Title: Collision risk of White-fronted Geese with wind turbines

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Abstract Recently, to help curb anthropogenic climate change and fossil fuel depletion, there has been a rapid increase in the number of wind farms being built worldwide. However, the construction of wind farms in the foraging areas of raptors or along the routes of migratory birds raises concerns about avian collisions and habitat loss. Here, we present an additional situation in which avian collisions may present a problem. That is, when wind farms are built between roosting and foraging areas of overwintering migratory birds, the bird flocks are forced to pass through the farm each morning and evening. Indeed, at the Awara Wind Farm in Fukui Prefecture, Japan, approximately three thousand White-fronted Geese *Anser albifrons frontalis* inhabit the site where the installation of 10 wind turbines has recently been completed. The collision risk posed by these turbines may affect the goose population. However, few studies have examined the effects of wind farms on the flight patterns of geese, making it difficult for stakeholders to achieve a consensus. The purpose of this study was to evaluate the avian collision risk for geese at the Awara Wind Farm. A collision model based on goose avoidance behavior was developed to estimate collision mortality, and an applied potential biological removal (PBR) analysis was used to determine the maximum allowable collision mortality (ACM) to maintain a sustainable goose population. The estimated annual collision mortality was 0–2 geese, whereas the allowable collision mortality was 75 geese per year, suggesting that the collision risk is sufficiently small for the population to persist. We also include a discussion of an adaptive management plans for regulating wind turbine operations when the actual collision mortality exceeds the socially acceptable level.

Key words *Anser albifrons frontalis*, Avoidance behavior, Collision risk, Potential biological removal, Wind turbine

Introduction

The installation of renewable energy facilities is increasing throughout the world in an effort to curb anthropogenic climate change and fossil fuel depletion. In Japan, the total number of wind turbines and total amount of energy produce by wind power had reached 1,517 towers and 1,854 MW, respectively, by March 2009 (NEDO 2009).

Despite an international consensus that wind energy is a positive development, wind turbines impact the environment and its inhabitants, especially birds and bats. The major potential risks that wind farms pose to birds are habitat loss, turbine collision, and disturbance (Langston & Pullan 2003; Desholm et al. 2006; Drewitt & Langston 2006). However, in Japan, there is a lack of empirical evidence with regard to the impact of avian collisions with wind turbines, which has made it difficult for stakeholders to achieve a consensus on the issue. Therefore, we evaluated the potential risk of avian collision at the recently completed Awara Wind Farm in Fukui Prefecture, Japan. Mitigation measures that can be taken by wind farms to maintain sustainable populations of birds are then discussed.

Wind farms are often in habitats that are suitable for birds and their migration routes because open landscapes provide good wind conditions for turbines. Therefore, numerous studies have investigated the risks of collision and disturbance of migratory birds on wind farms. For example, Desholm and Kahlert (2005) reported that less than 1% of ducks and geese fly close enough to turbines to risk collision, although a larger proportion of birds fly through wind farms at night than during the daytime. The majority of studies on collision mortality have reported low mortality for migratory birds (e.g., Smallwood & Thelander 2004; Pendlebury 2006). On the other hand, Larsen and Madsen (2000) showed a significant reduction in habitat use by Pink-footed Geese *Anser brachyrhynchus* when wind farms were constructed close to foraging areas, reporting that the avoidance distances from wind farms with turbines in lines and in clusters were approximately 100 m and 200 m, respectively. However, the present study does not focus on habitat loss, given that the proposed Awara Wind Farm is located sufficiently far from roosting and foraging areas (Fig. 1).

Estimating avian collision risk is important for developing a management strategy and establishing a consensus among stakeholders. Mechanistic models can help predict avian collision risk with turbines at a given location. Desholm et al. (2006) developed a framework for a collision model that considered flight frequency and avoidance behavior. Hydro Tasmania (2004) and Band et al. (2007) proposed predictive collision models for the collision mortality of migratory geese. However, their models assumed a direct positive relationship between mortality and abundance and did not account for avoidance behavior. Avoidance rates have been estimated at 95% or higher in most case studies (Chamberlain et al. 2006; Band et al. 2007). Seasonally migrating birds also frequently show avoidance behavior around wind turbines (Desholm & Kahlert 2005; Pendlebury 2006). Although many studies highlight the necessity of considering avoidance behavior in a collision model (Langston & Pullan 2003;

Chamberlain et al. 2006; Desholm et al. 2006; Band et al 2007; Kikuchi 2008; Lucas et al. 2008), to date, the avian avoidance factor has never been included in data-based models for estimating the number of bird–turbine collisions. The collision model used in this study incorporates two types of avoidance behaviors: the avoidance of the wind farm in general and that of individual turbines.

It is important to evaluate the collision risk on population persistence. Carrete et al. (2009) evaluated the effect of wind farms on a population of Egyptian Vultures *Neophron percnopterus* taking into account survival rate and collision mortality. Shimada and Matsuda (2008) proposed an adaptive management model to estimate uncertain bird strikes as the basis for maintaining population by controlling the operation rate of wind turbines according to collision mortality and population size. However, no study has estimated the allowable collision mortality (ACM), defined as the degree to which a population can be sustained relative to the number of collision mortalities incurred. Potential biological removal (PBR) analysis was applied, which has been used for conserving endangered marine mammals (Wade 1998), to determine the ACM for this population. The PBR was developed to identify populations subject to human-induced mortality that could lead to depletion, taking into account the uncertainty of the available information (Wade 1998).

