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Assessing areas suitable for offshore wind energy considering potential risk to breeding seabirds in northern Japan

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ABSTRACT

Offshore wind energy is expected to play a major role in realizing carbon neutrality. However, the installation of offshore wind turbines is of concern for breeding seabirds. Identifying areas with low potential risk for breeding seabirds in Japan is urgently needed. This study identified technically and legally potential areas for wind energy development that are suitable for breeding seabirds by integrating risk assessment models through a spatial approach using Geographic Information System (GIS). While many studies and the government have assessed the potential areas for offshore wind energy in northern Japan, this study shows that most of these legally potential areas overlap with major concern areas for breeding seabirds. Currently, Japanese rules do not sufficiently consider the risk to seabirds when zoning areas for installing offshore wind energy system. The results imply that the risk to breeding seabirds should be carefully examined when zoning areas for local offshore wind energy installations. The approach developed in this study is expected to aid in clearly identifying areas suitable for the installation of offshore wind turbines and minimize the impacts on breeding seabirds. It provides a balance between the expansion of offshore wind energy and conservation biology.

1. Introduction

The reduction of greenhouse gas emissions is a global objective. In 2020, the Japanese government declared its objective to reduce greenhouse gas emissions to the net-zero level by 2050 [1]. To date, the Japanese Ministry of Economy, Trade, and Industry has continued to renew the medium- and long-term energy policy of Japan, known as the “Strategic Energy Plan”, which states that photovoltaic and wind energy systems will be expanded to become the “main sources of power supply” of the nation [2]. As Japan is an island country, offshore wind energy is expected to play a major role in achieving this objective. By 2019, Japan had installed an offshore wind energy system of 4.39 MW capacity [3]. For further development of offshore wind energy projects, the Japanese government enacted “the Act of promoting utilization of sea areas in development of power generation facilities using maritime renewable energy resources” (the Act) in April 2019. The Act establishes frameworks for coordination with stakeholders and allows the design of “promoting zones” within territorial waters to enable the long-term use of offshore renewable energy facilities. To determine the promoting zones, the Act prescribes several requirements, including natural conditions and impact on shipping routes [4].

Offshore wind turbines are of two types: fixed-bottom and floating wind turbines [5]. A fixed-bottom turbine is connected to the seabed and is usually economical at water depths of less than 50–60 m. The floating turbine is on a floating foundation attached to the seabed by mooring lines to hold the assembly in position. Although fixed-bottom turbines are mainly installed worldwide, floating turbines are also planned to be installed in Japan, wherein the water depth increases markedly with the distance from the shore. While Japan is in the first stage of development of offshore wind energy, several studies on high-density offshore wind energy systems have indicated their adverse impacts on the regional ecosystems. Therefore, the construction of offshore wind turbines raises concerns related to environmental sustainability. Farr et al. [6] performed a systematic literature review to evaluate six categories of potential effects of deep water-based wind turbines on the environment such as changes to atmospheric and oceanic dynamics due to energy removal and modifications, electromagnetic field effects on marine species from power cables, habitat alterations to benthic and pelagic fish

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and invertebrate communities, underwater noise effects on marine species, structural impediments to wildlife, and changes to water quality. These potential effects could be of concern to Japan as well as the water depth is high.

Recently, the breeding populations of seabirds have rapidly decreased in Japan [7]. The construction of offshore wind farms may pose potential risks such as collision with wind turbines, loss or deterioration of feeding grounds, and changes in their distribution and behavior due to alterations in the quality of their feeding grounds [8]. However, only a few of these risks have been assessed so far. Therefore, it is necessary to perform a comprehensive assessment of the impacts of the construction of offshore wind farms on seabirds to determine suitable areas with a low impact. A sensitivity map is effective in identifying areas in which seabirds are likely to be significantly affected by the construction of offshore wind energy farms. For example, Garthe and Hüppop [9] created a sensitivity map for 26 species of seabirds in the Exclusive Economic Zone (EEZ) of Germany. Bradbury et al. [10] created a sensitivity map for 54 species in parts of the EEZ of UK and Scottish waters with a grid mesh resolution of several and a dozen kilometers, respectively. Kelsey et al. [11] assessed the density of population collision and displacement vulnerability to offshore wind energy systems on seabirds of the Pacific Outer Continental Shelf in the United States. While these approaches are effective for identifying suitable areas with a low potential risk to seabirds, these studies do not consider other restrictions such as technical or legal considerations. In addition to these studies, Goodale et al. [12] assessed the cumulative adverse effects on seabird foraging guilds in the potential development areas of offshore wind energy systems along the East Coast of the United States. Although several impact assessment models for seabirds have been suggested, these have uncertain factors, such as the determination of risk parameters [13]. Hence, it is important to compare the results from several models when a sensitivity map is used to delineate promoting zones for the installation of offshore wind systems.

Conversely, several studies have assessed the suitability of an area or energy potential of the offshore wind energy system considering technical or social restrictions worldwide [14–19]. In Japan, the Ministry of Environment (MOE) [20], the International Energy Agency (IEA) [21], Yamaguchi et al. [22], and Obane et al. [23] assessed suitability of sites for offshore wind energy systems considering technical and social constraints. However, these studies did not consider the potential risk to seabirds posed by the development of offshore wind turbines. Furthermore, current requirements in the Act for determining the promoting zones that allow the installation of offshore wind turbines do not consider the risk to breeding seabirds. Japan has many seabird breeding colonies around the coastline [24]. Based on conditions experienced in other countries, where offshore wind turbines have been installed, it is necessary to evaluate the potential risk to breeding seabirds and determine the promoting zones in areas with a low potential risk in Japan.

This study assessed preliminary areas suitable for offshore wind energy development with a low potential risk to breeding seabirds. This study integrates the conventional risk assessment model used for sensitivity mapping with a spatial approach to identify potential areas for offshore wind energy development using a Geographic Information System (GIS) approach. This approach is expected to reduce the possibility of reworking environmental impact assessments to efficiently demarcate areas suitable for offshore wind energy systems. In Japan, after the designation of promotion zones based on government considerations, a developer is selected based on several assessment points, including cost and feasibility. The selected developer must conduct an Environmental Impact Assessment (EIA) separately apart from the government evaluation. Approaches to the assessment and mitigation of the impact of seabirds may differ according to the planning or construction steps of offshore wind energy systems [25]. This study focuses on the assessment of the first site selection step by the government, which does not necessarily require a detailed and precise assessment. Nevertheless, this study compares the results of two risk assessment models for seabirds. This study selected Hokkaido in Japan as a case study area, as it has many potential areas for the development of offshore wind turbines that satisfy the requirements of the Act [23] along with many seabird colonies. During the breeding season, parents of seabirds take a central position as foragers, commuting daily between breeding colonies and foraging sites to provide food for their offspring. Breeding seabirds potentially can interact with a wind farm and face frequent collision and displacement risks. Therefore, this study focused only on the assessment of breeding seabirds during the breeding season, which can be estimated using data available for Japan.

2. Methodology

2.1. Overview of the assessment model

This study integrated risk assessment models for breeding seabirds through spatial analysis to identify legally potential areas for offshore wind energy development using a GIS approach. First, the risk to breeding seabirds was quantified in each of the 500-m grid meshes near Hokkaido using a publicly available database on breeding colonies of seabirds. Two types of risk assessment models were used, and the results from them were compared. Second, legally potential areas were identified for developing offshore wind energy systems considering zoning rules. Finally, this study showed the level of risk to breeding seabirds within potential areas for developing offshore wind energy systems.

