Ecological niche models for the assessment of site suitability of sea cucumbers and sea urchins in China

Jiangnan Sun1,2, Yushi Yu1,2, Zihe Zhao1, Donghong Yin1, Yaqing Chang1* & Chong Zhao1*

In the present study, the maximum entropy model (MaxEnt) based on the data of sea surface temperature (SST) and published information was used to assess the site suitability for the aquaculture expansion of the sea cucumber Apostichopus japonicus and the sea urchin Strongylocentrotus intermedius in China. According to the current assessment, the coastal areas of Hebei province and Tianjin have great prospects for A. japonicus aquaculture, while is currently being underutilized. In the south, more than 94% of the coastal areas in Zhejiang, Fujian, and Guangdong provinces are suitable for the growth of A. japonicus for six months, especially the coastal areas of Lianjiang, Changle, Fuqing and Putian in Fujian province. The water temperatures in more than 94% of China’s coastal areas are higher than 25 °C in July and August, which probably results in the mortality of S. intermedius in aquaculture. This clearly indicates that high water temperature is the bottleneck of S. intermedius aquaculture and well explains the limited expansion of this commercially important exotic species since the introduction in 1989. We suggest a new aquaculture model of S. intermedius that extends the seed production to November to avoid the mass mortality in summer. In the south, 64% of coastal areas in Zhejiang and Fujian provinces are suitable for the transplantation of S. intermedius to the south. The present study suggests the ecological niche model MaxEnt based on the data of SST and published information as a new tool for the assessment of the site suitability of sea cucumbers and sea urchins in China. This provides new insights into the aquaculture expansion of native and exotic species.

China has the largest aquaculture sector in the world, contributing to about 60 percent of the production for both domestic and international commercial demands1. The expansion of aquaculture in China is thus important for the increasing global food and nutrition security2. China has made remarkable progress in the expansion of aquaculture. Due to the transplantation of native species and the introduction of exotic species3, the mariculture area in China, for example, makes a nearly 80-fold increase from 25,000 hectares in 1954 to 1.996 million hectares in 20204,5. Based on the technological innovation, the aquaculture of native species not only occurs in the original sites, but also outside the range of the natural distribution6. Further, China is the largest producer of non-native aquatic species in the world1. By 2000, more than 60 exotic species had been introduced into China, contributing to 25% of the country's total production7. Despite the rapid development, there are still problems with aquaculture expansion in China, especially the aquaculture site selection8. Site selection is an important and pre-requisite step for aquaculture expansion as it provides the foundations for production, economic benefits, and the sustainability of aquaculture activities8. At present, the site selection largely depends on the method of trial and error for the aquaculture expansion of both native and exotic species in China, which is heavily influenced by the water environment of different regions9. It brings the difficulty in coordinating aquaculture expansion for fisher administrative authorities, especially considering that aquaculture in China is mainly dominated by small and medium-scale aqua-farms7,8. Therefore, it is important to establish an effective method to assess the site suitability in large-scale for aquaculture expansion according to water environment of different regions.

Water temperature is the most important factor for the spatial and temporal distribution of aquaculture species11,12. Monitoring water temperature changes in the targeted sea areas is an important method for the

---

1Key Laboratory of Mariculture and Stock Enhancement in North China’s Sea, Ministry of Agriculture and Rural Affairs, Dalian Ocean University, Dalian 116023, China. 2These authors contributed equally: Jiangnan Sun and Yushi Yu. *email: changlab@hotmail.com; chongzhao@dlou.edu.cn
assessment of the survival of aquaculture species at the site\textsuperscript{13,14}, but is not an effective approach for the large-scale management of the aquaculture expansion in China. The development of remote sensed technology ensures the wide coverage, high accuracy, and high accessibility to the data of sea surface temperature (SST)\textsuperscript{15}. An important indicator of sea water temperature, the data of SST has been well used to predict the resource distribution of various marine organisms, including Thunnus albacares\textsuperscript{16}, Dorsidicus gigas\textsuperscript{17}, and Gadus morhua\textsuperscript{18}. Since aquaculture is primarily conducted in coastal areas, it is directly affected by the local sea surface temperature. The SST data has been applied for the aquaculture site selection in a number of aquaculture species, including shellfish Mizuhopecten yessoensis\textsuperscript{19}, Mytilus galloprovincialis\textsuperscript{20}, and kelp Saccharina japonica\textsuperscript{21}. Furthermore, the data of SST was successfully used to evaluate coral reef restoration, which clearly suggests the potential application of SST data in the study of marine benthos\textsuperscript{22}. Here, we suggest an effective approach for assessing the site suitability for the aquaculture expansion in large-scale in China by analyzing remote sensed data of sea surface temperature and reviewing the published information of the targeted species.