Finally, we evaluated the effect of temporarily shutting down some turbines on the wind farm, an option that is likely important for the establishment of a consensus, on both avian mortality and wind power generation. Temporary shutdown would be an effective mitigation measure if collision risk is higher than that deemed acceptable (Hydro Tasmania 2004). When the collision risk increases based on the seasonal activity patterns of birds (Smallwood et al. 2009) or inclement weather conditions such as strong winds or dense fog (Percival 2004), temporary shutdown may be a sensible tradeoff between bird collision and complete loss of power generation for the wind farm (Smallwood et al. 2009). An adaptive management scenario that takes into account the ACM as well as the behaviors of White-fronted Geese and business risk was devised.

MATERIALS AND METHODS

1) Study area

The study was conducted at the future site of the Awara Wind Farm at the northwest end of Lake Kitakatako in the Fukui Prefecture, central Japan. It is situated between Lake Katanokamoike (a goose roosting area) and Sakai Plain (a foraging area; Fig. 1). Ten turbines (each producing 2 MW with a 40-m blade length, 75-m hub height, and a three-blade rotor) were installed in the wind farm, which will start commercial operations in February 2011 (Green Power Awara Co., Ltd. 2009).

Lake Katanokamoike was designated by the Ramsar Convention as an important roosting area for White-fronted Geese wintering in Japan. The geese remain at the lake for approximately 6 months (October to March) and forage mainly on the Sakai Plane, moving between the two areas in the morning and evening. The wintering geese population at Lake

Katanokamoike has comprised approximately 3000 birds since 2002 (Fig. 2). The population decreased before the hunting ban in 1971 and has gradually recovered since the 1980s (Takeshita & Kurechi 2000).

2) Bird survey

Although environmental impact assessments of wind farms are not a requirement of the environmental impact assessment law of Japan, the frequency of bird passage and evaluation of collision risk were surveyed to establish a consensus among stakeholders who are concerned about bird collisions. The company that owns the wind farm conducted meetings for this reason. The survey was conducted from January to March 2006 and from November 2006 to March 2007 during the goose wintering periods at the planned site including Lake Kitakatako. Visual observations were conducted in the morning and evening by expert bird watchers and three video cameras (Fig. 3). Experts made observations on four and 10 mornings (from 1 h before to 2 h after sunrise), and three and 10 evenings (from 2 h before to 1 h after sunset) in the winter seasons of 2005/06 and 2006/07, respectively. They also traced the flight trajectories of flocks and estimated flock sizes. Observation via video camera was conducted on 38 mornings (from 30 min before to 90 min after sunrise) and 38 evenings (from 90 min before to 30 min after sunset) in the 2006/07 winter season to determine the frequency and size of flocks passing by the planned site. Experts collected data on population size, flight trajectory, height, and speed. The range of observed flight height was categorized as <30 m, 30–110 m and >110 m. The site area is surrounded by open landscape, which enabled observers to obtain precise data.

Knowledge of avoidance rates on a wind farm is imperative for evaluating collision risk given that the avoidance rate may significantly reduce the collision risk. Desholm and Kahlert (2005) analyzed the flight trajectories of water birds (mainly Common Eider *Somateria mollissima* and geese) using a radar system on a wind farm and investigated the effect of avoidance behavior on collision risk by comparing the frequencies of passage through the wind farm before and after the farm was constructed.

3) Collision Model

It was assumed that the collision risk depends on the number of birds in flight at a given time at the planned site. The collision model included the probabilities of passing through the planned site (P_1), within the height of the rotor disk (P_2), within the area of the rotor disk (P_3), and the probability of colliding with blades (P_4) as the geese were migrating in the morning and evening. The collision model also included avoidance behavior data (Fig. 4).

Table 1 lists the symbols and parameters of the collision model. In the model, P_2 represents the frequency of geese passing through the site within a height of 35–115 m, which was the planned height of the rotor disk. However, given that the turbine height was changed after the survey was completed, the frequency was recalculated from the normal distribution obtained by frequencies of geese passing within heights of <30 m, 30–110 m, and >110 m.

The model assumed that geese migrate between the roosting and foraging areas twice a day, 180 days per year (6 months). S_i/S represents the frequency of birds passing through the planned site, where S_i is the number of observations of birds flying over the planned site, and S is the total number of observations. N_i/N represents the probability of a bird's passing through the planned site per occurrence, where N_i is the average number of birds that flew over the planned site, and N is the population size at Lake Katanokamoike. Therefore, the probability of a bird passing over the planned site was:

$$P_1 = (S_i / S)(N_i / N). \qquad (1)$$

The height of flight was categorized as <35 m, 35–115 m, or >115 m. The probability of a bird passing through at a 35–115 m height was:

$$P_2 = F_v / F, \qquad (2)$$

where F is the number of flocks, and F_v is the estimated flight frequencies between 35–115 m height, as shown in Table 1.

The probability of a bird passing within the area of the rotor disk was:

$$P_3 = T_r B_s / B_c, \qquad (3)$$

and B_c, B_s, and T_r are defined in Table 1. It was assumed that wind turbines were installed in two rows of five turbines each.