2.2. Risk assessment model for seabirds

This study quantified the risk to breeding seabirds in each of the 500-m grid meshes using the wind farm sensitivity index (WSI) because the data source for GIS analysis, such as bathymetry or wind speeds, is available as 500-m grid mesh data. WSI represents the risk to seabirds by building offshore wind farms and comprises population density of seabirds and species-specific sensitivity indices (SSI). Fig. 1. shows the overview of the risk assessment model. The WSI models developed by Garthe and Hüppop [9] and Bradbury et al. [10] were referred to among several similar models instead of the model developed by Kelsey [11] that requires regionally specific demographic or breeding parameters, which are unavailable for Japan, to calculate population vulnerability. While Goodale et al. [12] assessed the vulnerability of seven guilds from a total of 36 species, this study assessed the WSI for each breeding species because the number of target species was only 13. Although the basic idea is similar in both models, a small difference exists in the quantification of risk to seabirds. To date, the relative merits of these models have not been adequately studied. Hence, this study compared the results from both the models in Eq. (1) and (2) and analyzed their differences.

$$WSI_{Garthe} = \sum_{species} \ln(density_{species} + 1) \times SSI_{Garthe'\ species} \tag{1}$$

$$WSI_{Bradbury} = \sum_{species} \ln(density_{species} + 1) \times SSI_{Bradbury'\ species} \tag{2}$$

In European countries, population density data of seabirds at sea are available at the European Seabirds in the Sea Database [26]–[28]. These data were assessed based on counts from boats or planes over 10 to 30 years. However, such data are not available for Japan. Soanes et al. [29] suggested that the concentric maximum foraging area from the breeding colony is suitable for the prediction of the potential density of breeding seabirds at sea, when actual data are not available. Hence, this study estimated the density of breeding seabirds at sea using the maximum foraging area and location data from public databases, including location and population size of the breeding colony for each seabird species [24]. This approach was only used the summer breeding season. Furthermore, contrary to earlier studies based on empirical data of seabird distribution, our theoretical approach does not consider the temporal variations in colony size or foraging radiuses and does not

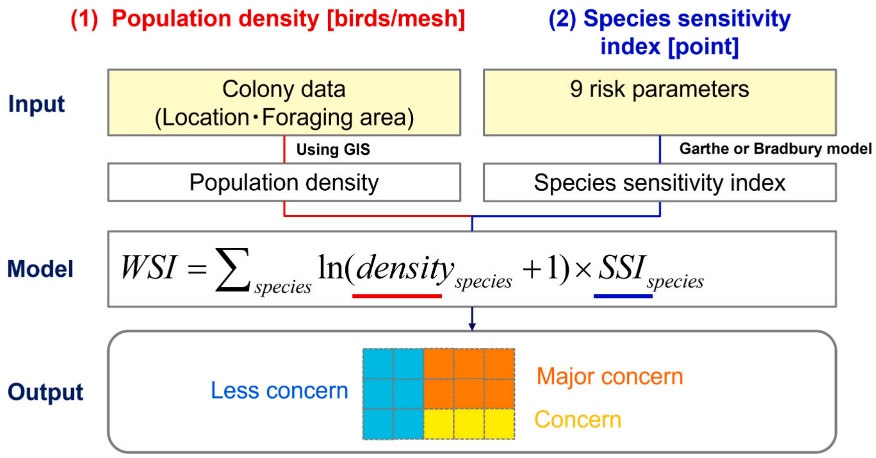


Fig. 1. Flow chart illustrating the risk assessment model for seabirds.

distinguish between foraging (stationary) and commuting movements of individual seabirds. Density of breeding seabirds at sea is obtained according to Eq. (3), where individual seabirds are expected to distribute equally within the maximum foraging range, independent of the distance from the colony.

$$density_{species} = \sum_i \frac{n_i}{(\pi r_i^2 - S_i)} \tag{3}$$

where.

n: number of nests in *i* of colony.

r: maximum foraging radius in *i* of colony.

S: land area in maximum foraging area in *i* of colony.

SSI, which is a part of WSI, is originally determined for each species of seabird using nine risk parameters as follows: *a*: flight altitude; *a'*: percentage of seabirds flying at blade height; *m*: flight maneuverability; *t*: percentage of time flying; *n*: nocturnal flight activity; *d*: disturbance by ship and helicopter traffic; *h*: flexibility in habitat use; *p*: biogeographical population size; *s*: adult survival rate; *c*: conservation status, concerning the risks of collision, displacement, and conservation level (Table 1). In the model developed by Garthe and Hüppop [9], each risk factor is crossed as shown in Eq. (4):

$$SSI_{Garthe} = \frac{(a+m+t+n)}{4} \times \frac{(d+h)}{2} \times \frac{(p+s+c)}{3} \tag{4}$$

However, the original Garthe and Hüppop model did not consider the avoidance rate suggested by the Kelsey model. According to several studies, the avoidance rate is identified as the most important consideration for collisions when assessing the vulnerability to seabirds [8,11,30,31]. Hence, this study revised the model to adopt the macro avoidance rate of collision (MA_c), percent time spent in the rotor-swept zone (*RSZ*), macro avoidance rate of displacement (MA_d) instead of flight altitude, flight maneuverability, percentage of time flying as shown in Eq. (5). The macro avoidance rate in this study is the rate at which birds avoid a windfarm outside its perimeter, defined as a 500 m buffer surrounding the outermost turbines according to Cook et al. [32]. This is the difference between the collision rates and the expected number of collisions given no avoidance behavior occurs for all individuals of a species. This study did not consider meso- and micro-avoidance, as well as the Kelsey model, because data on these parameters were insufficient.

$$SSI_{Garthe'} = \frac{(MA_c+RSZ+n)}{3} \times \frac{(MA_d+h)}{2} \times \frac{(p+s+c)}{3} \tag{5}$$

Contrarily, in the original model developed by Bradbury et al. [10], after independently calculating collision risk and displacement, the larger SSI is selected as shown in Eqs. (6)–(8):

$$SSI_{Bradbury} = \max(collision, displacement) \tag{6}$$

Table 1
Risk parameters in SSI.