Ecological niche models (ENMs) are a category of methods for a correlative model of the environmental conditions that meet ecological requirements of a species by using the data of species distribution and the environments\textsuperscript{23,24}. The results predicted by ecological niche models have higher resolution, compared with the methods based on physiological limiting factors\textsuperscript{25}. Ecological niche models based on the data of sea surface temperature have been used in fisheries. For example, the generalized additive model (GAM) and the generalized linear model (GLM) were used to predict the niche demands of Scomber japonicus\textsuperscript{26} and the maximum entropy model (MaxEnt) to predict the potential fishing areas for Illex argentinus and Cololabis satin\textsuperscript{27,28}. In particular, MaxEnt model outperforms other models in handling with small sample sizes and is thus suitable for aquatic organisms with limitedly recorded distribution data in field\textsuperscript{27}. Therefore, we propose that the MaxEnt is appropriate for the assessment of site suitability for the aquaculture expansion of native and exotic species in China, based on the data of SST and the species distribution data.

The sea cucumber Apostichopus japonicus mainly distributes in the western Pacific, including the Yellow Sea, the Sea of Japan, and the Sea of Okhotsk, with the northern boundary in Sakhalin Island area and the southern in Tanegashima of Japan\textsuperscript{30}. In China, this commercially important species naturally distributes in the coastal regions of Liaoning, Hebei and Shandong provinces, with the southern boundary in Lianyungang, Jiangsu Province\textsuperscript{31,32}. Water temperature varies from -2 to 30 °C in the natural distribution of A. japonicus\textsuperscript{31}. Based on the outbreaks in breeding and aquaculture technology in 1998, the aquaculture of A. japonicus has expanded rapidly in the north of China\textsuperscript{31}. From 2003 to 2012, the area of A. japonicus aquaculture in the north increased by an average of 31.0% per year\textsuperscript{33,34}. However, the expansion speed of A. japonicus aquaculture in the north declined sharply to only 3.9% of the annual average expansion rate in the most recent nine years\textsuperscript{34,35}. The transplantation to the south is a successful step in the aquaculture expansion of A. japonicus in China\textsuperscript{36}. Since 2006, the aquaculture of A. japonicus in the south has developed rapidly. In 2020, the production of A. japonicus in the south has accounted for about 14% of the total production of the country\textsuperscript{36,37}. However, the aquacultural area of A. japonicus in the south accounts for less than 0.8% of that of the country and the sites are very concentrated\textsuperscript{36,37}. Therefore, the key to further development of A. japonicus aquaculture in the south is to find efficient tools to evaluate more sites suitable for the aquaculture expansion. The sea urchin Strongylocentrotus intermedius naturally distributes in northern regions in the Pacific coastal waters of Choshi, Chiba, the Sea of Japan around Toyama, the Korean peninsula, Sakhalin, and Vladivostok\textsuperscript{38}. It was introduced to the coastal waters of Dalian in China for aquaculture in northern regions in the Pacific coastal waters of Choshi, Chiba, the Sea of Japan around Toyama, the Korean peninsula, Sakhalin, and Vladivostok\textsuperscript{38}. It was introduced to the coastal waters of Dalian in China for aquaculture in 1989\textsuperscript{39}. Due to the lack of effective methods to assess the niche needs of exotic species, however, the aquaculture of S. intermedius is still limited to small-scale coastal areas in China in over 30 years\textsuperscript{31,39}. The present study used the ecological niche model MaxEnt based on the SST data to explore potential suitable sites for the aquaculture expansion of A. japonicus and S. intermedius in China. The main purposes of the present study are to investigate the feasibility of applying ecological niche models in assessment of site suitability for aquaculture expansion and discuss possible ways to expand the aquacultural scale of A. japonicus and S. intermedius in China.

Methods

Distribution of A. japonicus and S. intermedius. The distribution data of A. japonicus and S. intermedius was derived from the Global Biodiversity Information Facility (GBIF; http://www.gbif.org) and the literature records\textsuperscript{40}. All data was carefully checked and deduplicated. The literature records without geographical coordinates were obtained using Google Earth (www.googleearth.com). A total of 22 samples of A. japonicus (8 samples from the GBIF and 14 samples from the literature records\textsuperscript{40}) and 32 samples of S. intermedius (all from the GBIF) were used in the ecological niche modeling (Tables 1, 2).

