



HOKKAIDO UNIVERSITY

Title	Improvement of an aquaculture site-selection model for Japanese kelp (<i>Saccharina japonica</i>) in southern Hokkaido, Japan : an application for the impacts of climate events
Author(s)	Liu, Yang; Saitoh, Sei-Ichi; Radiarta, I. Nyoman et al.
Citation	ICES Journal of Marine Science, 70(7), 1460-1470 https://doi.org/10.1093/icesjms/fst108
Issue Date	2013-11
Doc URL	https://hdl.handle.net/2115/57137
Rights	This is a pre-copyedited, author-produced PDF of an article accepted for publication in [ICES journal of marine science] following peer review. The definitive publisher-authenticated version [ICES J. Mar. Sci. (2013) 70 (7): 1460-1470] is available online at: http://icesjms.oxfordjournals.org/content/early/2013/08/24/icesjms.fst108 .
Type	journal article
File Information	inal-liu.pdf



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

Yang Liu¹, Sei-Ichi Saitoh¹, I. Nyoman Radiarta², Tomonori Isada¹, Toru Hirawake¹,
Hiroyuki Mizuta³ and Hajime Yasui⁴

¹Laboratory of Marine Bioresource and Environment Sensing, Faculty of Fisheries Sciences,
Hokkaido University, 3-1-1 Minato, Hakodate, Hokkaido 041-8611, Japan

²Research Center for Aquaculture, Agency for Marine and Fisheries Research, Ministry of
Marine Affairs and Fisheries. Jl. Ragunan 20, Pasar Minggu, Jakarta 12540, Indonesia

³Laboratory of Breeding Science, Faculty of Fisheries Sciences, Hokkaido University, 3-1-1
Minato, Hakodate, Hokkaido 041-8611, Japan

⁴Laboratory of Science and Technology on Fisheries Infrastructure System, Faculty of
Fisheries Sciences, Hokkaido University, 3-1-1 Minato, Hakodate, Hokkaido 041-8611, Japan

*Corresponding author: Yang Liu

E-mail: yangliu315@salmon.fish.hokudai.ac.jp , yangliu315@hotmail.co.jp

Laboratory of Marine Bio resource and Environment Sensing, Faculty of Fisheries Sciences,
Hokkaido University, 3-1-1, Minato, Hakodate, Hokkaido, 041-8611, Japan.

Tel: +81(138)-40-8844

24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45

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*, previously *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 (NO₃) conditions. Many studies have indicated that NO₃ 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 NO₃ data remains difficult. The resolution of NO₃ 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 $41^{\circ}40'$ – $42^{\circ}10'N$ and $140^{\circ}40'$ – $141^{\circ}10'E$, 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 nL_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-infrastructure 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-Marui* and R/V *Ushio-Marui* (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 NO₃ 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).

Estimating SSN from space

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

GIS model construction

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

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

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

3. Results

Local algorithm for SSN development

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

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

Also, we compared the new local SSN algorithm for Funka Bay with Goes *et al.*'s (1999) results, which developed a NO₃ 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 1 μM 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 decreased 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

exhaustion of NO₃ was observed in the photic zone at the end of the bloom (Levasseur and Therriault, 1987; Kudo *et al.*, 2000).

Model of the spatial distribution of suitability

On the basis of a previous model (Radiarta *et al.*, 2011), the improved SASSM was developed. Using 2010 data as an example, we compared the previous model (Fig. 7A) with the new models. The improvement included two steps, with the first being improved bathymetry. Comparison of the new distribution map (Fig. 7B) with the previous map shows slight differences in the potential area at Shikabe and Minamikayabe. This was a result of the previous model using 500-m gridded bathymetric data, whereas the new model (Fig. 7B) used more accurate 150-m gridded bathymetric data. However this did not result in any change in suitable areas. The second step involved adding an SSN parameter to improve the model. The new model (Fig. 7C) shows that the difference is in the distribution of the suitable area, especially areas with the highest suitability score of 8 (dark blue color). The previous (Fig. 7A) study showed that the most suitable areas (score 8) were distributed along the coast from Oshamanbe to Yakumo in Funka Bay, and also in the Shikabe, Minamikayabe, Todohokke, Esan, and Toi areas. According to the field survey and kelp production statistics from the Hokkaido government (Marinenet Hokkaido, 2010), the main kelp culture area is along the coastline from Shikabe to Hakodate, with the highest production in the Minamikayabe area. In other places, there was no kelp production inside Funka Bay; therefore, the relationship between high scores by the previous model and *in situ* kelp production has some 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.