	Parameter		Note
Collision risk	Flight altitude	*a*	Flight properties with regard to the potential to avoid collision with wind farms at sea. (Not used in the study)
	Flight altitude	*a'*	Percentage of seabirds flying at blade height. (Not used in the study)
	Flight maneuverability	*m*	The factor based on flight altitude assessments for regular seabirds at sea surveys. (Not used in the study)
	Percentage of time flying	*t*	Percentage of time flying obtained from seabirds at sea counts. (Not used in the study)
	Nocturnal flight activity	*n*	Score would be high for seabird acting at night.
	Macro avoidance	MA_c	Macro avoidance of collision risk.
	Rotor-swept zone	*RSZ*	Percent time spent in rotor-swept zone of a wind turbine.
Displacement risk	Disturbance by ship and helicopter traffic	*d*	Score would be high for seabird vulnerable by ship and helicopter traffic, because these seabirds are considered to be vulnerable to wind farms.
	Flexibility in habitat use	*h*	Habitats at sea defined by hydrographic characteristics.
	Macro avoidance	MA_d	Macro avoidance of displacement risk.
Conservation level	Biogeographical population size	*p*	Scored according to the respective biogeographical population size of each species.
	Adult survival rate	*s*	Score would be high for seabird with higher survival rate.
	Conservation status	*c*	Reflected both threat and conservation status of the species in Japan.

$$collision = a' \times \frac{(m+t+n)}{3} \times (p+s+c) \tag{7}$$

$$displacement = \frac{(d \times h) \times (p+s+c)}{10} \tag{8}$$

The model developed by Bradbury was also adapted to adopt the macro avoidance rate as shown in Eqs. (9)–(11):

$$SSI_{Bradbury'} = \max(collision', displacement') \tag{9}$$

$$collision' = \frac{(MA_c + RSZ + n)}{3} \times (p + s + c) \tag{10}$$

$$displacement' = \frac{(MA_d \times h) \times (p + s + c)}{10} \tag{11}$$

2.3. *Identifying potential areas for the development of offshore wind energy systems*

To identify legally potential areas for developing offshore wind energy systems, it is necessary to consider local zoning rules. In Japan, offshore wind farms are expected to be installed in the promoting zone based on the Act. To determine the promoting zone, the Act specifies the following six requirements: (i) natural condition; (ii) avoiding hindrance to shipping route and harbor use; (iii) integral use with harbor; (iv) power system interconnection; (v) avoiding hindrance to fishery; and (vi) avoiding fishing port, harbor, coastal conservation area, low-water line preservation area. Given these requirements, this study excluded the non-conforming area according to the Act by referring to the study by Obane et al. [23] (Table 2).

These legal constraints based on the Act are almost the same as those in Goodale et al. [12] except that this study covers the areas within Japanese territorial water (distance from shore is less than 22.2 km), while Goodale et al. included areas covered by the distance from the shore of 5.6–92.6 km.

This study defined the excluded areas as potential areas for offshore wind energy development in Hokkaido. Using GIS, the study area was divided into a mesh separated by 15 arc-seconds for latitude and 22.5 arc-seconds for longitude. The length of each side of the mesh was approximately 500 m, and the area of each mesh was approximately 0.025 km^2. The following seven parameters were considered based on risk assessment models for each mesh: (i) annual average wind speed; (ii) water depth; (iii) shipping density; (iv) distance from shore; (v) legal area; (vi) WSI; and (VII) population density of each seabird species. Table 3 summarizes data used for the GIS analysis.

3. Assumptions

3.1. *Studied area and species*

The Act allows to determine promoting zones for offshore wind farms only in Japanese territorial waters. Therefore, this study focused on the sea within 12 nautical miles (22.2 km) from Hokkaido main island (Fig. 2). Hokkaido possesses most of the legally potential areas for offshore wind energy development [23]. The electricity generated from offshore wind energy near Hokkaido will be used in the island or Japanese mainland by connecting to the transmission lines. In addition to possessing most of the legally potential areas, Hokkaido has the greatest number of colonies of seabirds in Japan. Based on information in the

Table 3
Data used for GIS analysis.

Category	Type	Notes	Base data
Water depth	Numerical	Average water depth within mesh.	JODC-Expert Grid data for Geography [33]
Annual average wind speed	Numerical	Annual average wind speed at 100 m height.	Wind map “NeoWins” [34]
Shipping density	Numerical	Total number of the ships with AIS in Jan 2014–Dec 2014 within mesh.	AIS data (latitude/ longitude) supplied by the Japanese Maritime Safety Agency
Distance from shore	Numerical	Minimum distance from the center of each mesh to shore	-
Legal area	Binary	Existence of legal area in mesh (Y or N).	Coastal preservation area [35] Natural park [35] Military maneuvers [36]
$WSI_{\text{Garthe-based}}$	Numerical	WSI by the Garthe-based model	-
$WSI_{\text{Bradbury-based}}$	Numerical	WSI by the Bradbury-based model	-
Population density of each seabird	Numerical	Population density of each seabird estimated using the colony database	Colony database [24]

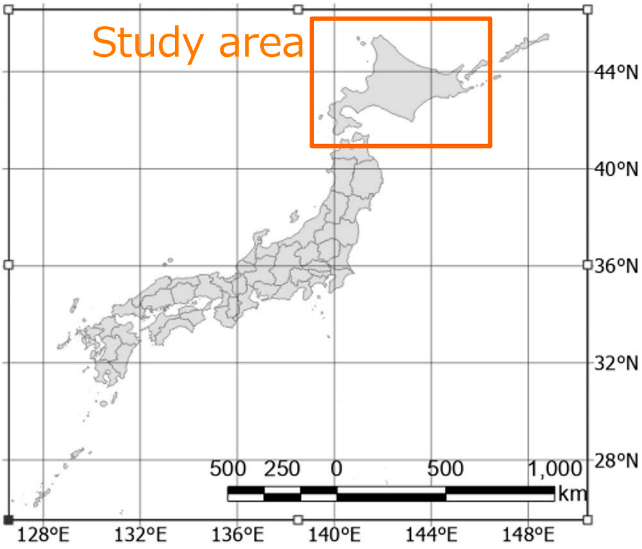


Fig. 2. Map of the study area.

Table 2
Areas excluded in this study.

Excluded area	Requirements in the Act
Annual wind speed is less than 7.0 m/s at 100 m Water depth is above 200 m*[1]	(VIII-1-i) Weather, marine, and natural condition shall be suitable for generation.
Traffic of vessels with automatic identification system (AIS) is above 31 ships/month within the mesh	(VIII-1-ii) Hindrance to shipping route or use of harbor shall be avoided.
-*[2]	(VIII-1-iii) It shall be recognized to integrally utilize both promotion area and harbor.
Area around isolated land from main grid mesh	(VIII-1-iv) It shall be assured to electrically connect to electric grid.
-*[2]	(VIII-1-v) Hindrance to fishery shall be avoided.
Coastal preservation area	(VIII-1-vi) Fishing port*[3], Harbor*[3], Coastal preservation area, and Low-water line conservation area*[4] shall not be included.
Natural parks	(III) Off-shore wind development shall be harmonized with marine environment and security.
Military maneuvers	

[*1] Assuming the installation of floating wind turbines in the future despite the description in the guidelines.

[*2] This study did not establish the excluded area based on the requirements in VIII-1-iii and VIII-1-v due to the difficulty in identifying the specific area to be excluded.

[*3] Fishing ports and harbors were not removed in this study because these areas are under the legal jurisdiction of the Port and Harbor Act and the Fishing Port Act.

Table 4
Studied species.

