Improvement of an aquaculture site-selection model for Japanese kelp (*Saccharina japonica*) in southern Hokkaido, Japan: An application for the impacts of climate events

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Abstract

Japanese kelp (*Saccharina japonica*) is one of the most valuable cultured and harvested kelp species in Japan. In this study, we added a physical parameter, sea surface nitrate (SSN) estimated from satellite remote sensing data, to develop a suitable aquaculture site-selection model (SASSM) for hanging cultures of Japanese kelp in southern Hokkaido, Japan. The local algorithm to estimate SSN was developed using satellite measurements of sea surface temperature and chlorophyll-a. We found a high correlation between satellite- and ship-measured data (r^2 = 0.87, RMSE = 1.39). Multi-criteria evaluation was adapted to the SASSM to rank sites on a scale of 1 (least suitable) to 8 (most suitable). We found that 64.4% of the areas were suitable (score above 7). Minamikayabe was identified as the most suitable area, and Funka Bay also contained potential aquaculture sites. In addition, we examined the impact of El Niño/La Niña–Southern Oscillation (ENSO) events on Japanese kelp aquaculture and site suitability from 2003 to 2010. During El Niño events, the number of suitable areas (scores 7 and 8) decreased significantly, indicating that climatic conditions should be considered for future development of marine aquaculture.

Keywords: ENSO, Japanese kelp, SASSM, satellite remote sensing, sea surface nitrate.

1. Introduction

Approximately 37 species of kelp grow in coastal areas of Japan (Yotsukura, 2010). One of the most important is Japanese kelp (*Saccharina japonica*, preciously *Laminaria japonica*). This native kelp is mainly distributed in southern Hokkaido (Ozaki *et al*., 2001), where it plays a key economic role in coastal communities. Wild harvest has dominated the production of Japanese kelp in Hokkaido (FAO, 2009). However, wild harvest has recently declined from about 30,000 dry tons per year in the 1970s to 14,587 tons in 2009 (Yotsukura, 2010). At the same time, as technology has improved, aquaculture production of Japanese kelp has gradually increased.

Because most aquaculture sites are in coastal areas (water depth < 60 m), aquaculture development can be influenced by many factors such as limited suitable areas, multi-use conflicts with other species, environment and climate changes, and impacts of human activities. Understanding the ecology and distribution of foundation species is vital for conservation and coastal management and development (Daniel *et al*., 2012). Geographic information systems (GIS) and satellite remote sensing technology have been widely used in the development of aquaculture and suitable aquaculture site-selection models (SASSM). Some studies have used SASSM to investigate suitable sites for Japanese kelp aquaculture (Radiarta *et al*., 2011). However, those models did not consider the nutrient conditions, specifically, nitrate (NO_3) conditions. Many studies have indicated that NO_3 can be an important factor in the growth and maturation of kelp (e.g., Deysher and Dean, 1986; Mizuta and Maita, 1991; Grant *et al*., 1998; Gao *et al*., 2012), but obtaining NO_3 data remains difficult. The resolution of NO_3 data obtained from conventional shipboard techniques is

inadequate for regular monitoring over large spatial scales. Satellites are an effective in providing spatial and temporal data. Unfortunately, NO_3 cannot be directly measured from space. However, the close relationship of NO_3 with sea surface temperature (SST) and chlorophyll-*a* (Chl-*a*), which can both be measured using satellite remote sensing, could be utilized to estimate NO_3 and extend the resolution of shipboard NO_3 estimates (Goes *et al*., 1999).

The objectives of this study were to 1) develop local algorithms to estimate sea surface nitrogen (SSN) from remote sensing data in the waters of southern Hokkaido, 2) include the new physical parameter SSN to develop a more accurate SASSM and identify the most suitable areas for Japanese kelp aquaculture, and 3) examine the potential impact of climate change on the development of Japanese kelp aquaculture.

2. Material and methods

Study area

The study area was the coastal waters of southern Hokkaido in northern Japan, including Funka Bay and the Tsugaru Strait. This area lies between 41˚40'–42˚10'N and 140˚40'–141˚10'E, with mean and maximum depths of 38 m and 107 m, respectively (Fig. 1A). The main Japanese kelp aquaculture area is along the coastline from Shikabe to Hakodate, Hokkaido (Fig. 1C).

The southern Hokkaido water region, especially Funka Bay, is affected by the coastal Oyashio Current and the Tsugaru Warm Current (TWC) (Ohtani, 1971, 1987; Isoda and Hasegawa, 1997; Takahashi *et al*., 2005). Warm, saline water occupies Funka Bay from

October to December, whereas cold, low-salinity water is usually present from March to May. The cold, low salinity water comes from coastal Oyashio water, which sometimes flows into Funka Bay on the southwest coast in winter and spring (Kono *et al*., 2004). The water in Funka Bay is replaced twice a year, and each replacement takes about 2 months (Miyake *et al*., 1988). These unique characteristics provide favorable environmental conditions for aquaculture activities (Radiarta *et al*., 2011). On the basis of city administrative boundaries, the aquaculture regions in this water area are divided into six zones.

Satellite data and processing

The data sources used included SST, Chl-*a* concentration, and suspended solid (SS) concentration, which were derived from the Moderate-Resolution Imaging Spectroradiometer (MODIS) and Sea-Viewing Wide Field-of-View Sensor (SeaWiFS) as level-2 data with 1-km resolution. The 2012.0 MODIS-Aqua reprocessing was completed in May 2012. This study used the new version (R2012.0) of daily data from January 2003 to May 2012. The data were obtained from the Distributed Active Archive Centers (DAAC), Goddard Space Flight Center (GSFC), National Aeronautics and Space Administration (NASA). Monthly averages of ${}_{n}L_{w}$ (555) images were used to calculate SS images based on Ahn *et al.*'s (2001) algorithm.

Advanced Land Observing Satellite (ALOS) Advanced Visible and Near-Infrared Radiometer type-2 (AVNIR-2) images acquired on 5 Nov. 2009, 5 Oct. 2010, and 7 Dec. 2010 with 10-m resolution were downloaded from the ALOS User Interface Gateway (AUIG) website (https://auig.eoc.jaxa.jp/auigs/en/top/index.html) as level 1B2G (geo-coded data).

These data were used for extracting social-infrastructural and constraint data, such as harbors, town/industrial areas, and river mouths.

The bathymetry data were obtained from the Japan Oceanographic Data Center (JODC) and were integrated and gridded at 150-m intervals.