Tucker (1996) and Band et al. (2007) estimated the probability of avian collision with blades without consideration of avoidance behavior, denoted here by P_4. The equation used by Band et al. (2007) was:

$$P_4 = 2\int_0^1 p(r)\left(\frac{r}{R}\right) d\left(\frac{r}{R}\right),$$

$$p(r) = (b\varpi / 2\pi v)\left(\left|c \sin\gamma + \alpha c \cos\gamma\right| + \xi\right), \quad (4)$$

$\xi = l$ if $\alpha < l/w$ and $\xi = \alpha w f$ if $\alpha > l/w$,

where r is the distance from the center of the rotor where a bird passes through or collides; α is the angle of invasion to the blade, $p(r)$ is the probability density function indicating that a bird passes through or collides at a distance r. The definitions of the remaining symbols used in Eq. (4) are shown in Table 1.

The Band et al. (2007) equation was used to obtain P_4 using the characteristics of the birds and wind turbines shown in Table 1. P_1 and P_2 represent the front of the planned site, and P_3 and P_4 represent the front of an individual turbine. Let T_c be the number of turbines in a row, and the collision probability within the entire planned site is given by $1 - (1 - P_3P_4)^{Tc}$. The estimated collision rate without avoidance behavior, denoted by C_n, was given by:

$$C_n = P_1 P_2 [1 - (1 - P_3 P_4)^{T_c}]. \quad (5)$$

To evaluate avoidance probability with avoidance behavior for the planned site as well as individual turbines, the method of Desholm and Kahlert (2005) was applied. They evaluated the Nysted Offshore Wind Farm in Denmark, which comprises 72 turbines in nine rows of eight turbines (T_c^*) each. The distance between the rows (D_r) is 480 m, and the distance between turbines within a row (D_c) is 850 m. The avoidance probability in front of the wind farm was given by:

$$A_f = 1 - (P_o / P_p), \quad (6)$$

where P_p is the probability that a flock would enter the planned site during the pre-construction period, and P_o is the probability that a flock would enter the planned site during operation. Let D_f be the distance between a bird flock and the nearest turbine tower, and the probability of a flock flying within D_f of at least one turbine is given by:

$$P_c = 1 - [1 - (1 - A_t)(2D_f / D_r)]^{T_c^*} , \qquad (7)$$

where A_t is the probability of a flock not flying within D_f of a turbine tower, i.e., the avoidance probability per turbine. Hence, A_t is given by:

$$A_t = 1 - [1 - (1 - P_c)^{1/T_c^*}](D_r / 2D_f) . \qquad (8)$$

Substituting P_1 and P_3 in Eq. (5) by $(1 - A_f)P_1$ and $(1 - A_t)P_3$, respectively, the collision rate with avoidance behavior, denoted by C_a, is given by:

$$C_a = (1 - A_f)P_1P_2\{1 - [1 - (1 - A_t)P_3P_4]^{T_c}\} . \qquad (9)$$

The per capita collision probability in a wintering season without and with avoidance behavior, denoted by P_n and P_a, is given by:

$$P_n = 1 - (1 - C_n)^{T_p} \text{ and } P_a = 1 - (1 - C_a)^{T_p} , \qquad (10)$$

where T_p is the number of passages per year (~360). If geese do not form a flock when they pass through the wind farm, an individual could still collide with a turbine. Therefore, It was assumed that x (= $N_\bullet$) is a number of bird collisions in a given year, obtained by the following binomial probability distribution:

$$\Pr[N_\bullet = x] = \binom{N_\bullet}{x} P_\bullet^{x} (1 - P_\bullet)^{N_\bullet - x} , \qquad (11)$$

where $N_\bullet$ is N_n or N_a, and $P_\bullet$ is P_n or P_a if avoidance behavior is ignored or incorporated, respectively.

4) Allowable Collision Mortality

It is necessary to evaluate the potential impact of a wind farm on population viability (e.g., collision risk and habitat loss) and to assess environmental risk. Shimada and Matsuda (2008) used PBR analysis as an indicator of the impact of a wind farm on a bird population. PBR is defined as:

$$PBR = N_{\min} \frac{1}{2} R_{\max} F_r \, , \qquad (12)$$

where N_{min} is the minimum population estimate, R_{max} is the maximum net productivity level, and F_r is a recovery factor of 0.1, 0.5, or 1 for endangered, vulnerable, or common species, respectively (Wade 1998). The assumption of the ACM theory includes all types of human-induced mortality. We assumed that human-induced mortality refers only to collision mortality because we are not aware of any other major factors affecting the survival this species. The validity of this value is discussed later.

RESULTS

1) Parameter Estimation

The observation was conducted for 52 mornings and 51 evenings in total. Flocks flew over the planned site only twice per day, and the average flock size flying over the planned site was approximately 200 birds. These data indicate that the main pathway of White-fronted Geese is via Lake Kitakatako rather than through the planned site. The observed frequencies of passages within heights of <30 m, 30–110 m and >110 m were 8, 105, and 20, respectively. The mean height and its standard deviation of the best-fit model for these frequencies were 78.0 and 38.9 m, respectively. The predicted frequency of passages within a height of 35–115m was 80.2%.

A collision model was developed with four phases and two avoidance behaviors to predict the annual collision mortality of geese at the proposed Awara Wind Farm. P_1, P_2, P_3, and P_4 were estimated at 0.11%, 80.2%, 13.4%, and 9.4%, respectively. The frequency of White-fronted Geese flying over the planned site was surveyed in the 2005/06 and 2006/07 winter seasons.