Family	Species	Scientific name	Conservation status[*]
Auk (*Alcidae*)	Common Murre	*Uria aalge*	Critically endangered (CR)
	Ancient Murrelet	*Synthliboramphus antiquus*	Critically endangered (CR)
	Tufted Puffin	*Fratercula cirrhata*	Critically endangered (CR)
	Spectacled Guillemot	*Cepphus carbo*	Vulnerable (VU)
	Rhinoceros Auklet	*Cerorhinca monocerata*	-
Gull (*Laridae*)	Slaty-backed Gull	*Larus schistisagus*	Near threatened (NT)
	Black-tailed Gull	*Larus crassirostris*	-
Cormorant (*Phalacrocoracidae*)	Japanese Cormorant	*Phalacrocorax capillatus*	-
	Pelagic Cormorant	*Phalacrocorax pelagicus*	Endangered (EN)
	Red-faced Cormorant	*Phalacrocorax urile*	Critically endangered (CR)
	Great Cormorant	*Phalacrocorax carbo*	-
Prion (*Procellariidae*)	Leach's Storm-petrel	*Oceanodroma leucorhoa*	-
	Streaked Shearwater	*Calonectris leucomelas*	-

[*] Status determined by the Japanese Ministry of Environment in September 2023.

colony database [24], this study selected 13 breeding species (Table 4), including the endangered Common Murre (*Uria aalge*), Ancient Murrelet (*Synthliboramphus antiquus*), Tufted Puffin species (*Fratercula cirrhata*), and Red-faced Cormorant (*Phalacrocorax urile*) in Hokkaido for analysis.

3.2. Population density

Colony data from the database were used to estimate population density [24]. The database contains maximum foraging radius, number of nests, peer-reviewed articles, technical reports, and private notes. Using this database, the longitude and latitude of each colony were added by referring to location information such as names of rocks and capes. Because some colony data were redundant, colony information was extracted based on peer-reviewed studies. Furthermore, to ensure reliability, this study did not include data collected prior to 1979 and private notes made by non-researchers. Finally, data from 211 colonies were extracted from the colony database.

This study used a GIS-based approach to estimate population density and ArcGIS Pro 10.6 (ESRI Inc.). Based on colony data, foraging areas in the sea were estimated for each colony by assuming concentric and uniform foraging areas. Population density from each of the 211 colonies was estimated for each 500-m grid mesh by dividing the number of nests by the area of foraging areas.

Fig. 3 shows species-wide foraging area in Hokkaido. While gulls (*Laridae*) and prions (*Procellariidae*) are distributed throughout the area near Hokkaido, auks (*Alcidae*) are distributed in the northern, western, and eastern areas. The foraging area of cormorants (*Phalacrocoracidae*) was smaller than that of the others, and it was distributed in specific areas. Fig. 4 shows the estimated densities of breeding seabirds at sea. In the northern and eastern parts of Hokkaido, the population density was relatively higher than that in other areas.

3.3. SSI

To estimate the SSI, a total of eight risk parameters were used as inputs and were scored from 1 to 5 following the methods described by Garthe- and Bradbury-based models. Estimated scores of studied species or related species were used for estimating the risks of collision and displacement (Table 5). The scores for macro avoidance, *RSZ*, used the same parameters for the same species or related species as in Kelsey et al. [11] and Adams et al. [37]. *RSZ* was assumed to be 20–200 m. Because offshore wind turbines must be installed in Japanese territorial waters, the maximum height of the wind turbines was assumed to be 200 m by considering the seascape. Adult survival rates were based on interviews from experts or experimental data. The score for nocturnal flight activity, disturbance by ship and helicopter traffic, and flexibility in habitat use were based on interviews of experts. The score for biogeographical population size was based on the number of nests in colony data. For conservation status, the score was based on the rank in the red list provided by the Japanese Ministry of Environment on September 2023. Although some studies considered uncertainty in the vulnerability of seabirds [11,31], this study did not consider it because long-term and broad measured density data of seabirds are not available.

Fig. 5 shows the assumed risk parameters for each species. Auks and cormorants have similar characteristics; their biogeographical population sizes, adult survival rates, and conservation statuses are relatively larger than those of other parameters. For gulls, the survival rate and

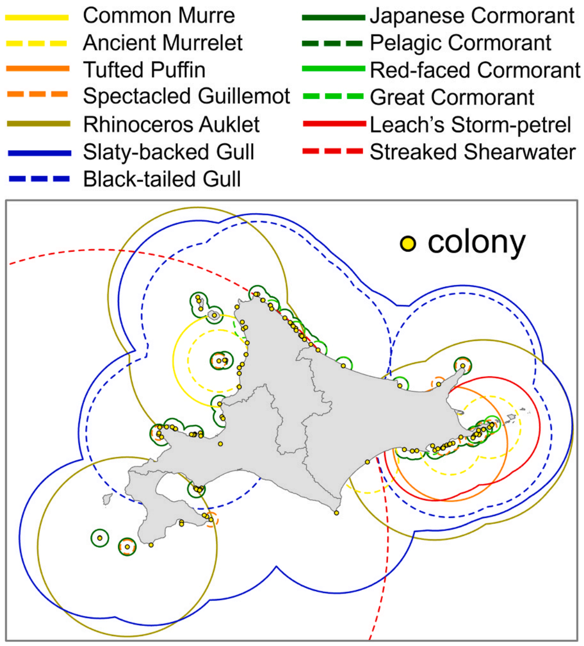


Fig. 3. Spatial image depicting the species-wide foraging areas.

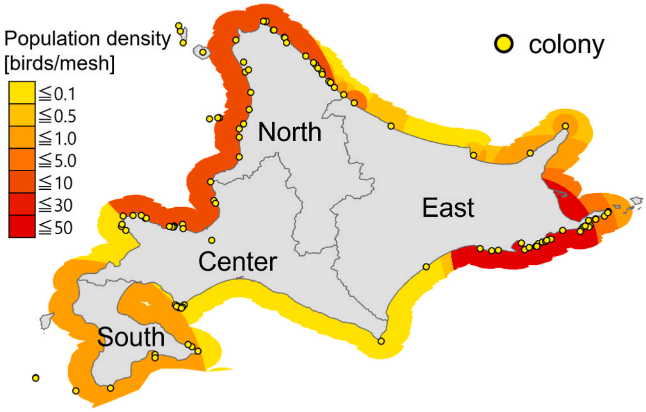


Fig. 4. Layout map showing the estimated population density.

Table 5
Reference of risk parameters in SSI.

	Parameter		Reference	Approach
Collision risk	Macro avoidance of collision risk	MA_c	Assessed score of same species or related species [11,37]	Measurement
	Rotor-swept zone	RSZ	Assessed score of same species or related species [11,37]	Measurement
	Nocturnal flight activity	n	Assessed score of same species or related species [8]	Expert elicitation
Displacement risk	Macro avoidance of displacement risk	MA_d	Assessed score of same species or related species [11,37]	Measurement
	Flexibility in habitat use	h	Assessed score of same species or related species [8]	Expert elicitation
Conservation level	Biogeographical population size	p	Based on the number of nests in Hokkaido [30] (1: 100,000– 2: 10,000–100,000 3: 1000–10,000 4: 100–1000 5: –100	Measurement
	Adult survival rate	s	Based on survival rate of related species [27]. (1: –75%, 2: 75%– 3: 80%– 4: 85%– 5: 90%–)	Measurement
	Conservation status	c	Based on the rank of red list in the Japanese Ministry of Environment in 2021. (1: Near threatened; 2: (Not defined); 3: Vulnerable; 4: Endangered; 5: Critically endangered)	Literature

RSZ were relatively higher. For prions, the adult survival rate and macro avoidance of displacement were relatively higher than those of the other species.

Fig. 6 shows the estimated SSIs according to the model. When the Garthe-based model was used, the rates of SSIs of auks and cormorants with higher conservation levels were higher. By contrast, when the Bradbury-based model was used, the SSIs of gulls and cormorants with higher conservation levels were higher. In both models, the SSIs of prions were relatively lower than those of the other species.