To process the remotely sensed data, this study used the SeaWiFS Data Analysis System (SeaDAS) 6.2 and ERDAS imagine 9.3. SeaDAS is a comprehensive image analysis package for processing, displaying, analyzing, and quality controlling ocean color data. The package was developed by GSFC/NASA and is operated in the Linux system. ERDAS Imagine is a remote sensing application with raster graphic editor capabilities that was designed for geospatial applications. The GIS and modeling software used in this study was ArcGIS 10.0, which was developed by the Environmental System Research Institute (ESRI, USA). ERDAS Imagine 9.3 and ArcGIS 10.0 use the Windows XP platform.

Shipboard data

Shipboard data were obtained during 15 cruises on the T/S *Oshoro-Maru* and R/V *Ushio-Maru* (Hokkaido University) between April 2010 and January 2012 (Table 1). Optical measurements, conductivity-temperature-depth (CTD) measurements, and water sampling were conducted at 33 stations in Funka Bay and 14 stations in the Tsugaru Strait (Fig. 1B). Water samples for Chl-*a* were analyzed using a Turner fluorometer. Concentrations of NO_3 were measured using a QuAAtro segmented flow analyzer and calibrated using reference material from the KANSO Company (http://www.kanso.co.jp/eng/index.html) for nutrients in seawater (RMNS).

133

134 **Estimating SSN from space**

135 Although a very linear relationship may exist between NO_3 and seawater temperature (T)
136 based on T–N relationships (Kamykowshi and Zentara, 1986; Chavez and Service, 1996),
137 phytoplankton nitrate uptake also has a significant impact on T–N relationships (Goes *et al*.,
138 2000). Therefore, we used T and Chl-*a* as the predictor variables to estimate SSN from space.
139 In this study, shipboard data from different cruises were pooled. The data set was restricted to
140 surface water samples. The relationships between NO_3 and its predictor variables were
141 examined using the statistical, step-wise linear regression fitting routine of JMP software
142 (SAS Institute). The post-processing of the output SSN data was conducted using
143 image-smoothing technology to remove noise from images. All raster images were smoothed
144 using the Neighborhood Analysis tool (3 × 3 pixels, mean filter type) of ArcGIS software.

145

146 **GIS model construction**

147 This study added the physical parameter, SSN, to develop a more accurate SASSM for
148 Japanese kelp in southern Hokkaido. Parameter values were ranked and classified into eight
149 levels following Radiarta *et al*. (2011). Suitable levels (scores) for SSN parameters were
150 defined according to the relationship between nitrate uptakes and nitrate concentrations for
151 discs from *Saccharina japonica* followed by Michaelis–Menten kinetics (Mizuta, 2003; Ozaki
152 *et al*., 2001). Nitrate concentrations were determined according to half-saturated concentration
153 (K_m) (Parsons *et al*., 1984) and the maximum uptake rate (V_{max}) (Wilkinson, 1961). Based on
154 Ozaki *et al*.'s (2001) results, K_m = 1.7 μM, V_{max} = 1.2 μgN/cm^2/h and K_m = 3.3 μM, V_{max} =

155 1.0 μgN/cm^2/h for the median and marginal parts of *Saccharina japonica*, respectively, were
156 used in this study. The area ratio of the median and marginal parts of the spores of *Saccharina*
157 *japonica* was 1:2; therefore, the final results of K_m = 2.23 μM and V_{max} = 1.17μgN/cm^2/h
158 were obtained by averaging each part and multiplying by the area ratio. NO_3 concentrations
159 were ranked and classified from 1 (least suitable) to 8 (most suitable) by calculations from
160 nitrate uptake rates at 0.146 μgN/cm^2/h (Table 2).

161 Figure 2 shows the schematic framework for the Japanese kelp SASSM. The GIS model
162 was formed by three sub-models including the biophysical model (SST, SS, SSN, bathymetry,
163 and slope), social-infrastructural model (distance to a town or city, pier and land-based
164 facilities), and constraints model (harbor, area near town, and river mouth). Parameter weights
165 were determined by pairwise comparisons according to the analytical hierarchy process for
166 decision making (Saaty, 1977). The kelp productions of each zone were used to verify the
167 model. Finally, to model the potential impact of climate variation on kelp aquaculture, we
168 analyzed years with different climatology (El Niño and normal years) during 2003 to 2010.

169

170 **3. Results**

171 **Local algorithm for SSN development**

172 Some studies have estimated SSN in the Pacific using satellite-observed data (Goes *et al*.,
173 1999; Switzer *et al*., 2003). However, few studies have focused on the regional scale,
174 especially Funka Bay, Japan. We developed local algorithms to examine variations in SSN as
175 a function of SST and Chl-*a* in the waters of southern Hokkaido. Before the calculations, we
176 verified the accuracy of the predictors from the satellite remote sensing data. Comparison of

the MODIS data and *in situ* data showed a strong relationship between satellite- and ship-observed SSTs, with a coefficient of determination (r^2) of 0.96 (Fig. 3A). Figure 3B presents a comparison of satellite Chl-*a* and *in situ* measurements. Although some satellite-derived Chl-*a* values were over- or underestimated compared to *in situ* measurements, the correlation between both parameters was statistically significant ($r^2 = 0.62$, $p < 0.001$, $n = 124$). These relationships indicated that the satellite data provide reasonable SST and Chl-*a* for this region. When the statistical fitting procedure was applied, the relationship could be described by the following equation:

$$SSN=18.302-1.629(T)+0.036(T)^2-2.045(\text{Chl-}a)+0.041(\text{Chl-}a)^2 \quad (1)$$

Also, we compared the new local SSN algorithm for Funka Bay with Goes *et al.*'s (1999) results, which developed a NO_3 predictive algorithm for the coast of Sanriku, northeast Japan, using similar methods. From the results of Goes *et al.*'s (1999) algorithm for Funka Bay, Fig. 4A shows that predictions of SSN based solely on T may not be appropriate, as the r^2 of the relationship between shipboard and satellite-estimated SSN was only about 0.16, and the root mean square error (RMSE) of the predicted SSN was 5.90. The addition of Chl-*a* led to a statistically significant increase in the value of r^2 to 0.82, whereas the RMSE decreased to 2.38. But most of the predicted SSN values were overestimates compared with shipboard data (Fig. 4B). Therefore, we tested the newly developed SSN algorithm in Funka Bay, and the results showed a significant relationship between shipboard and satellite-estimated SSN ($r^2 = 0.87$, RMSE = 1.39) (Fig. 4C).