Sea surface temperature data processing. The data of sea surface temperature (SST) was derived from a daily Advanced Very High Resolution Radiometer (AVHRR) infrared satellite with a high resolution of 1 km (https://neo.sci.gsfc.nasa.gov). To reduce the effect of cloud cover, SST data was used to generate the monthly composite imagery. We calculated the mean, difference and standard deviation of monthly SST data from 2003 to 2020.

According to the water temperature ranges for the survival of A. japonicus (− 2 to 30 °C) and S. intermedius (− 2 to 25 °C), the coastal areas of China were divided into survivable areas and non-survivable areas\textsuperscript{35}. Data was collected within 20 km from the coast and calculated using the geographic information processing tools ArcMap (version 10.5). The suitable water temperature range for the growth of A. japonicus and S. intermedius is from 10 to 20°C\textsuperscript{41}. By comparing the SST data of species distributions in different months, the highest probability of being suitable for A. japonicus reached 91.3% in May (mean water temperature 16.0 °C), and 87.1% for S.
intermedius in June (mean water temperature 14.7 °C). Therefore, the data of SST in May and June were selected as the reference environment in the model for Apostichopus japonicus and S. intermedius, respectively.

Ecological niche models for A. japonicus and S. intermedius in China. The ecological niche model MaxEnt was built using MaxEnt 3.4.1. A total of 25% of the distribution data were randomly selected as the test set, and the rest of the data (75%) as the training set. We ran the algorithm either for 10 iterations or until convergence. The receiver operating characteristic curve (ROC) was utilized to evaluate the prediction accuracy of the model. AUC value > 0.9 indicates that the model predicts the true presences perfectly41. To clearly divide the suitable distribution areas, the coastline was classified into three levels (lowly, moderately, and highly suitable) using a Jenks’s natural breaks approach according to suitability values42. The results were collected and computed using ArcMap 10.5.

Results and discussion

Aquaculture expansion of A. japonicus in China. Based on the water temperature range for the survival of A. japonicus (~2 to 30 °C)31, we analyzed the sites where A. japonicus can survive along the Chinese coast in each month of the whole year (Fig. 1). The present study indicates that A. japonicus can survive year-round in more than 98% of the northern coastal areas (Fig. 1). Therefore, the northern coast of China is suitable for the expansion of A. japonicus aquaculture. At present, the area of A. japonicus aquaculture in the north is 2409.5 km², accounting for only 4.6% of the areas that are suitable for aquaculture expansion5. Notably, Shandong and Liaoning provinces account for 96.1% of A. japonicus aquaculture areas5. According to the assessment results of the ecological niche model, 79% of the coastal areas of Shandong and Liaoning provinces are consistently suitable (moderate or high suitability) for the growth of A. japonicus for six months (April to June, September to November; Fig. 2). Furthermore, about 1128.9 km² of the coastal areas (within 20 km from the coast) are suitable for A. japonicus to grow for a maximum of nine months (from April to December), mainly located in the northern part of the Yellow Sea (Fig. 2). Therefore, it is promising to continue the expansion of the aquaculture scale of A. japonicus in Shandong and Liaoning provinces. In recent years, the growth of A. japonicus production in Shandong has stagnated and the production in Liaoning has decreased, which leads to the decrease in the total production of A. japonicus in China5. Therefore, aquaculture of A. japonicus in other sites needs to be promoted. Hebei province and Tianjin are two important sites for A. japonicus aquaculture in the north35,43. Coastal water temperatures are within the temperature range for the survival of A. japonicus all year round in both sites (Fig. 1). More than 40% of the coastal areas in Hebei province and Tianjin are suitable for the growth of A. japonicus starting from March, which is earlier than that in 66.1% of Shandong province and 100% of Liaoning province (Fig. 2). Furthermore, 86.5% of the coastal areas of Hebei province and Tianjin are suitable for the growth of A. japonicus for six months (April to June, September to November), which is greater than that of the