Desholm and Kahlert (2005) suggested that the types of avoidance behaviors had a large effect on the collision rate and estimated A_f and A_t to be 88.9% and 92.2%, respectively.

2) Estimated collision mortality and ACM

The collision risk when assuming avoidance behavior was sufficiently low but still positive (see Table 2). The probability of no collision occurring in a year was 54.4 % (= $(1 – P_a)^N$), and the expected number of collisions was 0–2 at the 95% confidence level. When avoidance behavior was ignored, the expected number of collisions was 52–84.

PBR based on N_{min}, R_{max}, and F_r was applied to obtain the ACM. N and R_{max} were estimated to equal 3507 and 0.092, respectively, by regression analyses using data for the growth of the goose population at Lake Katanokamoike (Fig. 2). N_{min} is usually given by the 20th percentile of a log-normal distribution based on N; therefore, the N_{min} used in this study was

3266. The value of F_r was 0.5 because White-fronted Geese are designated as a vulnerable species in Fukui Prefecture and a Natural Monument species in Japan. The PBR at Lake Katanokamoike was estimated at 75.4 using Eq. (12). This implies that collision events are allowable until mortality reaches 75.4 geese per year. The estimated collision mortality would be low and would not likely have a significant impact on the population of White-fronted Geese if the geese indeed avoided the wind farm as assumed.

DISCUSSION

Turbine collision and the potential disturbance of daily migration were of great concern for this geese population because a proposed wind farm was planned for an area between a major roosting and a major foraging area. In addition, the roosting area at Lake Katanokamoike is protected under the Ramsar Convention. The collision model developed here will be useful to estimate the avian collision risk at future wind farms. The frequency of passage, flight behavior, weather, and topography around the wind farm as well as the seasons must be considered because collision mortality does not simply increase with abundance (Lucas et al. 2008). With regard to flight behavior, our collision model assumed two types of avoidance behaviors: avoidance of the wind farm in general and avoidance of individual wind turbines after birds entered the farm. Desholm and Kahlert (2005) considered avoidance behavior using survey data of geese and ducks for a wind farm in a migration route. Raptors, for example, such as Burrowing Owls *Athene cunicularia hypugaea* flew close to operating turbine blades and perched on the turbine (Smallwood et al. 2007). Conversely, geese tended not to enter the wind farm between turbines arranged in a cluster (Larsen & Madsen 2000), and the percentage of flocks entering the wind farm decreased significantly from pre-construction to initial operation (Desholm & Kahlert 2005). Overall, the avoidance probability of raptors in their habitat is notably lower than that of geese along migration routes. When developing a collision model for raptors, it might be better to evaluate the time spent in the neighborhood of wind farms rather than the frequency of passage.

The estimated collision risk considering avoidance behavior, based on unverified assumptions and limited data, was 0–2 individuals per year (95% CI of N_a in Table 2). One assumption of the model is that flocks fly through all sections of the wind turbines ($T_c = 5$) even though they might actually only cross a corner or a portion of the wind farm. In addition, the model assumed that birds would fly head on into rotor disks and that the turbines would be in constant operation. These are major factors that could lead to overestimation of collision mortality.

If 10 turbines were placed in one straight row, N_a and N_n would be 0.61 and 67.8, respectively, and the predicted collision mortality would not change significantly with the conformation of turbines. Desholm and Kahlert (2005) did not consider the vertical reach of turbine blades or that birds may fly below or above a turbine’s reach. These assumptions may also result in overestimation of the calculated collision risk. On the other hand, the collision risk would increase under poor visibility (Desholm & Kahlert 2005) or strong wind (Barrios &

Rodríguez 2004; Smallwood et al. 2009). However, it was observed that White-fronted Geese often did not visit Sakai Plain in such adverse weather conditions. Finally, except during bad weather conditions, avoidance behavior might reduce the collision risk, as birds may avoid flying through bad weather conditions during seasonal migration (Newton 2007).

The calculated PBR may not represent a low enough agreeable threshold of collision risk among stakeholders. For example, the former mayor of Kaga City argued that only a collision risk of zero would be acceptable. This suggests that the purpose of calculating the collision risk is not simply to maintain the local population. Given that White-fronted Geese are listed as Near Threatened in Japan as well as Least Concerned in the IUCN Redlist and that the population has been undergoing rapid recovery (Fig. 2), the recovery factor F_r was set to 1, producing a PBR of 150.9, which is larger than the PBR when $F_r = 0.5$. However, even if this species were considered endangered, i.e., $F_r = 0.1$, the PBR would be only 15 individuals per year. PBR should include all human-induced mortality. However, the rates of other causes of mortality, such as collision with electric cables, buildings, and cars, are not known. If the effect of avoidance behavior is assumed as described above, the expected collision mortality caused by the wind farm is much smaller than the PBR. Therefore, the expected collision mortality is not a primary factor in population extinction risk.

The goal of developing a collision risk model is not only to estimate mortality level, but also to evaluate the impacts on the population and help to devise a management strategy for the wind farm. PBR was developed to identify populations subject to human-caused mortality that could lead to depletion (Wade 1998). PBR has been used to guide management practices of marine mammals and is designed to take into account the uncertainty of available information and provide an appropriately conservative estimate (Wade 1998). Although the immigration for R_{max} at Lake Katanokamoike was ignored, the growth rate of the White-fronted Goose in Japan (R_{max} = 0.11: S. Moriguchi, unpublished) shows the same tendency as the value in this study.