199

200 **Verification and seasonal variability in the predicted SSN**

201 Using the developed local algorithm, we generated 113 predicted monthly SSN maps (from
202 January 2003 to May 2012). To reflect the spatial distribution of predicted SSN
203 concentrations in the coastal waters of southern Hokkaido, the monthly maps for 2010 were
204 used as an example (Fig. 5). The predicted SSN concentration began to increase in December
205 and reached its maximum in February (12–15 μM), but was very low from April to October.
206 In particular, predicted concentrations were less than 1μM during August and September.
207 This finding is consistent with other local studies (Maita *et al.,* 1991; Kudo *et al*., 2000), and
208 it occurs because of the nutrient-rich period in the photic zone supplied by strong vertical
209 mixing during winter (Sugie *et al*., 2010).

210 Some satellite data were affected by clouds on the observation dates and could not be used.
211 Therefore, we compared the shipboard SSN for stations ST.13 and SE.9 (see Fig. 1B) during
212 April 2010 to January 2012 and satellite-estimated SSN on clear observation days during
213 January 2003 to May 2012 to verify the accuracy of the predicted values and show seasonal
214 variability. The results are shown in Fig. 6. The seasonal variation in SSN had higher values
215 in the winter (average 14.8 μM in February) and lower values in the summer (average 0.07
216 μM in August). The predicted SSN was consistent with the *in situ* data. The SSN suddenly
217 deceased from March-April, which may have been a result of the occurrence of a spring
218 bloom. The concentration of Chl-*a* increased significantly in March (Maita *et al*., 1991;
219 Sasaki *et al*., 2005). Phytoplankton biomass was found to be limited by NO_3, and the

220 exhaustion of NO_3 was observed in the photic zone at the end of the bloom (Levasseur and
221 Therriault, 1987; Kudo *et al*., 2000).
222
223 **Model of the spatial distribution of suitability**
224 On the basis of a previous model (Radiarta *et al*., 2011), the improved SASSM was
225 developed. Using 2010 data as an example, we compared the previous model (Fig. 7A) with
226 the new models. The improvement included two steps, with the first being improved
227 bathymetry. Comparison of the new distribution map (Fig. 7B) with the previous map shows
228 slight differences in the potential area at Shikabe and Minamikayabe. This was a result of the
229 previous model using 500-m gridded bathymetric data, whereas the new model (Fig. 7B) used
230 more accurate 150-m gridded bathymetric data. However this did not result in any change in
231 suitable areas. The second step involved adding an SSN parameter to improve the model. The
232 new model (Fig. 7C) shows that the difference is in the distribution of the suitable area,
233 especially areas with the highest suitability score of 8 (dark blue color). The previous (Fig. 7A)
234 study showed that the most suitable areas (score 8) were distributed along the coast from
235 Oshamanbe to Yakumo in Funka Bay, and also in the Shikabe, Minamikayabe, Todohokke,
236 Esan, and Toi areas. According to the field survey and kelp production statistics from the
237 Hokkaido government (Marinenet Hokkaido, 2010), the main kelp culture area is along the
238 coastline from Shikabe to Hakodate, with the highest production in the Minamikayabe area.
239 In other places, there was no kelp production inside Funka Bay; therefore, the relationship
240 between high scores by the previous model and *in situ* kelp production has some
241 contradictions. However, when the new physical parameter of SSN was included, the most

suitable area was still shown in the main kelp culture areas but was no longer shown in Funka Bay. The new model (Fig. 7C) was well verified by *in situ* kelp production.

Temporal variations in suitability area

The final models of the growing season (May–July) for Japanese kelp aquaculture in southern Hokkaido during 2003 to 2010 are shown in Fig. 8. These results showed high suitability scores (above 7) for most of the kelp aquaculture areas in southern Hokkaido during the growing season, especially Minamikayabe, which was the most suitable area (score 8). The waters near Hakodate Mountain were less suitable (score 5) for kelp aquaculture. From the comparison of suitable areas during the 8 years, it was observed that the most suitable areas (scores 7 and 8) decreased significantly in 2004, 2007, and 2010.

Climate events and Kelp production

The sustainability of aquaculture can be influenced by environmental changes (Taylor *et al*., 2008; Cocharane *et al*., 2009; Baba *et al*., 2009; Saitoh *et al*., 2011). However, few studies have explored the impacts of climate change on Japanese kelp aquaculture. Therefore, we combined suitability scores with kelp production and climatic events, namely the El Niño/La Niña–Southern Oscillation (ENSO), to examine the potential impacts of climate change on the development of Japanese kelp aquaculture. The Oceanic Niño Index (ONI) was used as a measure of the strength of an ENSO episode (http://gcmd.nasa.gov/records/GCMD_NOAA_NWS_CPC_ONI.html). We sorted El Niño and La Niña episodes into three categories, strong, moderate, and weak, based on ONI values.

The thresholds for ONI values were obtained from Chris and Stan (2008). From the monthly time series of ONI during 2003–2012 (Fig. 9), El Niño was found to occur during 2004–2005, 2006–2007, and 2009–2010, and La Niña occurred during 2008–2009 and 2010–2011.

Monthly kelp production data (Fig. 9) are published by the Fisheries Department of the Hokkaido government and are available at the Marinenet Hokkaido website: http://www.fishexp.hro.or.jp/marineinfo/internetdb/index.htm. The annual kelp production of Minamikayabe accounts for about 60% of total Hokkaido kelp production. Production has changed over the years, especially decreasing in 2004 and 2007.

4. Discussion

Estimated SSN and improved SASSM model

Previous studies that have examined site-selection models have focused on the physical parameters of SST, SS, bathymetry, and slope. However, the present study demonstrates that the model could be improved by including local southern Hokkaido water characteristics. Because NO_3 is an essential element for Japanese kelp growth, this study considered the SSN to develop a more accurate model. Many studies have demonstrated the possibility of estimating SSN at a large scale based on satellite SST because of the sensitivity of T–N relationships (Traganza *et al.*, 1983; Switzer *et al.*, 2003). Also, phytoplankton nitrate uptake could have a significant impact on T–N relationships (Goes *et al.*, 2000). Therefore, we developed a local algorithm to estimate SSN based on T and Chl-*a* in southern Hokkaido. In comparing this algorithm with other NO_3 predictive algorithms (see Fig. 4), we understand that different water regions have different dynamics. If this approach were to be applied in

other regions, we recommend a starting point of shipboard nitrate measurements for the development of a new, location-specific algorithm. Additionally, satellite-predicted SSNs are not as accurate as shipboard measurements, and SSN concentrations along coastal regions are highly susceptible to the effects of human activities, such as agricultural sewage discharge (Del Amo *et al*., 1997). Therefore, satellite data cannot replace shipboard measurements, but can be a useful tool for obtaining synoptic information on SSN concentrations. With advances in satellite technology, satellite-based estimates will continue to improve.

