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Prediction of potential habitats and distribution of the marine invasive sea squirt, *Herdmania momus*

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Abstract: The influx of marine exotic and alien species is disrupting marine ecosystems and aquaculture. *Herdmania momus*, reported as an invasive species, is distributed all along the coast of Jeju Island and has been confirmed to be distributed and spread to Busan. The potential habitats and distribution of *H. momus* were estimated using the maximum entropy (MaxEnt) model, quantum geographic information system (QGIS), and Bio-ocean rasters for analysis of climate and environment (Bio-ORACLE), which can predict the distribution and spread based only on species occurrence data using species distribution model (SDM). Temperature and salinity were selected as environmental variables based on previous literature. Additionally, two different representative concentration pathway (RCP) scenarios (RCP 4.5 and RCP 8.5) were set up to estimate future and potential habitats owing to climate change. The prediction of potential habitats and distribution for *H. momus* using MaxEnt confirmed maximum temperature as the highest contributor (77.1%), and mean salinity, the lowest (0%). And the potential habitats and distribution of *H. momus* were the highest on Jeju Island, and no potential habitat or distribution was seen in the Yellow Sea. Different RCP scenarios showed that at RCP 4.5, *H. momus* would be distributed along the coast of Jeju Island in the year 2050 and that the distribution would expand to parts of the Korea Strait by the year 2100. RCP 8.5, the distribution in 2050 is predicted to be similar to that at RCP 4.5; however, by 2100, the distribution is predicted to expand to parts of the Korea Strait and the East Sea. This study can be utilized as basic data to effectively control the ecological injuries by *H. momus* by predicting its spread and distribution both at present and in the future.

Keywords: *Herdmania momus*, prediction, distribution, MaxEnt, RCP scenarios

INTRODUCTION

Marine invertebrates have shown high invasion rates in recent times (Lee *et al.* 2008; Robinson *et al.* 2011; Capinha *et al.* 2012), and have been increasing exponentially owing to human activities such as trade and aquaculture, thereby disrupting native ecosystems (Kerckhof *et al.* 2007; Meyerson and Mooney 2007; Vander Zanden *et al.* 2010). However, accurate field surveys are not available because of the wide range of oceanic characteristics and depths in the ocean, and it is difficult to accurately determine their distribution through direct field surveys (Kaschner *et al.* 2006; Valavanis *et al.* 2008; Franklin 2010). Also, owing to limited data availability and gathering of new collection data, characterization of the distribution and spread of these invasive species is problematic (Valavanis *et al.* 2008; Franklin 2010). These short-comings have been overcome with the development of tools such as GIS (Geographic Information System), SDMs (Species Distribution Model) that would provide information on marine ecosystems. These tools have enabled several studies on the distribution and prediction of various marine species such as fish, jellyfish, coral, crabs, and algae, including marine invasive species of tunicates (Maravelias and Reid 1997; Guinotte *et al.* 2006; Graham *et al.* 2007; Tittensor *et al.* 2009; Comptom *et al.* 2010; de Rivera *et al.* 2011; Tyberghein *et al.* 2012; Januario *et al.* 2015; Assis *et al.* 2018). SDMs are currently used to predict geographic distributions (Elith and Leathwick 2009). They are also used for biodiversity assessment, habitat restoration, and risk assessment of invasive species on land, freshwater, and marine ecosystems (Elith *et al.* 2006; Kwon *et al.* 2012; Lee *et al.* 2016). In addition, the development of GIS has led to the further expansion of species distribution prediction methods (Foody 2008; Swenson 2008).