Acknowledgements

This work was supported by “Hakodate Marine Bio Cluster Project” in the knowledge Cluster Program from 2009 and the Grant-in-Aid for the Regional Innovation Strategy Support Program (Global Type) from the Ministry of Education, Culture, Sports, Science and Technology (MEXT), Japan. It was also supported by the Japan Aerospace Exploration Agency (JAXA) SGLI/GCOM-C Project. Especially, we appreciate two anonymous reviewers for providing constructive comments.

References

- Ahn, Y.H., Moon, J.E., and Gallegos, S. 2001. Development of suspended particulate matter algorithms for ocean color remote sensing. *Korean Journal of Remote Sensing*, 17: 285-295.
- Baba, K., Sugawara, R., Nitta, H., Endou, K., and Miyazono, A. 2009. Relationship between spat density, food availability, and growth of spawners in cultured *Mizuhopecten yessoensis* in Funka Bay: concurrence with El Niño Southern Oscillation. *Canadian Journal of Fisheries and Aquatic Sciences*, 66: 6-17.
- Chavez, F.P., and Service, S.K. 1996. Temperature-nitrate relationships in the central and eastern tropical Pacific. *Journal of Geophysical Research*, 101: 20553-20563.
- Chris, S., and Stan, C. 2008. El Niño and La Niña episodes and their impact on the weather in the Las Vegas Valley, National Weather Service, Las Vegas, NV. Available online: <http://www.wrh.noaa.gov/vef/projects.php>.
- Cochrane, K., Young, C.D., Soto, D., and Bahri, T. 2009. Climate change implications for fisheries and aquaculture: overview of current scientific knowledge. FAO Fisheries and aquaculture technical paper No. 530. UNEP. 2009. The climate change fact sheet.
- Daniel, G., Touria, B., Jacques, P., Mickaël, V., and Axel, E. 2012. Modeling kelp forest distribution and biomass along temperate rocky coastlines. *Marine Biology*, Doi: 10.1007/s00227-012-2089-0.
- Del Amo, Y., Le Pape, O., Tréguer, P., Quéguiner, B., Ménesguen, A., and Aminot, A. 1997. Impacts of high-nitrate freshwater inputs on macrotidal ecosystems. I. Seasonal evolution

393 of nutrient limitation for the diatom-dominated phytoplankton of the Bay of Brest (France).
 394 Marine Ecology Progress Series, 161: 213-224.

395 Deysher, L.E., and Dean, T.A. 1986. *In situ* recruitment of sporophytes of the giant kelp,
 396 *Macrocystis pyrifera* (L.) C.A. Agardh: effects of physical factors. Journal of Experimental
 397 Marine Biology and Ecology, 103: 41-63.

398 FAO 2004-2013. Cultured Aquatic Species Information Programme. *Laminaria japonica*.
 399 Cultured Aquatic Species Information Programme. Text by Chen, J. In: FAO Fisheries and
 400 Aquaculture Department. Rome. Updated 1 January 2004.
 401 http://www.fao.org/fishery/culturedspecies/Laminaria_japonica/en (last accessed 21 June
 402 2013).

403 FAO website. FAO Fisheries and Aquaculture Department: *Laminaria japonica*.
 404 http://www.fao.org/fishery/culturedspecies/Laminaria_japonica/en.

405 Gao, X., Agatsuma, Y., and Taniguchi, K. 2012. Effect of nitrate fertilization of gametophytes
 406 of the kelp *Undaria pinnatifida* on growth and maturation of the sporophytes cultivated in
 407 Matsushima Bay, northern Honshu, Japan. Aquaculture International, Doi:
 408 10.1007/s10499-012-9533-5.

409 Goes, J.I., Saino, T., Oaku, H., and Jiang, D.L. 1999. A method for estimating sea surface
 410 nitrate concentrations from remotely sensed SST and Chlorophyll a – A case study for the
 411 North Pacific Ocean using OCTS/ADEOS data. IEEE Transactions on Geoscience and
 412 Remote Sensing, 37: 1633-1644.

413 Goes, J.I., Saino, T., Oaku, H., Ishizaka, J., Wong, C.S., and Nojiri, Y. 2000. Basin scale
 414 estimates of Sea Surface Nitrate and New Production from remotely sensed Sea Surface
 415 Temperature and Chlorophyll. *Geophysical Research Letters*, 27: 1263-1266.

416 Grant, J., Stenton-Dozey, J., Montiero, P., Pitcher, G., and Heasman, K. 1998. Shellfish
 417 culture in the Benguela system: A carbon budget of Saldanha Bay for raft culture of
 418 *Mytilus Galloprovincialis*. *Journal of Shellfish Research*, 17: 41-49.

419 Hirose, N., and Fukudome, K. 2006. Monitoring the Tsushima Warm Current improves
 420 seasonal prediction of the regional snowfall, *Scientific Online Letters on the Atmosphere*, 2:
 421 61-63.