The final results of the improved SASSM showed increased accuracy in the actual kelp culture region, which was verified by kelp production statistics for Hokkaido. However, regions that have not been producing kelp may also be suitable for aquaculture. The suitability map (Fig. 7C) showed a score of 7 along most of the coastline. Field surveys indicated that certain amounts of wild kelp exist in Funka Bay, although few commercial kelp enterprises are found in this area. This may be because aquaculture production in Funka Bay focuses mainly on cultured scallop. To avoid multi-use conflicts within the limited aquaculture area, few kelp cultures are found in Funka Bay. However, Japanese kelp is an important traditional product in southern Hokkaido. In Minamikayabe, more than 2000 fishermen engage in kelp aquaculture, which has increased the kelp production in this area. Therefore, with reasonable planning and management, Funka Bay may be a potential area for Japanese kelp culture.

Relationships among ENSO, currents, and kelp aquaculture zones

The Oyashio is a western boundary current of subarctic circulation in the North Pacific. In recent years the southward intrusion of the Oyashio has shown large seasonal variation and comparable interannual variations (Qiu, 2002), and it has been observed that these variations are associated with global changes in atmospheric circulation (Sekine, 1988; Tatebe and Yasuda, 2005). The dominant climate variabilities in the western North Pacific are high frequency variations associated with ENSO events (McKinnell and Dagg, 2010).

Conversely, the Tsushima Warm Current is the only major warm current flowing in the Japan Sea, and it forms a major part of the volume transport of the TWC, which flows into the North Pacific Ocean through the Tsugaru Strait (Ohtani, 1987; Onishi and Ohtani, 1997). Seasonal variations in flow corresponded to seasonal changes in the sea level differences between the Japan Sea side and Pacific Ocean side of the Tsugaru Strait (Nishida *et al*., 2003; Tanno *et al*., 2005). Hirose and Fukudome (2006) showed a relationship between the volume transport of the TWC in autumn and interannual variation in local evaporation and precipitation in winter. Also, Yasuda and Hanawa (1997) suggested that variation in the TWC, as part of the western boundary current of the subtropical gyre, is influenced by atmospheric and oceanic variability over the North Pacific. ENSO events have been implicated as major factors controlling the winter climate over the North Pacific (Zhang *et al*., 1996). Lyu and Kim (2003) suggested that long-term variations in transport through the Tsushima Strait are related to changes, such as El Niño, in the Pacific Ocean. Hong *et al*.'s (2001) results showed that variation in the SST anomaly in the Japan Sea occurs simultaneously with the development of ENSO events in the tropical Pacific Ocean. Additionally, Hirose *et al*.'s

(2009) results indicated that the western Pacific index in winter follows the volume transport of the TWC in autumn and connects with the El Niño index.

Therefore, the oceanic variability and atmospheric circulation are strongly coupled. Climate change associated spatial and temporal fluctuations in the Coastal Oyashio Current and TWC can have significant influences on Japanese kelp aquaculture along the coast of southern Hokkaido. The mature phase of an ENSO often occurs in winter, and the growing season of Japanese kelp is from May to July. Therefore, we attempted to compare suitable areas and kelp production in El Niño years with those in other years to determine the impacts of a climate event (El Niño event) on the growing season of Japanese kelp aquaculture. Table 3 shows differences in Japanese kelp production and site suitability with ENSO events during 2003 to 2010. The suitability scores of sites in an El Niño year differed from those in a normal year. During El Niño, the suitable sites (scores 7 and 8) decreased significantly compared with other years. The amount of suitable area (score 8) decreased by 0.3%, 0.2%, and 0.8% in 2004, 2007, and 2010, respectively. In other years, more than 3.5% of the area was rated as the most suitable. These results are consistent with actual kelp production data, which showed total production of 5.4, 4.5, and 5.4 thousand tons in 2004, 2007, and 2010, respectively. Such changes may reflect the impact of climate change through seawater temperature on aquaculture areas. Japanese kelp is a temperate cold water species, and when seawater temperatures exceed 23°C, most of the kelp blade will rot (FAO, http://www.fao.org/fishery/culturedspecies/Laminaria_japonica/en). The harvest season is from July to September (see Fig. 9). During El Niño events, the seawater temperature increases in this region, which can shorten the kelp growing season and reduce production.

Thus, during El Niño years, kelp harvesters should closely monitor changes in water temperatures and prepare to harvest earlier than in a normal year.

5. Conclusion

This study proposes a method to estimate SSN at a local scale using satellite-observed SST and chlorophyll-*a*. The improved SASSM effectively identified the most suitable areas for Japanese kelp aquaculture in southern Hokkaido, and the results were consistent with *in situ* production data. In addition to the traditional Japanese kelp aquaculture area, we also identified some potentially suitable aquaculture areas in Funka Bay, which can provide a basis for future management. We also examined the impacts of climate change on the availability of suitable sites. The results suggested that climate variability could influence the development of Japanese kelp aquaculture through changes in site suitability. These changes should be considered when managing kelp aquaculture.

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Table 1. Water sampling during the cruises (Apr. 2010 – Jan. 2012) on the T/S *Oshoro-Maru* and R/V *Ushio-Maru* in southern Hokkaido, Japan.

Year	Date	Cruise	Number of Stations
2010	Apr.19-21	US194	32
	May 21-23	US196	11
	Jun.19	US199	16
	Aug.20-22	US201_1	23
	Aug.28-30	US201_2	15
	Oct.21-23	US208	32
	Nov.10-13	US210	15
2011	Feb.6-8	US219	11
	Feb.24	OS225	12
	Mar.6	US222	1
	May14-16	US228	23
	Jul.27-28	US232	13
	Sep.27-29	US237	10
	Nov.17-19	US242	10
2012	Jan.10	US246	5

536 Table 2. Nitrate requirements and suitability scores for Japanese kelp aquaculture in southern

537 Hokkaido, Japan.

Suitability Score	NO_3 concentration (μM)	Nitrate uptake rate (μgN/cm^2 per h)
1	< 0.56	< 0.146
2	0.56 - 1.12	0.146 - 0.292
3	1.12 - 1.67	0.292 - 0.437
4	1.67 - 2.23	0.437 - 0.583
5	2.23 - 4.47	0.583- 0.875
6	4.47 - 6.70	0.875 - 1.021
7	6.70 - 15.64	1.021 - 1.167
8	> 15.64	> 1.167

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Table 3. Difference in Japanese kelp production and site suitability (expressed as the percentage of the total potential area) between ENSO and normal growing seasons in southern Hokkaido, Japan.