Recently, the maximum entropy (MaxEnt) model using presence only data of species has been used frequently. With the ability to predict the distribution of wild animals, plants and marine organisms even in the absence of sufficient data, this is presently a commonly used model not only in South Korea (Seo 2008; Park 2018) but also globally (Elith *et al.* 2006; Hernandez *et al.* 2006; Phillips *et al.* 2006; Wisz *et al.* 2008; Elith *et al.* 2011; Merow *et al.* 2013). Many recent studies have utilized the MaxEnt model (Radosavljevic and Anderson 2014) and more than 1,000 studies have been published since 2006, because of the advantages of accurate prediction of species distribution and easy programing features (Merow *et al.* 2013). Research on the distribution and spread of invasive species in Korea and abroad is being actively conducted on terrestrial organisms (Cho *et al.* 2015; Park *et al.* 2017); however, marine foreign species are not being investigated to the same extent (Robinson *et al.* 2011; Park *et al.* 2018).

One of the marine invasive sea squirts, *Herdmania momus*, belonging to the class Ascidiacea and phylum Chordata, is a solitary ascidian and is distributed in tropical and temperate regions with the exception of the Eastern Pacific and Eastern Atlantic oceans (Kott 2005). *Herdmania momus* is known as an invasive species that migrated from the Red Sea to the Mediterranean Sea when the Suez Canal was opened (Shenkar and Loya 2008). In Korea, this alien species was first reported from Seogwipo in 1969 (Rho 1971), and was expected to compete with seashells and abalone that feed on algae and damage the aquaculture industry on Jeju Island (Yi and Kim 2016). Furthermore, it has been confirmed recently that *H. momus* was usually distributed in depth of 9-10 m, spread all over Jeju Island and distributed in Busan (Shin *et al.* 2013; Park 2019). Owing to rapid development and growth rates, *H. momus* is expected to increase the pace and widen the range of distribution. In Korea, studies on the spread and distribution of *H. momus* are insufficient, and there are no studies to predict its spread of distribution (Park 2019). This study is based on the MaxEnt model, which can predict the distribution of species using only presence information (Phillips *et al.* 2006, 2017), and QGIS was used to prepare the main map of *H. momus* and predict its potential habitats and distribution (QGIS Development Team 2018). Marine invasive species were known to be affected and distributed by rising temperatures due to climate change (Raitsos *et al.* 2010). Therefore, two different RCP scenarios, RCP 4.5 and RCP 8.5, were set to predict the potential habitats and distribution of *H. momus* for the future. Thus, this study was conducted to provide basic data on the distribution of *H. momus* and control of domestic marine ecosystems by predicting the spread and distribution of *H. momus* owing to climate change caused by a rise in temperatures.

MATERIALS AND METHODS

Collections of *H. momus* were done from 2010 to 2018 to check its occurrence status from a total 81 harbors: 33 harbors in the East Sea, 18 harbors in the South Sea, 14 harbors in the Yellow Sea and 16 harbors in the Jeju Island. The list of the harbors with geographical coordination was shown in appendix 1. However, *H. momus* samples were collected only from several harbors on Jeju Island and at Busan (Fig. 1, Table 1).

Ascidians belonging to the phylum Chordata are known to be affected by temperature and salinity (Thiyagarajan and Qian 2003; Tyberghein *et al.* 2012; Januario *et al.* 2015; Kim *et al.* 2019). Based on the experimental results of egg development of *H. momus* (Park 2019), salinity (psu) and temperature (°C) were selected as environmental variables (Table 2). The data for environmental variables such as maximum temperature, average temperature, lowest temperature, highest salinity, average salinity, and lowest salinity were obtained from the Bio-ORACLE database (Tyberghein *et al.* 2012). Remotely sensed data were tak-