| Country | Location | Decimal latitude | Decimal longitude |
|---------|----------|------------------|--------------------|
| Japan   | Akita    | 39.870000        | 139.810000         |
| Japan   | Akita    | 39.940000        | 139.720000         |
| Japan   | Honshu Island | 34.266667     | 136.850000         |
| Japan   | Kanagawa | 35.000000        | 139.000000         |
| Japan   | Kanagawa | 35.141123        | 139.161404         |
| Japan   | Kyushu Island | 31.411111       | 130.192222         |
| Japan   | Naozaki  | 33.531797        | 126.679906         |
| Japan   | Tokyo Bay | 35.347196       | 139.781252         |
| China   | Beidaihe | 39.849239        | 119.548181         |
| China   | Changdao | 37.837209        | 120.768637         |
| China   | Dalian   | 38.865251        | 121.557398         |
| China   | Haiyangdao | 39.063592      | 123.136940         |
| China   | Jiaonan  | 35.929793        | 120.240497         |
| China   | Jimingdao | 37.453114       | 122.486838         |
| China   | Lianyungang | 34.777225      | 119.395653         |
| China   | Liaodao  | 37.227993        | 122.601828         |
| China   | Longkou  | 37.709209        | 120.355467         |
| China   | Leshun   | 38.786683        | 121.259265         |
| China   | Pingshangdao | 35.008112     | 119.895586         |
| China   | Rizhao   | 35.401317        | 119.572670         |
| China   | Rongcheng | 37.149907      | 122.495721         |
| China   | Sangdao  | 37.777860        | 120.460846         |

Table 1. Distribution data of Apostichopus japonicus. The distribution data of A. japonicus in Japan was obtained from the Global Biodiversity Information Facility (GBIF, http://www.gbif.org). The distribution data in China was obtained from literature40.
coastal areas of Shandong and Liaoning provinces (Fig. 2). In 2020, the aquaculture area of *A. japonicus* in Hebei province and Tianjin, most of which is in pond culture, accounts for less than 4% of the total area in northern China and only 1.7% of the local coastal area. The present results indicate that there is still a large potential for the aquaculture expansion of *A. japonicus* in the north, especially in the coastal areas of Hebei province and Tianjin, although other factors should be further considered.

In addition to the expansion in the natural distribution areas, the transplantation of *A. japonicus* to the south is an important method for the aquaculture expansion of *A. japonicus* in China. By the transplantation of small *A. japonicus* (~ 38 g per individual) to the coastal areas of Fujian in November, the body weight of *A. japonicus* increases by about three-fold (~ 135 g per individual) after four months of aquaculture. According to the present study, more than 94% of the coastal areas of Zhejiang, Fujian, and Guangdong provinces are suitable (moderate or high suitability) for the growth of *A. japonicus* for six months (from November to the next April, Fig. 2). At present, the *A. japonicus* aquaculture in Fujian is mainly in Xiapu area, and the production accounts for 96.2% of the total production of the province. According to the present assessment of the ecological niche model, the coastal areas of Lianjiang, Changle, Fuqing, and Putian in Fujian province (a total of 1424.1 km²) are highly suitable for *A. japonicus* aquaculture (from November to the next April, Fig. 2). It is thus feasible to largely expand the transplantation scale of *A. japonicus* to Fujian province. In addition, the southern part of Zhejiang province is another suitable site for the transplantation of *A. japonicus*. The coastal areas in the south of Taizhou in Zhejiang province are suitable for *A. japonicus* aquaculture from October until next April (Fig. 2). Fujian and Zhejiang provinces accounted for less than 1% of the *A. japonicus* aquaculture area in China, but contributed more than 14.3% to the total production in 2020. This efficient aquaculture mode is thus an important step to improve the scale of *A. japonicus* aquaculture in China. The present study revealed a number of sites that are suitable for expansion of *A. japonicus* aquaculture in the south and supports the large expansion of *A. japonicus* aquaculture to the south. However, it should be noted that the present study made a preliminary assessment of