It is necessary for stakeholders to come to a consensus on the wind farm construction and management plan. If the actual collision mortality exceeds the socially acceptable level, or if White-fronted Geese change their habitat from Lake Katanokamoike, the collision risk should be reduced by controlling the operation rate of the wind turbines. Three ways to reduce collision risk include shutting down wind turbines 1) when a large flock flies over the wind farm, 2) when any flocks fly over the wind farm in the morning or evening, or 3) every morning and evening during the wintering season.

Because birds flock and pass over Lake Kitakatako at predictable times within 30–90 min of sunrise and sunset, the above conservation measures are feasible and should not lead to substantial loss in power generation or profit. Specifically, the cost of shutting down 10 turbines for 30 minutes each day throughout the half year is 7.2 million yen under the following conditions: the price of electrical power is 10 yen/kWh, the maximum output power is 2,000 kW/turbine, and the operation rate is 20%. In addition, an effective management strategy should consider adjusting the operation rate with respect to actual mortality obtained by successive monitoring (Shimada & Matsuda 2008). Because the Awara Wind Farm is planned for an open landscape, it would be relatively easy to locate bird carcasses to determine the actual number of avian collisions in the future.

Conservation measures such as temporary shutdowns may increase business risk and discourage the future development of wind power plants. Shimada and Matsuda (2008) provided an adaptive risk management assessment that takes operation control and conservation measures into account. Matsuda et al. (1999) described the importance of falsifiability when building a management strategy. Follow-up monitoring is essential for accurate future estimations. It is important that the wind power project adopt further conservation measures as discussed above if the actual risk exceeds the socially acceptable level.

Climate change could lead to major declines in populations of long-distance migratory birds as a result of a temporal mismatching between the seasonal activities of avian predators and their prey (Both et al. 2006). Thus, there is a risk trade-off in wind power generation between avian collisions and greenhouse gas emissions. This study emphasizes the importance of risk evaluations for the adaptive management procedures of wind power projects.

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http://www.wbsj.org/nature/hogo/others/fuuryoku/shiryo100927_09.pdf (in Japanese). (Accessed 14 Oct 2010).

Fig. 1. Map of the study area and the planned Awara Wind Farm showing the positions of 10 turbines.

Fig. 2. The population size of White-fronted Geese at Lake Katanokamoike in wintering season. The solid line represents the exponential regression curve ($R^2 = 0.88$, $n = 21$) from observation data denoted by circles. The dotted lines indicate 95% confidence interval. Data source: "Annual Report of Kaga City Kamoike Observation Center" by Wild Bird Society of Japan (1999; 2000; 2001; 2002; 2003; 2004; 2005; 2006).

Fig. 3. Position and angle of three video cameras (a–c and A–C before and after 12 December 2007, respectively), observation points by two or three expert bird watchers (Sts 1, 3–6), and the observation schedule in January, March, November, and December 2006 and February 2007. All points were used in the preliminary research. The table shows the adopted observation points for geese during each month of investigations.

Fig. 4. Flow chart consisting of the four phases of the collision model of flight probability without avoidance behavior (i.e., P_1, P_2, P_3 and P_4) and with two types of avoidance probability denoted by the avoidance probability in front of the wind farm and per turbine in the wind farm (A_f and A_t respectively). The model considers the repetition for after birds pass by one turbine, and T_c shows the total number of turbines in each row.

Table 1. List of symbols and values used in the collision model for the planned wind farm.

Symbol	Meaning and where used	Value
B_c	Cross-section area of the planned site with a height of 80 m and a width of 1,000 m	80000 m^2
B_s	Area swept by a rotor diameter of 82.6 m[a]	5359 m^2
F	Number of flocks that fly over the planned site and Lake Kitakatako	133[b]
S_i	Number of observations that birds fly over the planned site	See Table 2
F_v	Estimated flight frequencies at 35–115-m height	106.7
N	Estimated population size at Lake Katanokamoike	3507
N_{min}	The 20th percentile of a log-normal distribution based on the population size at Lake Katanokamoike	3266
N_i	Average number of birds that fly over the planned site	See Table 2
P_1	Probability of passing through the planned site	See Eq. (1)
P_2	Probability of passing within a height of 35–115 m	See Eq. (2)
P_3	Probability of passing within the area of the rotor disk	See Eq. (3)
P_4	Probability of colliding with blades while passing through a rotor disk	9.4% by Eq. (4)
S	Number of observations	See Table 2
T_c	Number of turbines in each row	5
T_n	Number of total turbines in the wind farm	10[c]
T_p	Number of passages per individual (in the morning and evening) in a year	360
T_r	Number of turbine rows in the wind farm	2
Parameters for P_4		
f	Flight type (flapping = 1, gliding = 2/π)	1[d]
R	Rotor radius	41.3 m[a]
b	Number of blades	3[a]
c	Maximum chord width	3 m[a]
l	Average body length of 64–78cm[d]	0.71 m
v	Average flight speed of outward (=59.1 km/h) and homeward (=56.2 km/h) journeys to foraging area[e]	16.0 m/s
w	Wing span	1.45 m[d]
γ	Pitch angle of blade	0.021 rad[a]
ω	Rotation speed	2.02 rad/s[a]
Parameters for avoidance behavior		
A_f	Avoidance probability in front of the wind farm	See Eq. (6)
A_t	Avoidance probability per turbine in the wind farm	See Eq. (8)
D_c	Distance between the turbines in a row (m)	850 m[f]
D_f	Distance between a bird flock and the nearest turbine tower (m)	50 m[f]
D_r	Distance between rows (m)	480 m[f]
P_c	Probability of a bird flock flying within D_f of a turbine tower	0.123[f]
P_o	Probability of a flock entering the wind farm during operation	0.045[f]
P_p	Probability of a flock entering the wind farm during pre-construction	0.404[f]
T_c^*	Number of turbines in each row at Nysted Offshore Wind Farm	8[f]