Table 1. Collected sites of *Herdmania momus* in Korea

Region	Site	GPS	Year						
			2010	2011	2012	2014	2015	2016	2018
Jeju-do	Jeju	33°31′16,01″N, 126°32′13,60″E	+				+	+	+
	Jocheon	33°32′31.23″N, 126°38′02.02″E				+	+	+	+
	Gimnyeong	33°33′30.98″N, 126°44′12.86″E			+			+	+
	Jongdal	33°29′48.56″N, 126°54′40.83″E			+		+	+	+
	Seongsanpo	33°13′30.98″N, 126°55′30.96″E		+		+	+	+	+
	Pyoseon	33°19′32.17″N, 126°50′47.18″E						+	+
	Wimi	33°16′16.23″N, 126°39′42.55″E					+	+	+
	Seogwipo	33°14′23.23″N, 126°33′42.20″E	+	+	+	+	+	+	+
	Munseom	33°13′30.98″N, 126°33′57.92″E	+						+
	Moseulpo	33°12′58.75″N, 126°15′02.91″E					+	+	+
	Hanrim	33°24′45.79″N, 126°15′21.09″E			+	+	+	+	+
	Ongpo	33°28′05.76″N, 126°19′24.20″E			+	+	+	+	+
	Aewol	33°30′30.54″N, 126°27′55.46″E		+			+	+	+
	Dodu	33°24′15.91″N, 126°14′57.94″E					+	+	+
Busan	Sinseondae	35°06′03.66″N, 129°05′39.45″E							+
	Passaenger terminal	35°05′54.74″N, 129°02′18.45″E							+

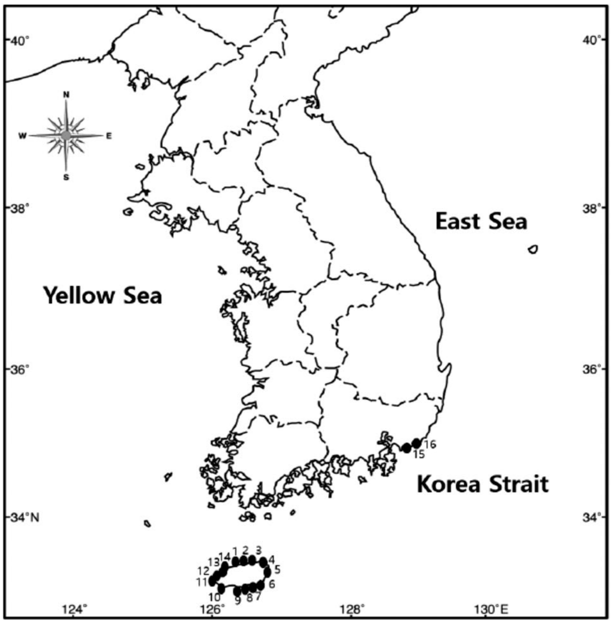

Fig. 1. A map showing the presence sites of *Herdmania momus* in Korea. 1. Jeju, 2. Jocheon, 3. Gimnyeong, 4. Jongdal, 5. Seongsanpo, 6. Pyoseon, 7. Wimi, 8. Seogwipo, 9. Munseom, 10. Mosulpo, 11. Hanrim, 12. Ongpo, 13. Aewol, 14. Dodu. 15. Passenger terminal, Busan, 16. Sinseondae, Busan.

Table 2. Environmental variables used in this study

No.	Environmental variables	Unit
1	Temperature (max)	°C
2	Temperature (mean)	
3	Temperauture (min)	
4	Salinity (max)	psu
5	Salinity (mean)	
6	Salinity (min)	

en from various ocean-observing satellite sensors. The monthly satellite data was used (Aqua-MODIS, http://oceancolor.gsfc.nasa.gov/ for sea surface temperature; WOD09, Boyer *et al.* 2009 for Salinity) from 2010 to 2018 at a 5 arcmin (c. 9.2 km) spatial resolution (Tyberghein *et al.* 2012). 10-fold cross-validation was performed to increase the reliability of the model, and the Jackknife technique was used to identify the importance of environmental variables. All analyses used linear and quadratic features (other MaxEnt settings at their default value). The number of iterations was increased to 5,000 for model accuracy. Distribution maps were created using QGIS (version 2.18.16; QGIS Development Team 2018), and the MaxEnt program (version 3.4.1; Phillips *et al.* 2006, 2017) was used. Furthermore, two different RCP scenarios, RCP 4.5 (if most of greenhouse gas reduction policies were implemented) and RCP 8.5 (Extreme emissions scenario