3.4. Technological assumptions on offshore wind turbines

The type of foundation used for offshore wind turbines differs depending on the water depth, and it can generally be classified as either bottom-fixed or floating. In this study, it was assumed that the bottom-fixed wind turbines are installed in areas with water depth < 60 m and the floating wind turbines are installed in water depths of 60–200 m. Floating wind turbines are currently at the demonstration stage in Japan [38,39].

Offshore wind turbines are arranged at intervals to reduce wake loss and maximize plant level profitability. In this study, an installation density of 6.0 MW/km^2 was used, which is based on the actual average installation density achieved in the North Sea [40].

4. Results and discussion

4.1. Level of concern based on WSI

This study assessed the level of concern based on the estimated WSI in the sea near Hokkaido (Fig. 7). A slight difference between the results from the Garthe- and Bradbury-based models were observed. For example, the WSI estimated by the Garthe-based model was higher in the Wakkanai area, the northern part of Hokkaido Island. This is because cormorants and auks with higher SSI of conservation levels according to the Garthe-based model are distributed in these areas. The WSI estimated by the Bradbury-based model was higher in the Nemuro area in the eastern part of Hokkaido Island because gulls with higher SSI of collision risk according to the Bradbury-based model are distributed in these areas. Thus, the results of WSI were different for the two WSI models. Despite this, the major concern area can be observed in the northern and eastern areas. In the north area, nine of the 13 seabird species, including the Great Cormorant (*Phalacrocorax carbo*), Spectacled Guillemot (*Cepphus carbo*), Common Murre, and Japanese Cormorant (*P. capillatus*) with higher SSI of conservation levels are distributed according to the Garthe-based model. Slaty-backed Gulls (*Larus schistisagus*) and Black-tailed Gulls (*L. crassirostris*) with higher SSI of collision risk are distributed according to the Bradbury-based model. In the east area, nine of the 13 seabird species, including the Red-faced Cormorant, Spectacled Guillemot, Tufted Puffin, and Japanese Cormorant with higher SSI of conservation level are distributed according to the Garthe-based model. Slaty-backed and Black-tailed Gulls with higher SSI of collision risk are distributed according to the Bradbury-based model. Furthermore, population density (30–50 birds/mesh) is relatively higher in the northern and eastern areas than in the other areas. Hence, the WSI was larger in these areas irrespective of the model used.

Conversely, almost all of the south falls under the area of lesser concern, and only a few foraging seabirds are observed because of the presence of a few colonies. However, migratory birds may pass through this area. According to a local survey in the area [41], it has been reported that Slaty-backed Gulls, Japanese Cormorants, Ancient Murrelets, Common Gulls (*L. canus*), and Black-legged Kttiwakes (*Rissa tridactyla*) which are not the target species in the study, pass through this area during autumn or winter. Hence, it should be noted that the area of lesser concern does not necessarily mean no risk areas to the seabirds.

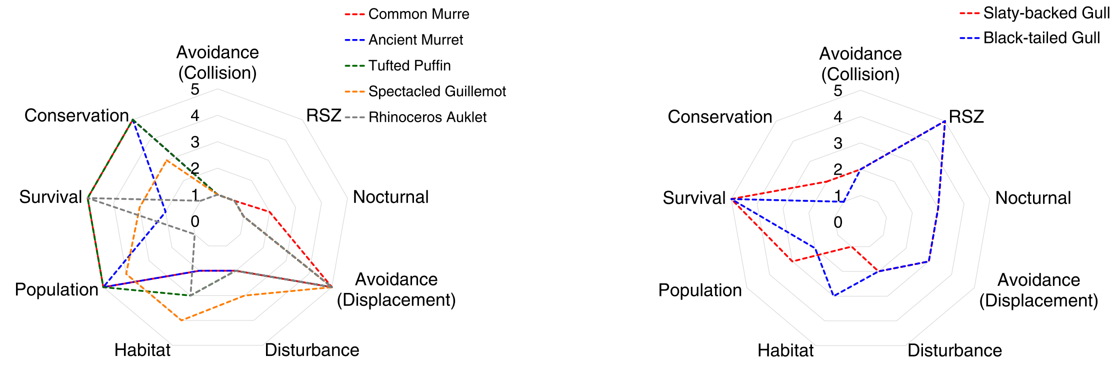
Areas of concern can be observed in some parts of the central and eastern areas, in particular, for either the species whose SSI of conservation level is high or for those with high SSI of collision risk. As described above, the concern level can be a relative index. When the promoting zones are to be described for each area, careful consideration according to the concern level would be required in EIA.

4.2. Level of concern in the potential promoting zone for offshore wind farms

This study extracted the potential promoting zone, overlapped the concern level based on the WSI and classified the extracted area into potential promoting zone for bottom-fixed wind turbines (water depth: 0–60 m) and floating wind turbines (water depth: 60–200 m).

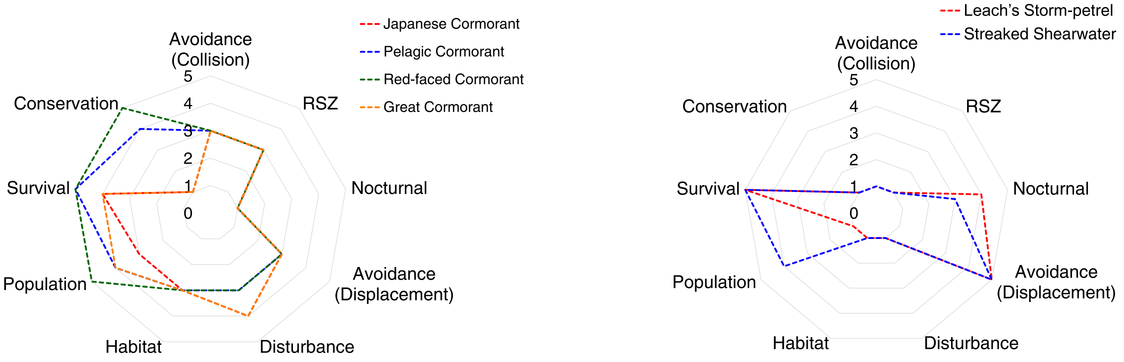
The potential promoting zones for bottom-fixed wind turbines exist especially in the northern and eastern areas. As the floating wind turbine remains under demonstration in Japan, bottom-fixed wind turbines are expected to be developed first. Therefore, considering the feasibility, the determination of the promoting zones in the northern and eastern areas can be planned. The northern and eastern areas have shallow waters where wind speeds are higher; however, most of these areas are also of major concern (Fig. 8). Hence, when bottom-fixed wind turbines are to be installed in these areas, careful consideration in the EIA process will be required.