	Suitability scores (%)								El niño/	Total-production
Year	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**La niña event ***	**(10^3 tons)****
May - Jul. 2003	0.0	0.0	0.0	8.3	10.3	23.3	50.5	3.7	Normal	6.2
May - Jul. 2004	0.0	0.0	6.8	7.8	18.5	36.9	29.6	0.3	Weak El Niño	5.4
May - Jul. 2005	0.0	0.0	0.0	6.9	11.1	19.7	53.1	8.9	Normal	5.7
May - Jul. 2006	0.0	0.0	0.0	6.9	12.2	18.7	56.7	5.0	Weak La Niña	5.6
May - Jul. 2007	0.0	0.0	6.3	8.2	17.1	36.7	31.2	0.2	Weak El Niño	4.5
May - Jul. 2008	0.0	0.0	0.0	7.6	11.4	25.1	45.3	3.5	Moderate La Niña	5.6
May - Jul. 2009	0.0	0.0	0.0	5.4	12.0	21.0	47.5	5.3	Weak La Niña	5.9
May - Jul. 2010	0.0	0.0	5.9	8.7	19.0	35.3	29.4	0.8	Strong El Niño	5.4

*ONI: http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ensoyears.html
**Production data: http://www.fishexp.hro.or.jp/marineinfo/internetdb/index.htm

Figure captions

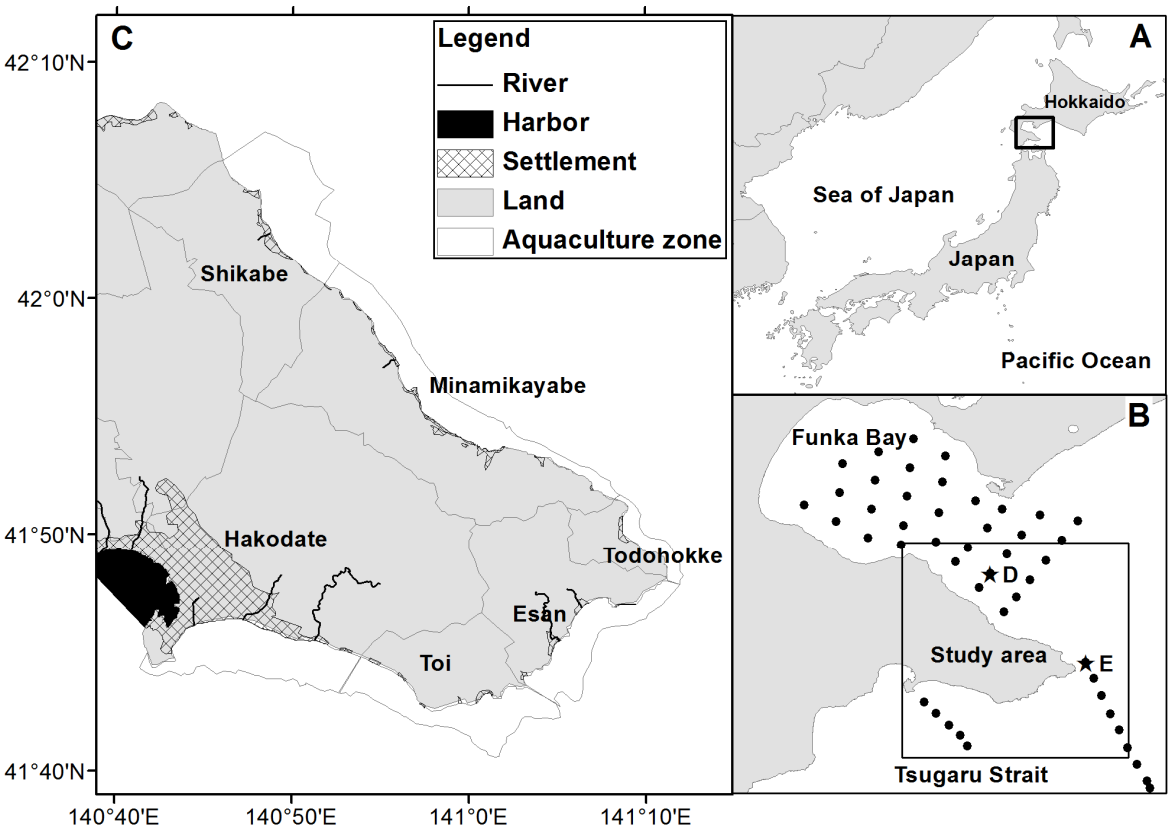


Figure 1. (a) Study area in southern Hokkaido, Japan. (b) Filled circles represent local sampling stations in Funka Bay and the Tsugaru Strait. The star marked D is ST.13, and the star marked E is SE.9. (c) Zones of marine aquaculture in southern Hokkaido, Japan.