| Country | Location | Decimal latitude | Decimal longitude |
|---------|----------|-----------------|-------------------|
| Russia  | Kamchatka | 53.032574        | 158.627045        |
| Russia  | Pacific Ocean | 46.270000       | 138.280000        |
| Russia  | Primor’ye       | 42.951544        | 131.874120        |
| Russia  | Primor’ye       | 43.031341        | 131.893620        |
| Russia  | Primor’ye       | 43.021210        | 131.926885        |
| Russia  | Primor’ye       | 42.791375        | 132.811740        |
| Russia  | Primor’ye       | 44.345581        | 135.836700        |
| Russia  | Primor’ye       | 44.953698        | 136.556621        |
| Korea   | Chungcheongnam-do | 36.228073     | 126.073823        |
| Korea   | Chungcheongnam-do | 36.851054       | 126.197033        |
| Japan   | Akita         | 39.920000        | 139.720000        |
| Japan   | Akita         | 39.740000        | 140.130000        |
| Japan   | Hakodate      | 41.777654        | 140.658779        |
| Japan   | Hokkaido      | 41.771628        | 140.667977        |
| Japan   | Hokkaido      | 42.413605        | 141.594635        |
| Japan   | Hokkaido      | 43.903900        | 144.661000        |
| Japan   | Hokkaido      | 43.018299        | 144.837010        |
| Japan   | Iwate         | 39.383400        | 141.933000        |
| Japan   | Iwate Prefecture | 40.307570      | 142.012183        |
| Japan   | Okinawa       | 41.134700        | 140.827000        |
| Japan   | Nagasaki      | 32.742500        | 129.864717        |
| Japan   | Peter the Great Bay | 42.892662     | 132.052293        |
| Japan   | Sea of Japan  | 46.273900        | 138.279000        |
| Japan   | Sea of Japan  | 43.599730        | 140.247664        |
| Japan   | Sea of Japan  | 43.619782        | 140.900788        |
| Japan   | Sea of Japan  | 43.839914        | 140.955960        |
| Japan   | Sea of Japan  | 44.032690        | 141.066343        |
| Japan   | Sea of Japan  | 44.032690        | 141.075542        |
| Japan   | Sea of Japan  | 42.062923        | 141.204323        |
| Japan   | Sea of Japan  | 44.862960        | 141.268714        |
| Japan   | Sea of Japan  | 44.218221        | 144.552631        |

Table 2. Distribution data of *Strongylocentrotus intermedius*. The data was derived from the Global Biodiversity Information Facility (http://www.gbif.org).
Aquaculture expansion of *S. intermedius* in China. The water temperature range for the survival of *S. intermedius* is from −2 to 25°C\(^\circ\). Temperature at 22 °C significantly affected the food consumption and gonad production of *S. intermedius*, while water temperatures above 25 °C caused mass mortality of *S. intermedius*. According to the present study, the water temperatures in more than 94% of China's coastal areas are higher than 25 °C in July and August (Fig. 3). High water temperature in July and August is thus the bottleneck for *S. intermedius* aquaculture in China, which well explains why the aquaculture of *S. intermedius* is still limited to small-scale coastal areas in China. It is essential to break the high-water temperature bottleneck for the expansion of *S. intermedius* aquaculture, because more than 90% of the northern coastal areas are available for aquaculture after July and August (Fig. 3). Seed production of *S. intermedius* currently carries out in every October in northern China and provides individuals of 1–2 cm in test diameter for the longline culture and stock.
enhancement in the coming spring\textsuperscript{50}. The subsequent longline culture and stock enhancement, however, suffer from the high water temperature, which causes mass mortality\textsuperscript{31}. According to the present study, we suggest a new aquaculture model for \textit{S. intermedius} that extends the seed production to every November for the longline culture and stock enhancement, which can avoid the mass mortality in summer. Notably, there are about 7537.3 km\textsuperscript{2} area where water temperature is lower than 25 °C all over the year, including the areas in Yantai and Weihai in Shandong province, and those in Dalian in Liaoning province (Fig. 3). These areas should be well managed for the expansion of \textit{S. intermedius} aquaculture. In addition, heat exchange is another valuable method for the aquaculture of \textit{S. intermedius} at high water temperatures in the areas with cold water underground.

Provided that the bottleneck is broken, not only \textit{S. intermedius} aquaculture can be greatly expanded in the north, but also \textit{S. intermedius} is suitable for the transplantation to the south. Sixty-four percent of the coastal areas in Zhejiang and Fujian provinces are suitable (moderate or high suitability) for \textit{S. intermedius} aquaculture from November to the next April (Fig. 4). Our previous study indicates that small \textit{S. intermedius} (3 cm in test diameter) transplanted to Fujian in November grew to the market size (~ 5.5 cm in test diameter) in the next May\textsuperscript{51}. Furthermore, the abalone and kelp aquaculture are well developed in Fujian province and the unused
abalone cages and adequate feed supply can be used well for the aquaculture of *S. intermedius*\(^5\,\!^1\,\!^2\). Therefore, the transplantation of *S. intermedius* to the south is a promising method for the aquaculture expansion of *S. intermedius* in China, provided that the industrial high water temperature bottleneck can be addressed. According to the present study, a preliminary judgment can be made on whether a site is suitable for the expansion of *S. intermedius* aquaculture. More factors need to be taken into consideration before field application.