Conversely, the potential promoting zone for floating wind turbines can be observed in all areas apart from the shore (Fig. 9). Compared to



(A) Alcidae (auks)

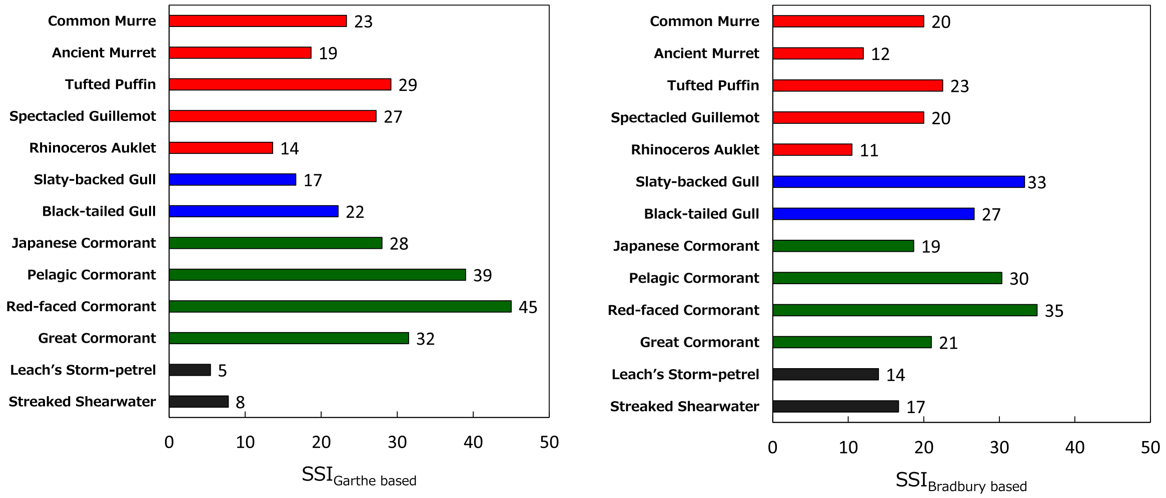
(B) Laridae (gulls)



(C) Phalacrocoracidae (cormorants)

(D) Procellariidae (prions)

Fig. 5. Diagrams illustrating the assessed risk parameters in SSI according to species.



(A) SSI estimated by the Garthe-based model

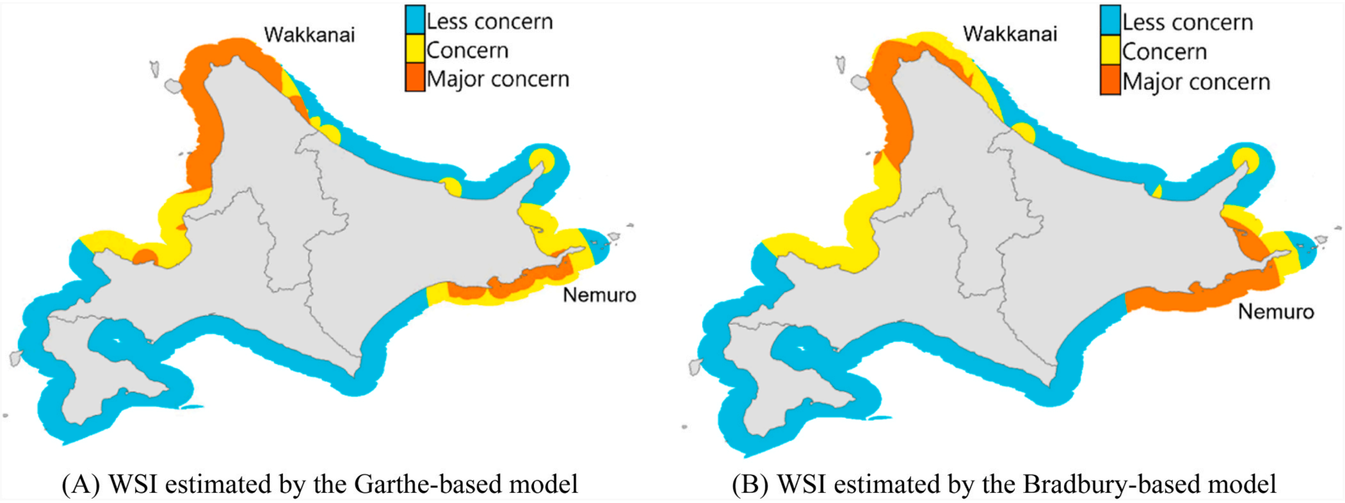
(B) SSI estimated by the Bradbury-based model

Fig. 6. Plots showing the estimated species sensitivity indices (SSI). *The colors of the bars show the family of the sea birds (red: Phalacrocoracidae; blue: Laridae; green: Alcidae; black: Procellariidae).

bottom-fixed wind turbines, it is possible to install floating wind turbines in areas, such as the southern area, with less concern. Therefore, the potential installation capacity of floating wind turbines in the lesser concern area increased (Fig. 10). In Japan, floating wind turbines are under demonstration. However, when this technology is developed, considering installation is crucial for reducing the risk to seabirds.

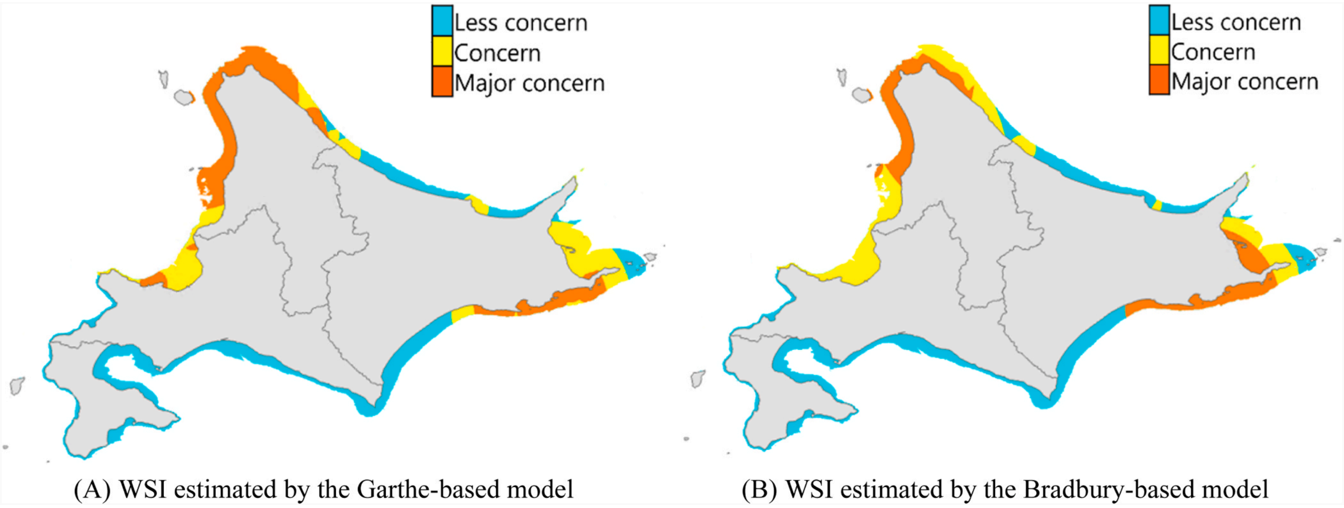
4.3. Area-wide level of concern in the potential promoting zones

In Japan, the potential promoting zone for an offshore wind farm will be considered by the municipality. This study estimated the potential installation capacity in the potential promoting zone based on the level of concern (Fig. 11). As for bottom-fixed wind turbines, although potential installation capacities in the eastern and northern areas are relatively higher than those in other areas, almost all of the eastern and northern areas are in the major concern areas (Fig. 11 [A]). Hence,