[a] 2 MW Permanent Magnet Synchronous Gearless Wind Turbine Generator by The Japan Steel Works, Ltd.

[b] JPec Co., Ltd. (2006a; 2006b; 2007)

[c] Green Power Awara Co., Ltd. (2009)

[d] Svensson et al. (1999)

[e] Wild Bird Society of Japan (2010)

[f] Desholm and Kahlert (2005)

Table 2. Collision risk estimate of White-fronted Geese on the future Awara Wind Farm with and without avoidance behavior

Symbol	Meaning	Value	
		No avoid	Avoid
S_i	Number of days flying over the planned site	2[a]	2[a]
S	Number of observations	103[a]	103[a]
N_i	Average number of birds that fly over the planned site	200[a]	200[a]
P_1	Probability of passing through the planned site	0.11%	0.01%
C_n, or C_a	Collision rate without or with avoidance behavior	0.0054%	0.000048%
P_n, or P_a	Per capita collision probability in a wintering season without or with avoidance behavior	1.94%	0.017%
N_n, or N_a	Number of bird collisions without or with avoidance behavior in a given year	68.0	0.61
95% CI of $N_\bullet$	95% confidence interval of N_n or N_a	52–84	0–2

$N_\bullet$ is N_n or N_a. P_1, C_n, and C_a, are obtained by Eqs. (1), (5), and (9). P_n and P_a are obtained by Eq. (10). N_n and N_a, and its 95% confidence interval are obtained by Eq. (11).

[a] JPec Co., Ltd. (2006a; 2006b; 2007)

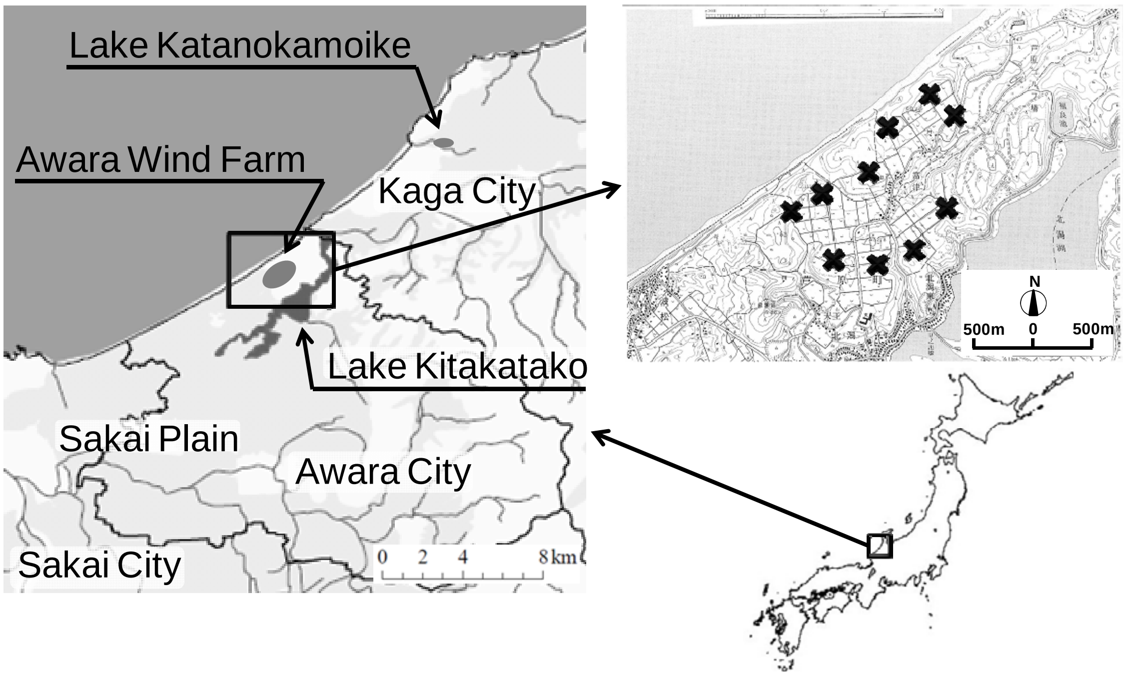

Lake Katanokamoike
Awara Wind Farm
Kaga City
Lake Kitakatako
Sakai Plain
Awara City
Sakai City
0 2 4 8km
N
500m 0 500m