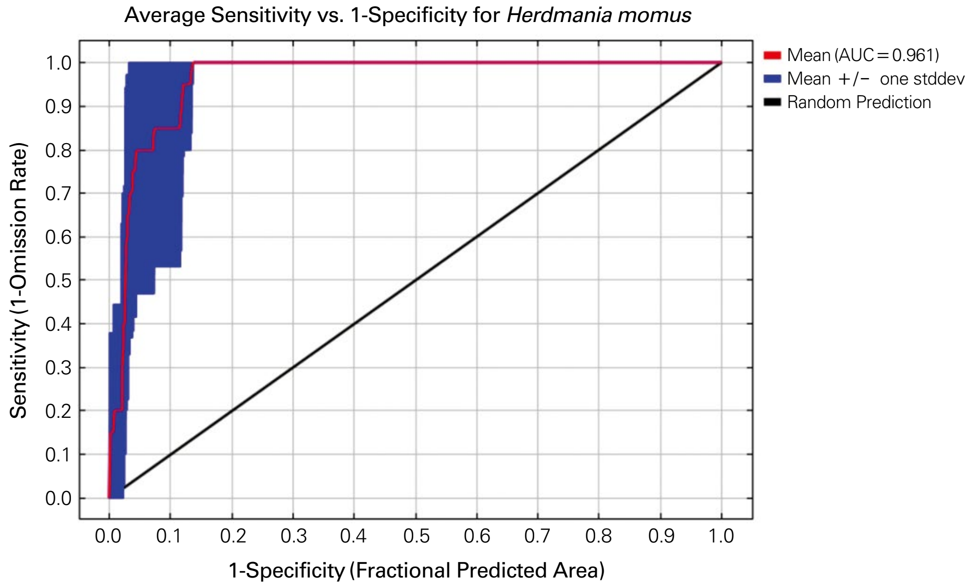

Fig. 2. Area under curve (AUC) obtained in the receiver operating characteristic (ROC) curve with the species distribution model of *Herdmania momus.*

of greenhouse gases) were established for 2050 and 2100 (Stocker *et al.* 2013) for the prediction of potential future habitats and distribution of *H. momus.*

RESULTS

The results of the analysis using MaxEnt model show that area under curve (AUC) of the receiver operating characteristics (ROC) curve was 0.961 (Fig. 2), indicating that this predictive model shows high performance (Franklin 2010). Maximum temperature contributed the highest (77.1%) to potential habitats and distribution of *H. momus* at with a permutation importance index of 0.3%, and the lowest contribution (0.0%) was from the average salinity. Contributions of average and minimum temperatures were 9.7 and 9.2%, respectively, with permutation importance indexes of 21.3 and 75.2%, respectively. The maximum and minimum salinities contributed 1.6 and 2.4%, respectively, to the model with permutation importance indexes of 1.0 and 2.2%, respectively (Table 3). The permutation importance Jackknife analysis showed that the minimum, average, and maximum temperatures had considerably affected on distribution, and the highest salinity was also considered to be an important factor of distribution (Fig. 3). In addition, habitat distribution increased with increasing temperature, and the distribution was estimated to decrease when the salinity was beyond the optimum range in the response curve analysis (Fig. 4). According to the results of the prediction, the spread and distribution of the domestic *H. momus* are predicted to be most affected by temperature and salinity, which is consistent with the results reported for a sea squirt, *Ciona robusta* (Park 2019). Experimental results of the distribution and spread of *H. momus*, belonging to the same phylum as *C. robusta*, also showed temperature as the most influential environmental factor, and salinity was also reported as an important factor (Januario *et al.* 2015), which is consistent with the results of this study. The results of the present study indicate that the spread and distribution of *H. momus* were limited by temperature and salinity. Considering the annual salinity fluctuations of the East Sea (32–34 psu), the South Sea (31–34 psu) and the West Sea (28–32 psu), the salinity

Table 3. Analysis of percent contribution and permutation importance of environmental variables for the prediction of potential habitats of *Herdmania momus*

