wind power producers will be able to use this information before the EIA, which is expected to contribute to prompt site selection. On the other hand, there are cases where the location of good wind conditions is an environment used by birds, and the construction of wind turbines cannot be avoided. Systems that respond to bird flight conditions to stop the operation of wind turbines and to encourage avoidance behaviour are being developed and implemented (Georgiev & Zehtindjiev, 2021; May et al., 2020; Pescador et al., 2019). Proper mitigation after the construction and operation of wind turbines will also be an essential process to reduce human–wildlife conflicts.

AUTHOR CONTRIBUTIONS

Taito Kamata and Tsuneo Sekijima conceived the ideas and designed methodology; Taito Kamata, Hitomi Sato, Haruka Mukai, Takahiro Sato and Shintaro Yamada collected the data; Taito Kamata and Hitomi Sato analysed the data; Taito Kamata, Hitomi Sato and Tsuneo Sekjima led the writing of the manuscript. All authors contributed critically to the drafts and gave final approval for publication.

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CONFLICT OF INTEREST STATEMENT

The authors declare that they have no competing interests.

PEER REVIEW

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DATA AVAILABILITY STATEMENT

Data available from the Dryad Digital Repository https://doi.org/10.5061/dryad.73n5tb323).

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SUPPORTING INFORMATION

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

Figure S1. Definitions of wind turbine standards.

Figure S2. Positioning counts of trajectories tracked by ornithodolite.

Figure S3. Flock size of trajectories tracked by ornithodolite.

Figure S4. SD of altitude within trajectories.

Table S1. Variance analysis of flight altitude in ornithodolite tracking.

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