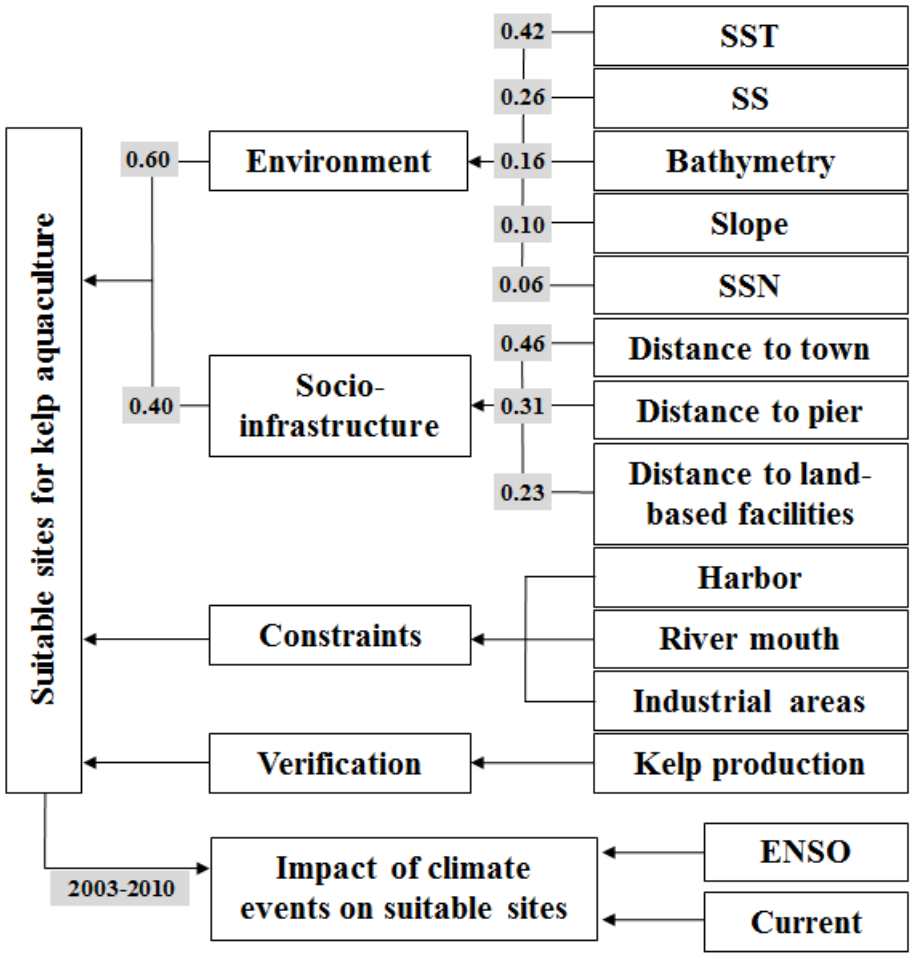


Figure 2. Hierarchical scheme and parameter weights of the SASSM for Japanese kelp in southern Hokkaido, Japan.

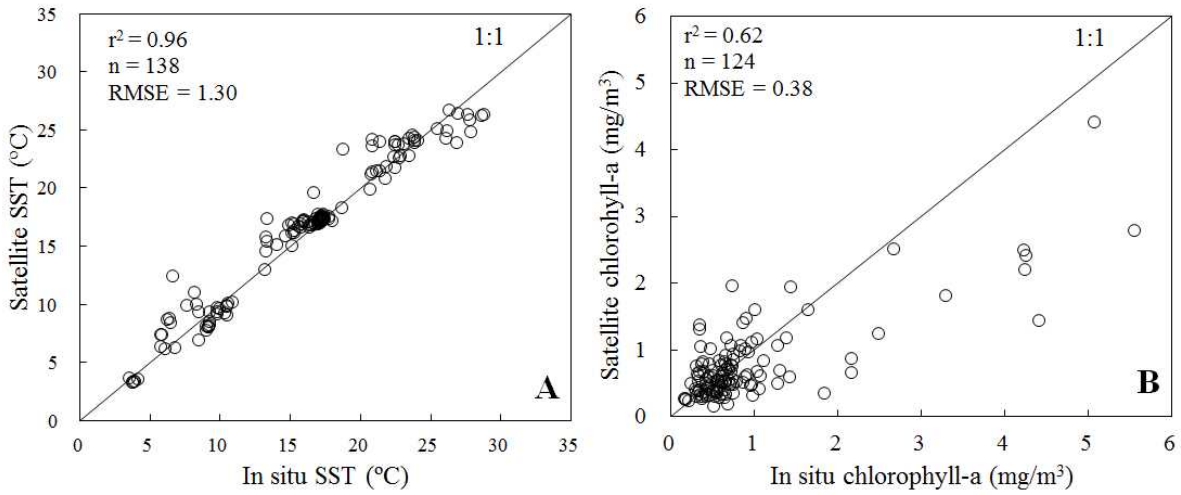
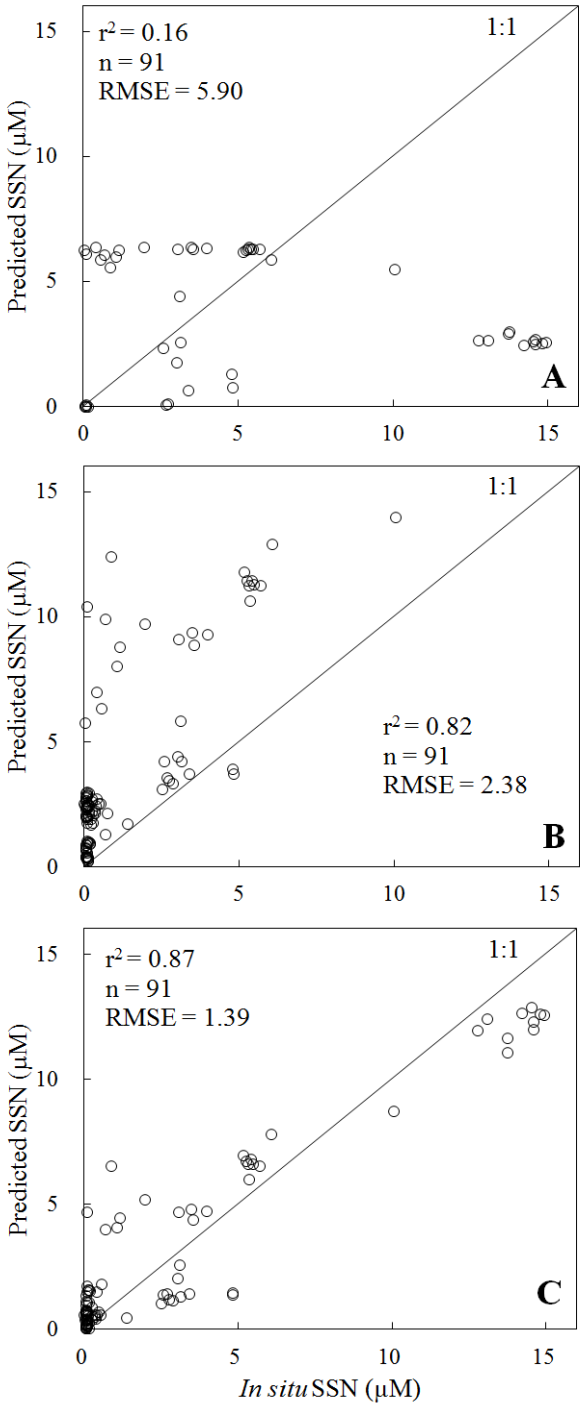


Figure 3. Variation in (a) SST and (b) Chl-*a* between *in situ* and satellite data in southern Hokkaido, Japan.