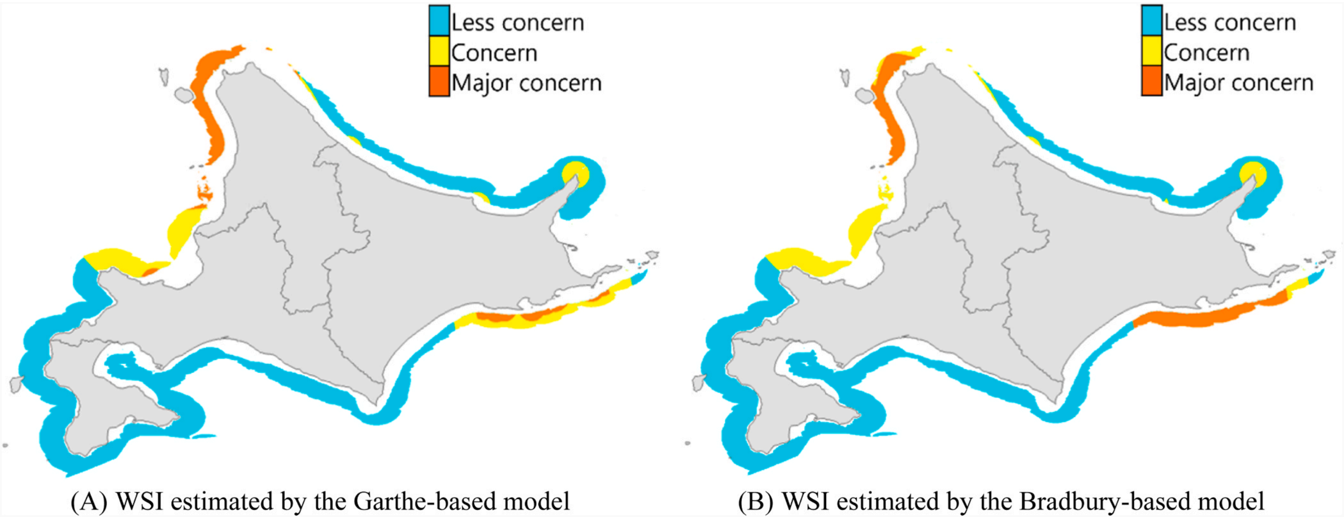
(A) WSI estimated by the Garthe-based model (B) WSI estimated by the Bradbury-based model

Fig. 7. Layout map showing the concern level based on wind farm sensitivity index near Hokkaido.



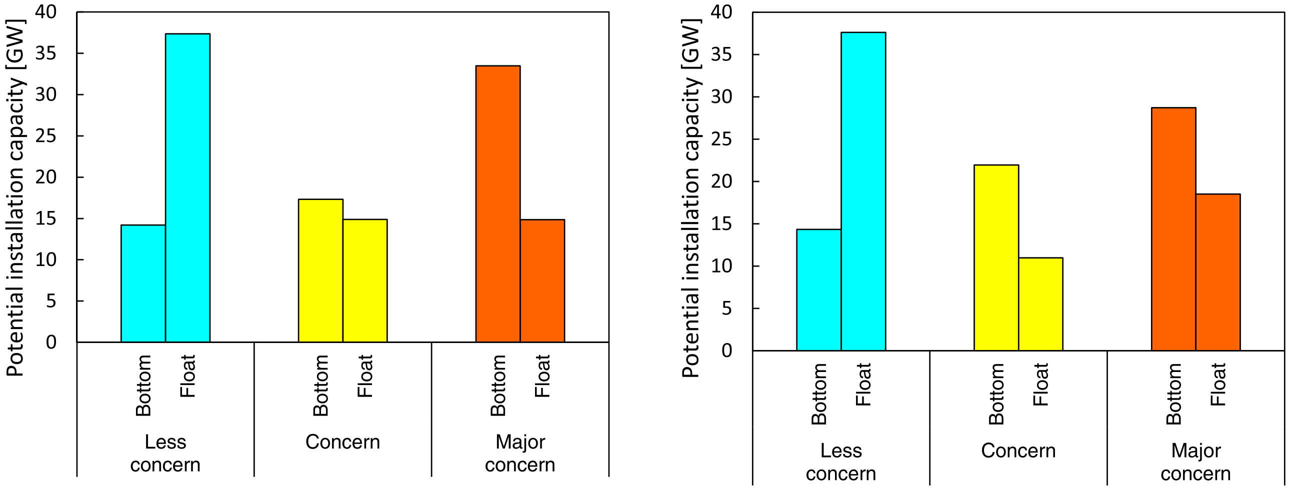
(A) WSI estimated by the Garthe-based model (B) WSI estimated by the Bradbury-based model

Fig. 8. Layout map of the concern level in the potential promoting zone for bottom-fixed turbines.



(A) WSI estimated by the Garthe-based model (B) WSI estimated by the Bradbury-based model

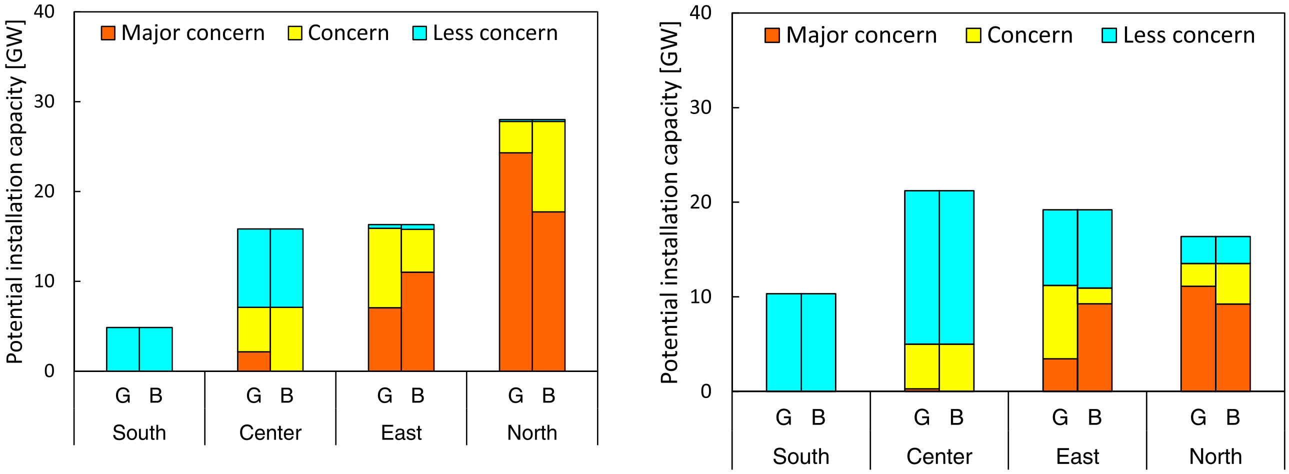
Fig. 9. Layout map of the concern level in the potential promoting zone for floating-fixed turbines.



(A) Garthe-based model

(B) Bradbury-based model

Fig. 10. Histograms of potential installation capacities in the potential promoting zone (Bottom: fixed-bottom wind turbines, Float: Floating wind turbines).