**Conclusion**

Based on the SST data and the geographic information of the native species *A. japonicus* and the exotic species *S. intermedius*, we established an ecological niche model MaxEnt for the two aquacultural species. According to the present assessment, there is a great potential for the aquaculture expansion of *A. japonicus* in the north, especially the coastal areas of Hebei province and Tianjin. Furthermore, large expansion of *A. japonicus* aquaculture to the south is promising, since there are a number of suitable sites besides Xiapu. The present study indicates that ecological niche model can be used as a tool to assess the suitable sites for the aquaculture expansion of the native

---

**Figure 3.** Maps of survivable areas and non-survivable areas for *Strongylocentrotus intermedius* in China. The coastal areas marked in green indicate that sea surface temperatures are in the range where *S. intermedius* can survive. The red indicates sea surface temperatures that exceed the tolerance of *S. intermedius*. 
species in China. The present study highlights that high water temperature in July and August is the bottleneck for the expansion of *S. intermedius* aquaculture and this well explains the limited aquaculture expansion of *S. intermedius* in China. A new aquaculture model is suggested to break the high-water temperature bottleneck. Furthermore, the transplantation of *S. intermedius* to the south is a promising method for the aquaculture expansion. We propose that it is important to establish ecological niche models for the exotic species before they are introduced. The present study establishes a new tool for the preliminarily assessment of site suitability for the aquaculture expansion of sea cucumbers and sea urchins in China using the ecological niche model MaxEnt based on the SST data.

**Data availability**
GBIF data is available from [https://www.gbif.org/](https://www.gbif.org/). The data of sea surface temperature is available from [https://neo.sci.gsfc.nasa.gov/](https://neo.sci.gsfc.nasa.gov/).

---

**Figure 4.** Site suitability for *Strongylocentrotus intermedius* aquaculture in China. The blue represents the areas that are highly suitable for *S. intermedius* aquaculture. The yellow indicates that the suitability index is medium. The red indicates that the suitability index is low.
References

1. FAO (Food and Agriculture Organization of the United Nations, Fisheries and Aquaculture Department). The State of World Fisheries and Aquaculture 2020 (Food and Agriculture Organization of the United Nations, 2020).

2. Costello, C. et al. The future of food from the sea. Nature 588(7836), 1–6 (2020).

3. Sarah, A. B. et al. Trends in the detection of aquatic non-indigenous species across global marine, estuarine and freshwater ecosystems: A 50-year perspective. Divers. Distrib. 26(12), 1780–1797 (2020).

4. FAMA (Fisheries Administration of the Ministry of Agriculture of the PRC). China Fishery Statistical Yearbook (China Academic Journal Electronic Publishing House, 1949–1975). https://www.caes.ac.cn/yqyyjt.htm. (in Chinese).

5. FAMA (Fisheries Administration of the Ministry of Agriculture of the PRC). China Fishery Statistical Yearbook (China Agriculture Press, 2021). (in Chinese).

6. Shelton, W. L. & Rothbard, S. Exotic species in global aquaculture—a review. Int. J. Aquat. 58(1), 3–28 (2006).

7. Ju, R. et al. Emerging risks of non-native species escapes from aquaculture: Call for policy improvements in China and other developing countries. J. Appl. Ecol. 57, 86–90 (2020).

8. Zhu, C. & Dong S. Aquaculture site selection and carrying capacity management in the People's Republic of China. In Site Selection and Carrying Capacities for Inland and Coastal Aquaculture (eds Ross, L. G., Telfer, T. C., Falconer, L., Soto, D. & Aguilar Manjarrez, J.) 219–230 (FAO-Institute of Aquaculture, Expert Workshop, 6–8 December 2010, University of Stirling, UK, FAO, Rome, 2013).

9. Falconer, L., Telfer, T. C. & Ross, L. G. Investigation of a novel approach for aquaculture site selection. J. Environ. Manag. 181, 791–804 (2016).

10. Liu, Y. et al. Spatial and temporal variations of potential habitats of jumbo flying squid (Dosidicus gigas) off Peru under increasing sea surface Temperature. Fish. Sci. (2020). (in Chinese with an English Abstract).

11. Nian, R. et al. The identification and prediction in abundance variation of Atlantic cod via long short-term memory with periodicity, time-frequency co-movement, and lead-lag effect across sea surface temperature, sea surface salinity, catches, and prey biomass from 1919 to 2016. Front. Mar. Sci. 6, 665716 (2021).