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611 Figure 4. Relationship between shipboard- and satellite-estimated SSN using Goes *et al.*'s

612 (1999) algorithm (a) $NO_3 = -3.33 + 2.16(T) - 0.12(T)^2$, (b) $NO_3 = 25.22 - 1.96(T) + 0.04(T)$

613 $^2 - 1.21(\text{Chl-}a) - 0.05(\text{Chl-}a)^2$, (c) newly developed SSN predictive algorithm for Funka

614 Bay $SSN = 18.302 - 1.629(T) + 0.036(T)^2 - 2.045(\text{Chl-}a) + 0.041(\text{Chl-}a)^2$

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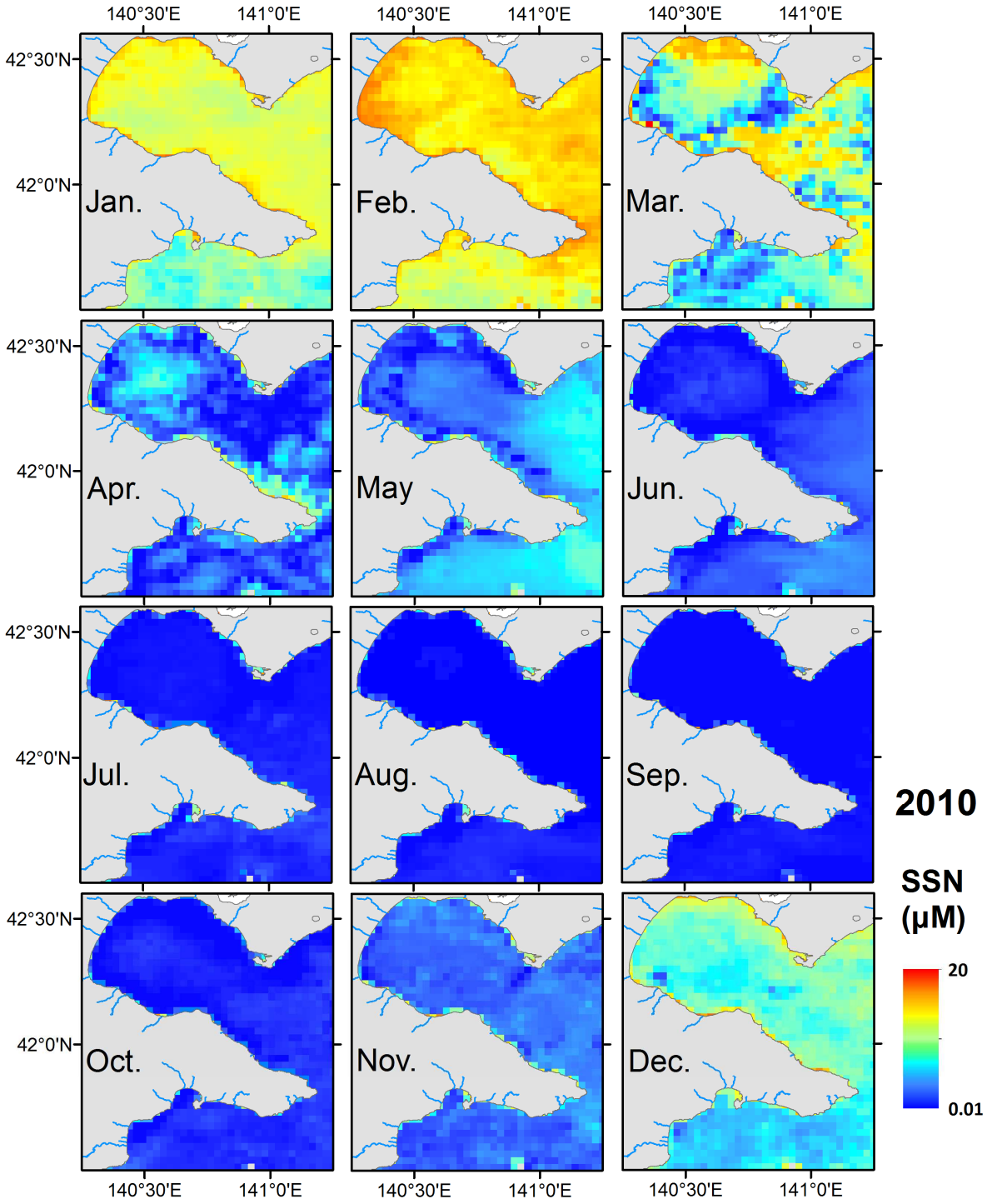

Figure 5. Monthly images of predicted SSN (μM) during Jan. 2010 to Dec. 2010 in the waters of Southern Hokkaido, Japan.

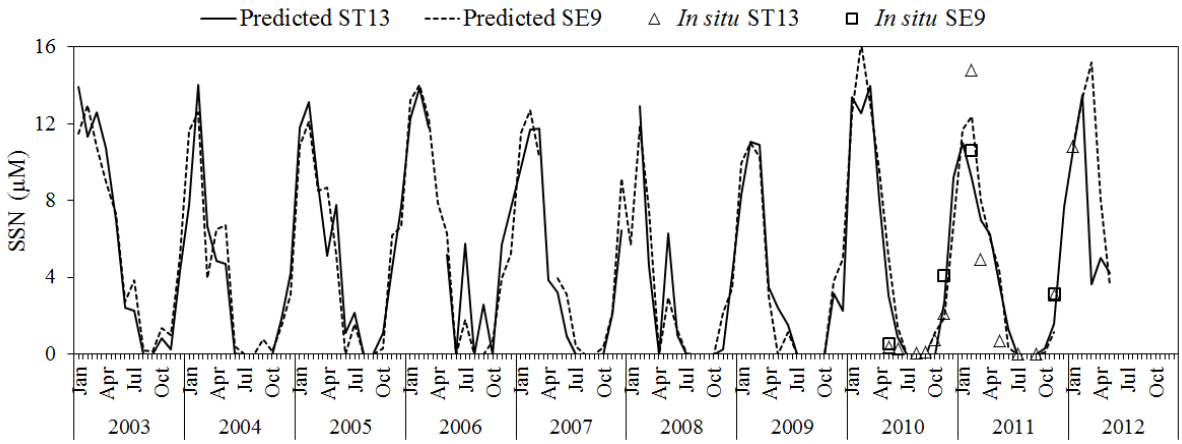

Figure 6. Seasonal variability and variation in *in situ* and satellite-predicted SSN (μM) at stations ST.13 and SE.9 during Jan. 2003 to May 2012 in southern Hokkaido, Japan.