Environmental variables	Percent contribution (%)			Permutation importance		
	Max	Mean	Min	Max	Mean	Min
Temperature	77.1	9.7	9.2	0.3	21.3	75.2
Salinity	1.6	0.0	2.4	1.0	0.0	2.2

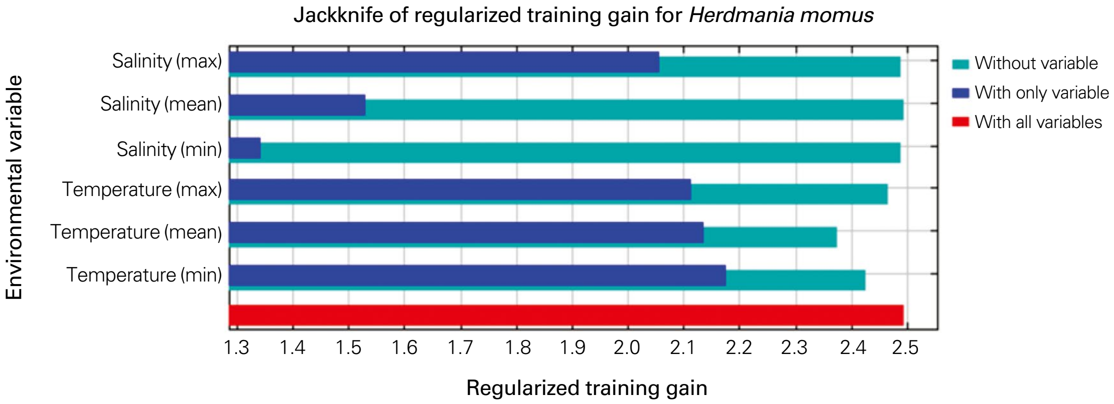

Fig. 3. Jackknife test of *Herdmania momus* in this study.