12. Rönnegård, L. & Bluhm, M. Biophysical models for Japanese scallop (Pecten yessoensis), aquaculture site selection in Fuku Bay, Hokkaido, Japan, using remotely sensed data and geographic information system. Aquacult. Int. 17(5), 403 (2009).

13. Gentry, R. et al. Mapping the global potential for marine aquaculture. Nat. Ecol. Evol. 1(9), 1317 (2017).

14. Kim, B. et al. Impact of seawater temperature on Korean aquaculture under representative concentration pathways (RCP) scenarios. Aquaculture 542(3), 736893 (2021).

15. Wentez, F. J. et al. Satellite measurements of sea surface temperature through clouds. Science 288(5467), 847–850 (2000).

16. Mediodia, H. Effects of sea surface temperature on tuna catch: Evidence from countries in the Eastern Pacific Ocean. Ocean. Coast. Manag. 209, 105657 (2021).

17. Liu, S., Zhang, Z., Wu, J. & Yu W. Spatial and temporal variations of potential habitats of jumbo flying squid (Dosidicus gigas) off Peru under increasing sea surface temperature. Fish. Sci. (2020). (in Chinese with an English Abstract).

18. Nian, R. et al. The identification and prediction in abundance variation of Atlantic cod via long short-term memory with periodicity, time–frequency co-movement, and lead–lag effect across sea surface temperature, sea surface salinity, catches, and prey biomass from 1919 to 2016. Front. Mar. Sci. 6, 665716 (2021).

19. Rönnegård, L. & Bluhm, M. Biophysical models for Japanese scallop (Pecten yessoensis), aquaculture site selection in Fuku Bay, Hokkaido, Japan, using remotely sensed data and geographic information system. Aquacult. Int. 17(5), 403 (2009).

20. Laama, C. & Bachar, N. Evaluation of site suitability for the expansion of mussel farming in the Bay of Souahlia (Algeria) using empirical models. J. Appl. Aquac. 31(4), 337–355 (2019).

21. Liu, Y. et al. Impact of oceanographic environmental shifts and atmospheric events on the sustainable development of coastal aquaculture: A case study of kelp and scallops in southern Hokkaido, Japan. Sustainability 7(2), 1263–1279 (2015).

22. Sillero, N. What does ecological modelling model? A proposed classification of ecological niche models based on their underlying methods. Ecol. Model. 222(8), 1343–1346 (2011).

23. Bo, Z., Xin-Jun, C. & Gang, L. Relationship between the resource and fishing ground of mackerel and environmental factors based on GAM and GLM models in the East China Sea and Yellow Sea. Shuosan Xuebao 32(3), 379–386 (2008) (in Chinese with an English abstract).

24. Chen, P. & Chen, X. Analysis of habitat distribution of Argentine shortfin squid (Illex argentinus) in the southwest Atlantic Ocean using maximum entropy model. Shuixian Xuebao 40(6), 893–902 (2016) (in Chinese with an English abstract).

25. Zhang, S., Shi, Y., Li, F., Zhu, M. & Wei, Z. Prediction of potential fishing ground for Pacific saury (Ammodytes japonicus) based on MAX-EN model. J. Ocean. Univ. China 29(2), 280–286 (2020) (in Chinese with an English abstract).

26. Phillips, S. & Elith, J. On estimating probability of presence from use–availability or presence–background data. Ecology 94(6), 1409–1419 (2013).

27. Yang, H. et al. Current advances and technological prospects of the sea cucumber seed industry in China. Mar. Sci. 7, 2–9 (2020) (in Chinese with an English abstract).

28. Chang, Y., Ding, J., Song, J. & Yang, W. Biology and Aquaculture of Sea Cucumbers and Sea Urchins (Ocean Press, Beijing, 2004) (in Chinese).

29. Li, C. & Hu, W. Status, trend and countermeasure in development of sea cucumber Apostichopus japonicus Selenka industry in China. Mar. Econ. China. 1, 3–20 (2017) (in Chinese with an English abstract).

30. FAMA (Fisheries Administration of the Ministry of Agriculture of the PRC). China Fishery Statistical Yearbook. China Agriculture Press, 2003. (in Chinese).

31. FAMA (Fisheries Administration of the Ministry of Agriculture of the PRC). China Fishery Statistical Yearbook (China Agriculture Press, 2012). (in Chinese).

32. He, C. & Huang, G. On Apostichopus japonicus culture in China and major culture provinces. Fish. Inf. St. (2014). (in Chinese with an English abstract).