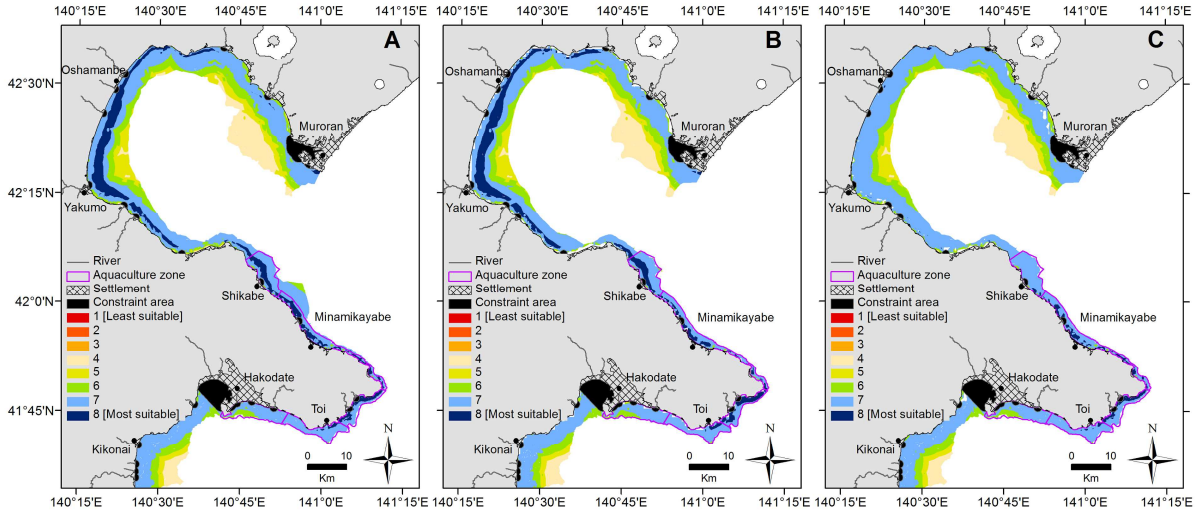

Figure 7. Suitability sites maps for Japanese kelp aquaculture in 2010 using (a) the previous model, (b) the SASSM with improved bathymetry, (c) the SASSM with improved bathymetry and SSN.

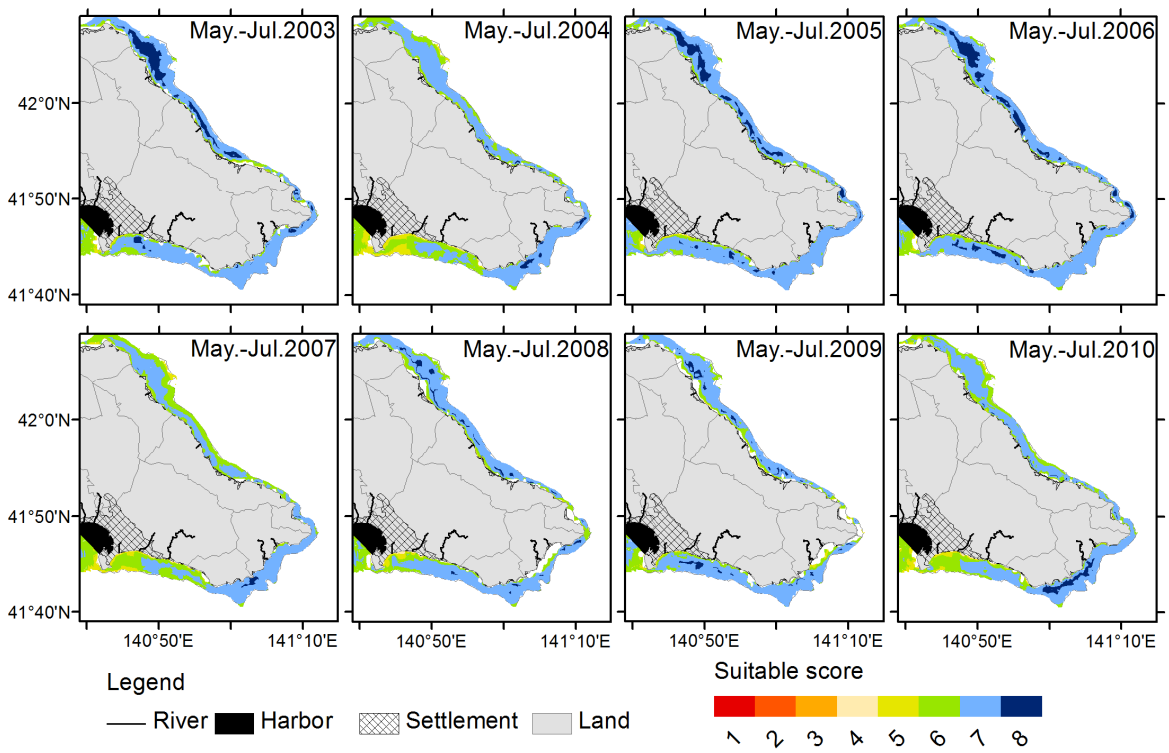

Figure 8. SASSM maps for Japanese kelp during the growing season (May–July) in southern Hokkaido, 2003 to 2010.

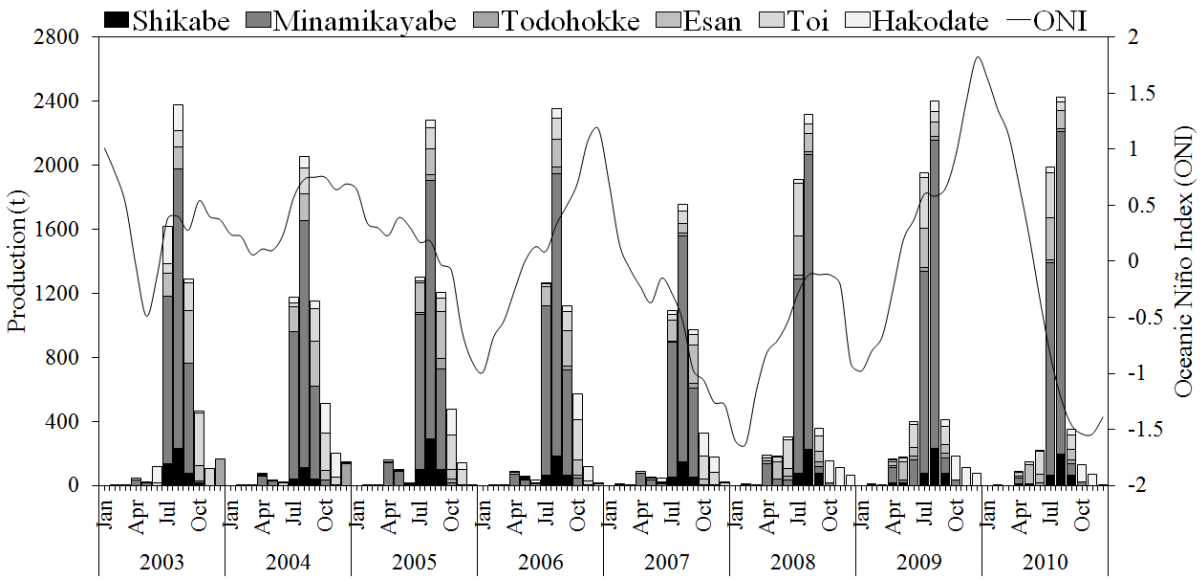

Figure 9. Monthly production of Japanese kelp and ONI in southern Hokkaido (2003–2010).