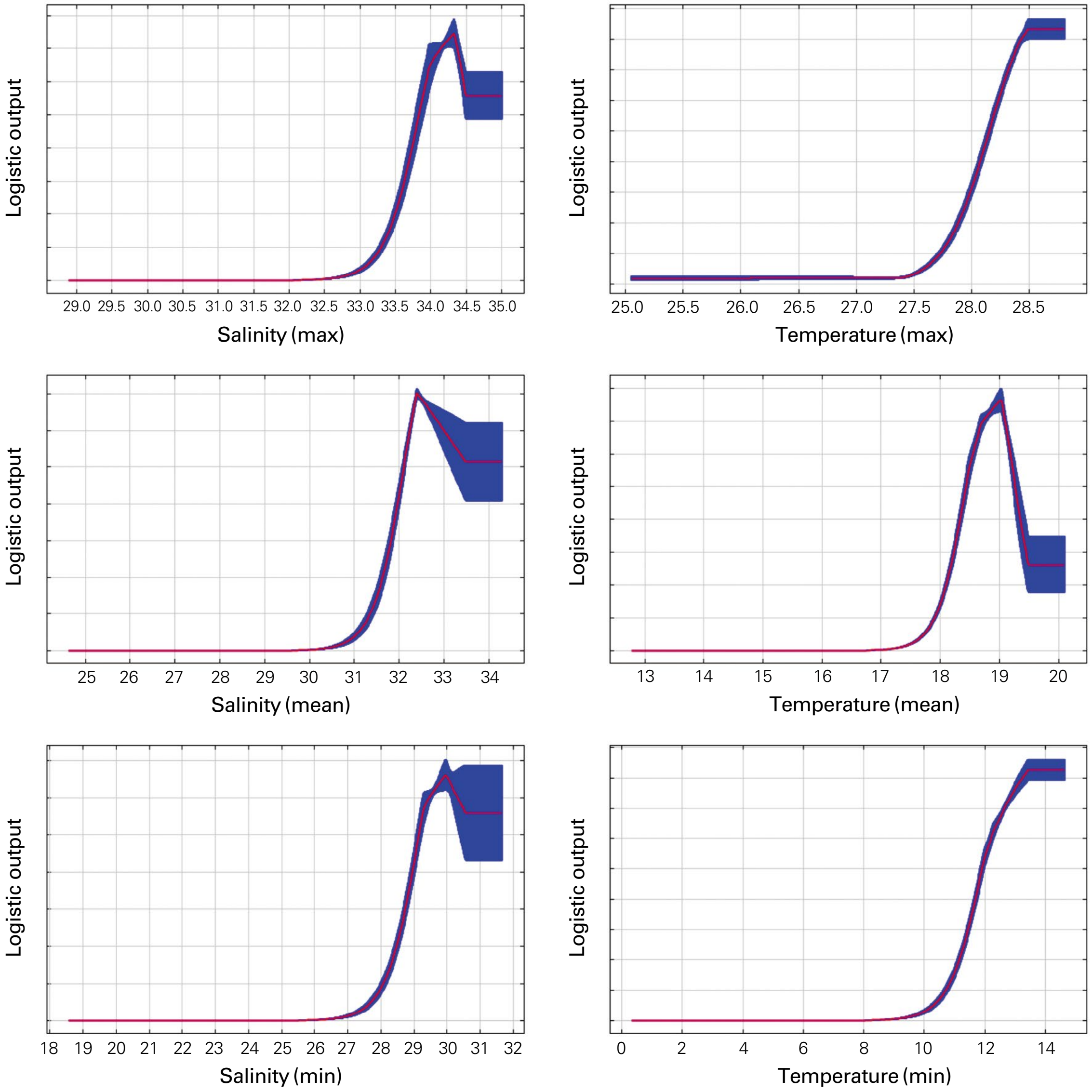

Fig. 4. Response curves of *Herdmania momus* for selected environmental variables.

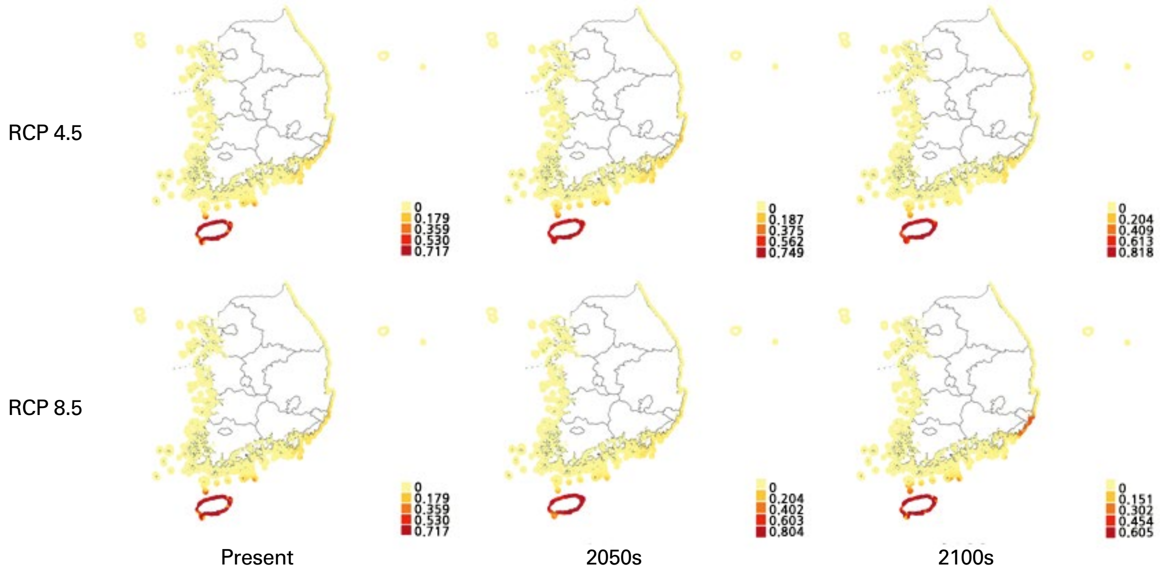

Fig. 5. Potential habitats and distribution of *Herdmania momus* predicted by RCP scenarios.

conditions of the Yellow Sea are not suitable for the distribution and spread of *H. momus*.