33. Su, L., Zhou, C., Hu, J. & Xu, J. Development status and sustainable development of Apostichopus japonicus industry in south China. Fish. Sci. Technol. Inf. 2, 57–60 (2014) (in Chinese).

34. Guo, F. Research and analysis report on sea cucumber Apostichopus japonicus aquaculture industry in typical regions of North and South China: A case study of Wafangdian city and Xiapi county. Masteral dissertation, Dalian Ocean University. 2021. (in Chinese with an English abstract).

35. Agatsuma, Y. Strongylocentrotus intermedius. In Sea Urchins: Biology and Ecology 4th edn (ed. Lawrence, J. M.) 609–621 (Elsevier, Amsterdam, 2020).

36. Wang, Z. & Chang, Y. Studies on hatching of Japanese sea urchin Strongylocentrotus intermedius. J. Fish. Sci. C 4(1), 60–67 (1997) (in Chinese with an English abstract).
40. Liao, Y. Fauna of China: Echinodermata: Holothuroidea (Science Press, 1997) (in Chinese).
41. Merckx, B. et al. Null models reveal preferential sampling, spatial autocorrelation and overfitting in habitat suitability modelling. *Ecol. Model.* 222(3), 588–597 (2011).
42. Matthew, A. A method for implementing a statistically significant number of data classes in the Jenks algorithm. In *Proceedings of the Sixth International Conference on Fuzzy Systems and Knowledge Discovery* 35–38 (Tianjin, China. 2009).
43. Zhao, G. Water environment analysis of two typical breeding patterns. *Master's dissertation, Hebei Agricultural University.* (2019). (in Chinese with an English abstract).
44. Liu, C. & Lan, Y. Situation and countermeasure of sea cucumber culturing industry in Fujian Province. *J. Fujian Fish.* (2013). (in Chinese with an English abstract).
45. Fei, G. et al. Effect of water temperature on digestive enzyme activity and gut mass in sea cucumber *Apostichopus japonicus* (Selenka), with special reference to aestivation. *J. Oceanol. Limnol.* 27(4), 714–722 (2009).
46. Han, C., Lin, P. et al. A study on key technique of *Stichopus japonicus* Selenka farming in southern sea area. *Mod. Fish. Inf.* (2011). (in Chinese with an English abstract).
47. Chang, Y., Wang, Z. & Wang, G. Effect of temperature and algae on feeding and growth in sea urchin, *Strongylocentrotus intermedius*. *J. Fish. China.* (1997). (in Chinese with an English abstract).
48. Lawrence, J. et al. Temperature effect of feed consumption, absorption, and assimilation efficiencies and production of the sea urchin *Strongylocentrotus intermedius*. *J. Shellfish Res.* 28, 389–395 (2009).
49. Zhao, C. et al. Effects of temperature and feeding regime on food consumption, growth, gonad production and quality of the sea urchin *Strongylocentrotus intermedius*. *J. Mar. Biol. Assoc.* 96(1), 185–193 (2015).
50. Lawrence, J., Zhao, C. & Chang, Y. Large-scale production of sea urchin (*Strongylocentrotus intermedius*) seed in a hatchery in China. *Aquac. Int.* 27(1), 1–7 (2019).
51. Chang, Y. et al. Aquaculture of *Strongylocentrotus intermedius* in Fujian coastal areas. *South China Fish. Sci.* 16(3), 1–9 (2020).
52. Yu, Z. Raft culture technique of sea urchin in south China. *China Fish.* 376(003), 57–57 (2007) (in Chinese).

**Acknowledgements**

This work was supported by the National Natural Science Foundation of China (41506177), A research project for marine economy development in Liaoning province (for Jun Ding), High-level talent support grant for innovation in Dalian (2020RD03), Liaoning Province “Xingliao Talents Plan” project (XLYC2002107), Key Special Project for Introduced Talents Team of Southern Marine Science and Engineering Guangdong Laboratory (GML2019ZD0402). We appreciate Wei Tang for her editorial suggestions.

**Author contributions**

Sun J, Zhao C, Yin D and Chang Y conceived and designed the study. Sun J, Yu Y and Zhao Z analyzed the data and prepared figures. Sun J and Zhao C drafted the manuscript. All authors gave final approval for publication.

**Competing interests**

The authors declare no competing interests.

**Additional information**

**Correspondence** and requests for materials should be addressed to Y.C. or C.Z.

**Reprints and permissions information** is available at www.nature.com/reprints.

**Publisher’s note** Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

**Open Access** This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit http://creativecommons.org/licenses/by/4.0/.

© The Author(s) 2022