(A) Bottom-fixed wind turbines

(B) Floating wind turbines

Fig. 11. Histograms of the potential installation capacity in the potential promoting zone based on the level of concern (G: Garthe-based model, B: Bradbury-based model).

careful consideration will be required when bottom-fixed wind turbines are to be installed especially in the northern and eastern areas. Contrarily, almost all areas in the southern and central areas are in the less concern category. While the risks to seabirds from the installation of wind farms in these areas are considered to be relatively lower than those in the other areas owing to fewer or no colonies, migratory birds may pass through this area. Compared to the eastern or northern areas, the southern and central areas can be prioritized because these are areas where offshore wind farms are to be developed.

If floating wind turbines are developed, the potential installation capacity of wind turbines in less concern areas will increase. However, most of the northern and eastern areas are in the major concern areas even for floating wind turbines (Fig. 11 [B]). As the potential installation capacities of wind turbines in the central areas are similar to those in the eastern and northern area, it is also important to consider the promoting zones in the central areas on a priority basis. In Hokkaido, floating wind turbine technology is expected to avoid the impact on seabirds.

5. Conclusions and political implications

This study assessed areas suitable for offshore wind energy development with less potential risk to seabirds by integrating risk assessment models and a spatial approach to identify potential areas. The main findings of this study are as follows.

First, by comparing the results from two models to assess the SSI, the differences in the characteristic of both models were shown. The SSI values obtained from both models were different. Hence, this study reinforces the importance of comparing several models during the assessment of the potential risk to seabirds. This study differs from those of the past that used only one model, and hence, it will enable an understanding of the uncertainty of each model for the identification of suitable areas for the installation of offshore wind energy systems.

Second, this study established suitable areas with less potential risk to seabirds in Hokkaido. Although many previous studies assessed the potential areas for offshore wind energy in Hokkaido, this study established that most of the legally and technically potential areas overlap with major concern areas regardless of the risk assessment model used. Currently, the requirements in the Act to establish promoting zones do not include concrete criteria for evaluating the impact on ecosystem; however, this study reinforces their importance. By identifying suitable areas in the planning stage, the risk of reworking EIA especially in medium or major concern areas is expected to reduce. The importance of assessment or monitoring before starting work on installing offshore wind farms is emphasized. Based on these pre-assessments, the wind farms can be oriented to adaptive management, such as designing the turbine layout or size.

Limitations exist in the analysis using these quantification models. For example, because some risk parameters were determined by expert elicitations, periodical relook on assumptions or SSI models by measuring biological data such as displacements is needed. Moreover, WSI does not directly assess the impact on the reduction of populations, as it is a relative index that depends on the number and variety of seabirds. Because this study focuses on the assessment of the first site selection by the government, careful examination based on experiments will be required for the EIA to be performed by selected developers. Although this study only focused on breeding seabirds, which is especially important in Hokkaido, it should be noted that non-breeding or migratory birds may pass the shore of Hokkaido throughout the year. Tracking studies and ship surveys have shown that non-breeding (e.g., juveniles) or migratory seabirds, such as kittiwakes, gulls, albatrosses, shearwaters, and phalaropes visit the shore of Hokkaido [41–47]. Further assessment of these birds in broader areas will enhance the comprehensive risk assessment of seabirds.

It should be noted that the population density used in the model is not based on empirical data but is an estimated value based on colony data. For a more detailed assessment using WSI, especially for non-breeding or migratory birds, the measured density of seabirds at sea obtained from national or local government projects can be used. In European countries, distribution density data on seabirds are obtained throughout the year, including both the non-breeding and breeding seasons. Distribution densities are measured by airplanes or boats under national projects spanning 10–30 years. Although such density data have not been developed in Japan, some studies have attempted to identify foraging areas and flight routes of seabirds by attaching GPS loggers or radio transmitters to seabirds [48–52]. Data from these approaches will be helpful for a more detailed assessment using the WSI.

Although assessments or legal criteria regarding potential risk to biology are inadequate, Japan has already started determining promoting zones for the installation of offshore wind farms. The approach of integrating risk assessment models for seabirds in a spatial context to identify potential areas for offshore wind energy development is useful especially in areas with abundant seabird habitats as in Hokkaido. The results of this study are expected to contribute toward the expansion of offshore wind turbines and preserving regional biology.

CRediT authorship contribution statement

Hideaki Obane: Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft. **Kentaro Kazama**: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing – review & editing. **Hiroshi Hashimoto**: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing – review & editing. **Yu Nagai**: review & editing, **Kenji Asano**: review & editing.

Declaration of Competing Interest

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

Data availability

Data will be made available on request.

Appendix A

To assess the SSI, this study referred to the distribution percentages of the same or related species in the altitude related to that of the offshore wind turbine for assessing the number of colonies for biological population size, adult survival, and conservation status. Table A.1 shows the summary of the characteristics of the studied seabirds for assessing the SSI. The scores of some species were referred to those of related species as shown in Table A.2.

Table A.1
Characteristics of the studied seabirds for assessing the SSI.

Family	Species	Number of nests	Adult survival rate [%]	Conservation status
Alcidae	Common Murre	9	87–95	Critically endangered (CR)
	Ancient Murrelet	22	77	Critically endangered (CR)
	Tufted Puffin	0	94.2	Critically endangered (CR)
	Spectacled Guillemot	304	80	Vulnerable (VU)
	Rhinoceros Auklet	474,308	94.2	-
Laridae	Slaty-backed Gull	3769	91	Near threatened (NT)
	Black-tailed Gull	25,684	79–92	-
Phalacrocoracidae	Japanese Cormorant	3176	88	-
	Pelagic Cormorant	106	95	Endangered (EN)
	Red-faced Cormorant	34	95	Critically endangered (CR)
	Great Cormorant	653	88	-
Procellariidae	Leach's Storm-petrel	704,260	73–93	-
	Streaked Shearwater	120	93–94	-

Table A.2
Related species for score.

Family	Species	Related species for score	Related species for survival rate	Related species for macr avoidance and RSZ
Alcidae	Common Murre	-	-	-
	Ancient Murrelet	Little Auk (*Alle alle*)	-	-
	Tufted Puffin	Atlantic Puffin (*Fratercula arctica*)	Atlantic Puffin (*F. arctica*)	-
	Spectacled Guillemot	Black Guillemot (*Cepphus grille*)	-	Pigeon Guillemot (*C. columba*)
	Rhinoceros Auklet	Atlantic Puffin (*F. arctica*)	Atlantic Puffin (*F. arctica*)	-
Laridae	Slaty-backed Gull	Herring Gull (*Larus argentatus*)	Herring Gull (*L. argentatus*)	Herring Gull (*L. argentatus*)
	Black-tailed Gull	Common Gull (*L. canus*)	California Gull (*L. californicus*)	Ring-billed Gull (*L. delawarensis*)
Phalacrocoracidae	Japanese Cormorant	Great Cormorant (*Phalacrocorax carbo*)	Great Cormorant (*P. carbo*)	Brandt's Cormorant (*P. penicillatus*)
	Pelagic Cormorant	European Shag (*P. aristotelis*)	-	-
	Red-faced Cormorant	European Shag (*P. aristotelis*)	Pelagic Cormorant (*P. pelagicus*)	Pelagic Cormorant (*P. pelagicus*)
	Great Cormorant	-	-	Brandt's Cormorant (*P. penicillatus*)
Procellariidae	Leach's Storm-petrel	-	-	-
	Streaked Shearwater	Manx Shearwater (*Puffinus puffinus*)	Short-tailed Shearwater (*P. tenuirostris*)	Flesh-footed Shearwater (*P. carneipes*)

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