Fig. 1

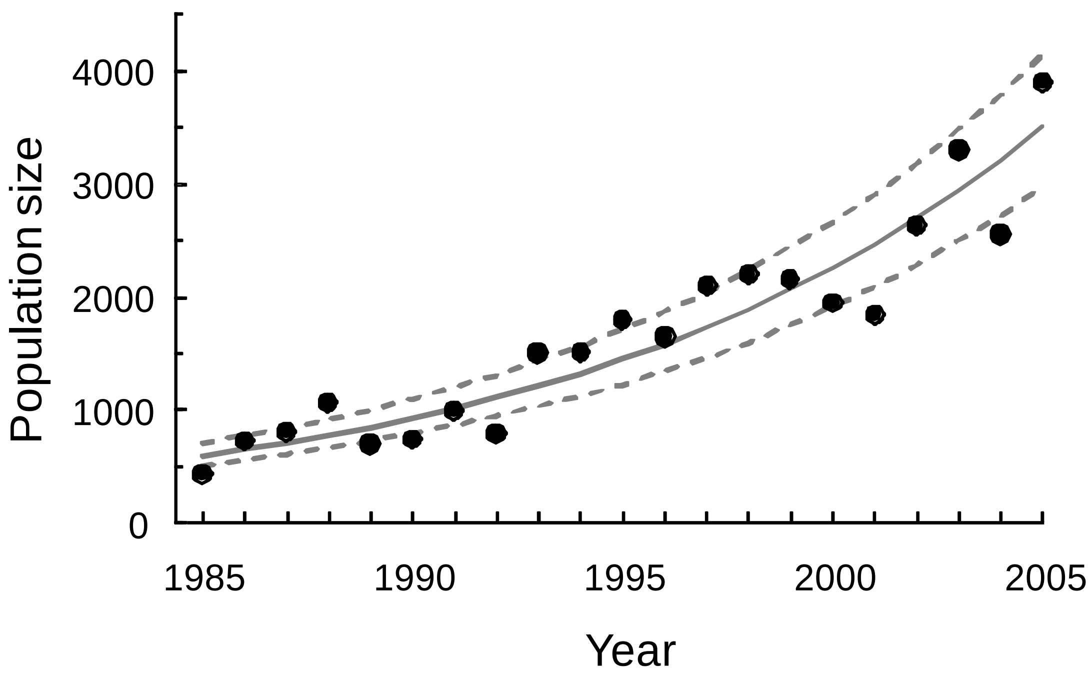
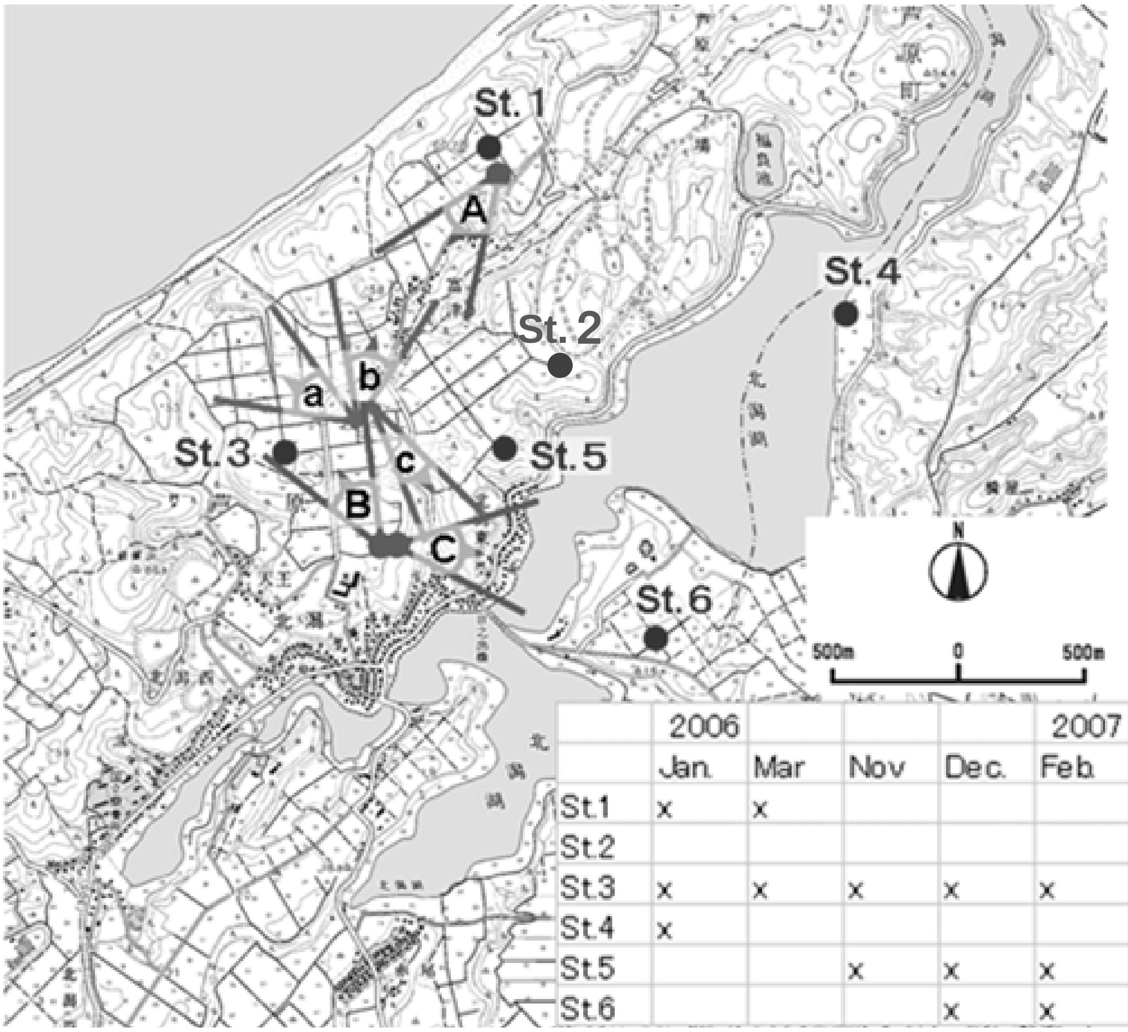
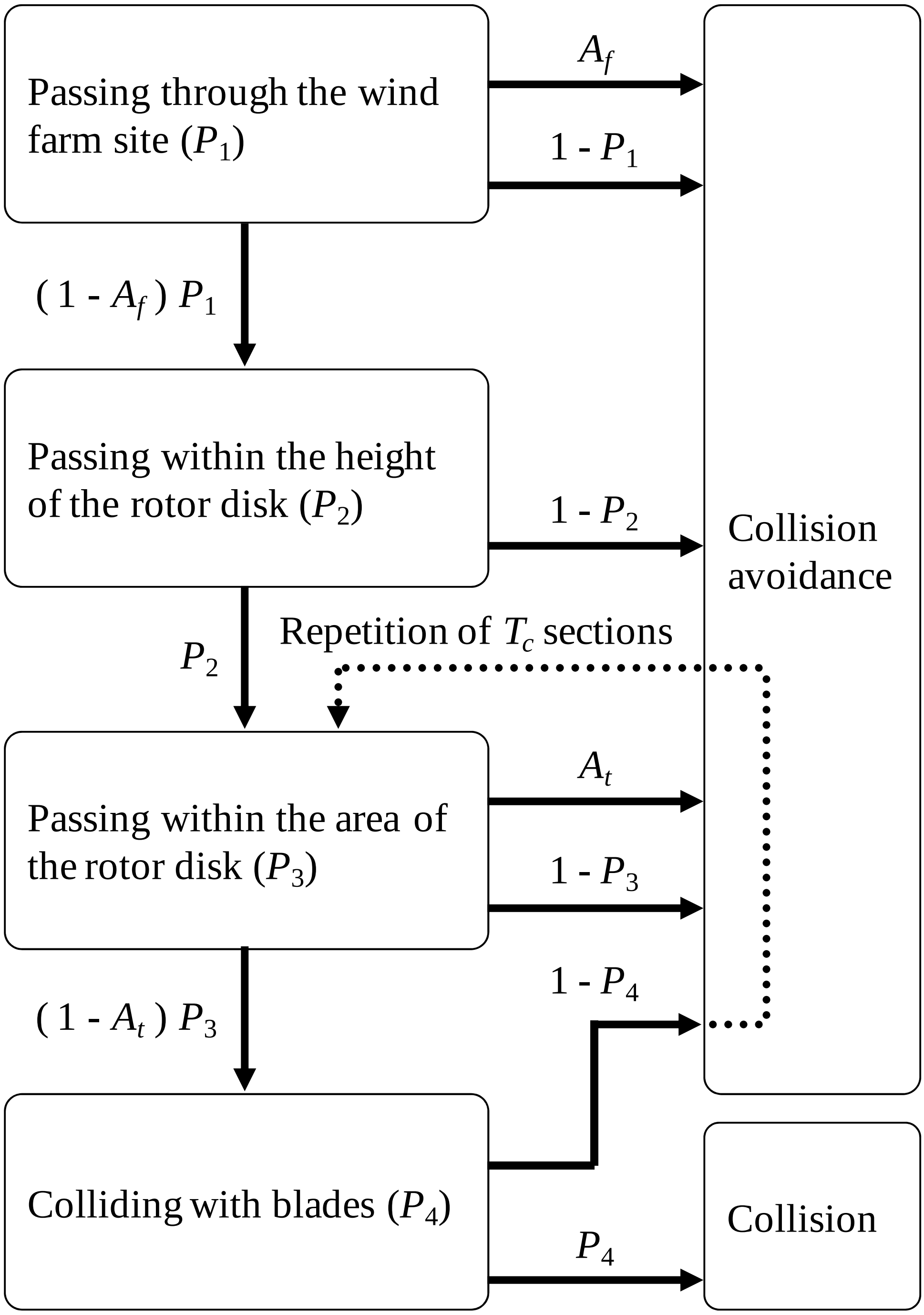

Population size
0
1000
2000
3000
4000
1985
1990
1995
2000
2005
Year

Fig. 2



	2006				2007
	Jan.	Mar	Nov	Dec.	Feb.
St.1	x	x			
St.2					
St.3	x	x	x	x	x
St.4	x				
St.5			x	x	x
St.6				x	x

Fig. 3



Passing through the wind farm site (P_1)
A_f
1 - P_1
(1 - A_f) P_1
Passing within the height of the rotor disk (P_2)
1 - P_2
Collision avoidance
P_2
Repetition of T_c sections
Passing within the area of the rotor disk (P_3)
A_t
1 - P_3
1 - P_4
(1 - A_t) P_3
Colliding with blades (P_4)
P_4
Collision

Fig. 4