DISCUSSION

The results of this study showed that the spread of *H. momus* was influenced by temperature and salinity, and it was especially affected by temperature. In particular, the change of max temperature by climate change showed major influence of their spread and distribution, and the change of the average and minimum temperatures is considered as the sensitive factors. According to the results of the model, the distribution of *H. momus* in the RCP 4.5 and 8.5 scenarios by 2050 and in the RCP 4.5 scenario by 2100 along the entire coasts of Jeju Island and the South Sea was shown to be similar to that observed at present. However, in the RCP 8.5 scenario, the distribution would be further extended to the entire coastal areas of Jeju Island and the South Sea in 2100, and would spread further, especially to the coast of the East Sea. Since the spread of *H. momus* is expected to increase economic damage including that to aquaculture and marine industries, long-term monitoring of *H. momus* in the South Sea and East Sea, centered on the Busan area, is a priority.

As climate change continues, the distribution and spread of *H. momus* is expected to increase economic damage, including damages to aquaculture and marine industries. The environmental variables used in this study were limited to temperature and salinity based on experiments on egg development and settlement of *H. momus* (Park 2019). However, chemical and physical variables such as pH, dissolved oxygen, nitrate, phosphate, chlorophyll, cloud cover etc. are considered as major environmental factors (Tyberghein *et al.* 2012). Therefore, to predict potential habitats and distribution more accurately, modeling with salinity and temperature, as well as other environmental variables should be performed. The results of this study showed the potential of spread of the *H. momus* by climate change, and are expected to be used as basic data for predicting the distribution of *H. momus*. To achieve effective management and prevention of damages, the continuous field survey and monitoring are required.

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Appendix 1. The list of the 81 harbors with geographical coordination selected for this study

Region	No.	Site	Geographical coordination
East Sea	1	Songjeong	35°10'50.2"N 129°12'22.4"E
	2	Daebyeon	35°13'26.3"N 129°13'39.6"E
	3	Jangsangpo	35°30'05.8"N 129°22'33.4"E
	4	Ulsan	35°30'40.2"N 129°23'10.2"E
	5	Bangeojin	35°28'54.7"N 129°25'51.5"E
	6	Gampo	35°48'19.1"N 129°30'12.4"E
	7	Yangpo	35°52'40.9"N 129°31'13.1"E
	8	Guryoungpo	35°59'02.9"N 129°33'15.1"E
	9	Ganggu	36°21'33.2"N 129°23'22.8"E
	10	Chuksan	36°30'29.6"N 129°26'50.1"E
	11	Hupo	36°40'50.0"N 129°27'19.6"E
	12	Hyeonnae	36°59'25.8"N 129°24'57.8"E
	13	Jukbyeon	37°03'18.4"N 129°25'27.3"E
	14	Imwon	37°13'41.3"N 129°20'35.6"E
	15	Sinnam	37°15'57.0"N 129°19'39.0"E
	16	Jangho	37°17'13.9"N 129°18'57.9"E
	17	Chogok	37°18'35.8"N 129°17'37.2"E
	18	Donghae	37°29'22.2"N 129°07'35.3"E
	19	Mukho	37°33'05.5"N 129°06'50.8"E
	20	Eodal	37°33'41.5"N 129°07'12.3"E
	21	Daejin (Donghae city)	37°34'51.2"N 129°06'46.2"E
	22	Gangneung	37°46'20.1"N 128°57'06.9"E
	23	Sacheon	37°50'14.3"N 128°52'35.5"E
	24	Jumunjin	37°53'39.2"N 128°49'57.8"E
	25	Namae	37°56'37.3"N 128°47'10.1"E
	26	Gisamun	38°00'28.9"N 128°43'50.2"E
	27	Mulchi	38°09'18.1"N 128°36'34.9"E
	28	Jangsa	38°13'35.4"N 128°35'20.1"E
	29	Ayajin	38°16'23.9"N 128°33'22.1"E
	30	Gonghyeonjin	38°21'15.1"N 128°30'43.5"E
	31	Geojin	38°26'55.2"N 128°27'41.1"E
	32	Chodo	38°29'08.9"N 128°26'19.3"E
	33	Daejin (Goseong-gun)	38°30'03.9"N 128°25'30.4"E
South Sea	34	Guemno	34°27'12.7"N 126°07'06.7"E
	35	Jindo	34°21'52.0"N 126°08'08.4"E
	36	Byeokpa	34°32'22.8"N 126°20'46.8"E
	37	Wando	34°18'56.5"N 126°45'31.8"E
	38	Nokdong	34°31'42.7"N 127°07'41.1"E
	39	Dolsan	34°36'52.0"N 127°43'18.4"E
	40	Gukdong	34°43'44.9"N 127°43'31.7"E
	41	Gwangyang	34°55'24.3"N 127°41'48.1"E
	42	Noryang	34°56'52.0"N 127°51'40.1"E
	43	Mijo	34°42'33.9"N 128°02'48.1"E
	44	Samcheonpo	34°55'33.2"N 128°05'13.5"E
	45	Samdeok	34°47'40.7"N 128°22'59.2"E
	46	Tongyeong	34°49'38.1"N 128°26'07.0"E
	47	Gujora	34°48'17.3"N 128°41'45.5"E
	48	Jangseungpo	34°51'51.5"N 128°43'26.9"E

Appendix 1. Continued

Region	No.	Site	Geographical coordination
South Sea	49	Dadaepo	35°03'18.4"N 128°58'22.2"E
	50	Busan port	35°05'58.5"N 129°02'18.7"E
	51	Mipo	35°09'28.8"N 129°10'16.0"E
Yellow Sea	52	Incheon port	37°27'38.3"N 126°37'32.3"E
	53	Ulwangri	37°26'23.8"N 126°22'34.6"E
	54	Jamjindo	37°24'59.8"N 126°24'55.3"E
	55	Tando	37°11'25.4"N 126°38'46.8"E
	56	Hongwon	36°09'26.8"N 126°30'03.3"E
	57	Maryang	36°08'01.0"N 126°30'12.4"E
	58	Gunsan	35°58'46.7"N 126°37'45.9"E
	59	Bieung	35°56'06.6"N 126°31'39.0"E
	60	Garyeok	35°43'37.4"N 126°31'44.7"E
	61	Gyeokpo	35°37'19.4"N 126°28'08.8"E
	62	Gomso	35°35'08.7"N 126°36'18.8"E
	63	Gyeoma	35°23'37.7"N 126°24'18.5"E
	64	Beopseongpo	35°21'39.9"N 126°26'24.7"E
	65	Mokpo	34°47'00.9"N 126°23'19.3"E
Jeju Island	66	Jeju port	33°31'13.2"N 126°32'03.3"E
	67	Jocheon	33°32'26.3"N 126°38'07.5"E
	68	Bukchon	33°33'01.9"N 126°41'39.7"E
	69	Gimnyeong	33°33'31.6"N 126°44'14.6"E
	70	Jongdal	33°29'47.4"N 126°54'44.0"E
	71	Seongsanpo	33°28'18.3"N 126°55'46.5"E
	72	Sincheon	33°20'28.5"N 126°51'26.0"E
	73	Pyoseon	33°19'32.7"N 126°50'45.2"E
	74	Wimi	33°16'14.1"N 126°39'44.8"E
	75	Seogwipo	33°14'25.8"N 126°33'34.2"E
	76	Munseom	33°13'38.4"N 126°34'05.0"E
	77	Moseulpo	33°13'01.7"N 126°14'57.5"E
	78	Hanrim	33°25'05.5"N 126°15'43.5"E
	79	Ongpo	33°24'15.1"N 126°15'02.2"E
	80	Aewol	33°28'01.5"N 126°19'19.4"E
	81	Dodu	33°30'29.7"N 126°27'55.7"E