422 Hirose, N., Nishimura, K., and Yamamoto, M. 2009. Observational evidence of a warm ocean
 423 current preceding a winter teleconnection pattern in the northwestern Pacific. *Geophysical*
 424 *Research Letters*, 36, L09705, doi:10.1029/2009GL037448.

425 Hong, C.H., Cho, K.D., and Kim, H.J. 2001. The relationship between ENSO events and sea
 426 surface temperature in the East Japan Sea. *Progress in Oceanography*, 49: 21-40.

427 Isoda, Y., and Hasegawa, K. 1997. Heat budget of Funka Bay. *Umi to Sora*, 3: 93-101. (in
 428 Japanese)

429 Kamykowski, D., and Zentara, S.J. 1986. Predicting plant nutrient concentrations from
 430 temperature and sigma-t in the upper kilometer of the world ocean. *Deep Sea Research*, 33:
 431 89-105.

432 Kono, T., Foreman, M., Chandler, P., and Kashiwai, M. 2004. Coastal Oyashio south of
 433 Hokkaido, Japan. *Journal of Physical Oceanography*, 34: 1477-1494.

434 Kudo, I., Yoshimura, Y., Yanada, M., and Matsunaga, K. 2000. Exhaustion of nitrate
 435 terminates a phytoplankton bloom in Funka Bay, Japan: change in $\text{SiO}_4\text{:NO}_3$ consumption
 436 rate during the bloom. Marine Ecology Progress Series, 193: 45-51.

437 Levasseur, M.E., and Therriault, J.C. 1987. Phytoplankton biomass and nutrient dynamics in a
 438 tidally induced upwelling: the role of the $\text{NO}_3\text{:SiO}_4$ ratio. Marine Ecology Progress Series,
 439 39: 87-97.

440 Lyu, S.J., and Kim, K. 2003. Absolute transport from the sea level difference across the Korea
 441 Strait. Geophysical research letters, 30: 1285, doi:10.1029/2002GL016233.

442 Maita, Y., Mizuta, H., and Yanada, M. 1991. Nutrient environment in natural and cultivated
 443 grounds of *Laminaria japonica*. Bulletin of the Faculty of Fisheries Hokkaido University,
 444 42: 98-106.

445 Marinenet Hokkaido. 2010. Search and aggregate statistics of the fishery catch from 1991 to
 446 2010. <http://www.fishexp.hro.or.jp/marineinfo/internetdb/index.htm>.

447 McKinnell, S.M., and Dagg, M.J. 2010. Marine ecosystems of the North Pacific ocean,
 448 2003-2008. PICES Special Publication, 4, 393p.

449 Miyake, H., Tanaka, I., and Murakami, T. 1988. Outflow of water from Funka Bay, Hokkaido,
 450 during early spring. Journal of the Oceanographical Society of Japan, 44: 163-170.

451 Mizuta, H. 2003. Distribution of *Laminaria* Species in the Coastal Oyashio Region and their
 452 Nutrient Requirements. Bulletin on Coastal Oceanography, 41: 33-38. (in Japanese)

453 Mizuta, H., and Maita, Y. 1991. Effects of nitrate supply on ammonium assimilations in the
 454 blade of *Laminaria japonica* (Phaeophyceae). Bulletin of the faculty of fisheries Hokkaido
 455 University, 42: 107-114.

456 Nishida, Y., Kanomata, I., Tanaka, I., Sato, S., Takahashi, S., and Matsubara, H. 2003.
 457 Seasonal and Interannual Variations of the Volume Transport through the Tsugaru Strait.
 458 Oceanography in Japan, 12: 487-499. (in Japanese)

459 Ohtani, K. 1971. Studies on the change of the hydrographic conditions in the Funka Bay II .
 460 Characteristics of the water occupying the Funka Bay. Bulletin of the faculty of fisheries
 461 Hokkaido University, 22: 58-66.

462 Ohtani, K. 1987. Westward Inflow of the Coastal Oyashio Water into the Tsugaru Strait.
 463 Bulletin of the Faculty of Fisheries, Hokkaido University, 38: 209-220. (in Japanese)

464 Onishi, M., and Ohtani, K. 1997. Volume transport of the Tsushima Warm Current, west of
 465 Tsugaru Strait bifurcation area. Journal of Oceanography, 53: 27-34.

466 Ozaki, A., Mizuta, H., and Yamamoto, H. 2001. Physiological differences between the
 467 nutrient uptakes of *Kjellmaniella crassifolia* and *Laminaria japonica* (Phaeophyceae).
 468 Fisheries Science, 67: 415-419.

469 Parsons, T.R., Maita, Y., and Lalli, C.M. 1984. A manual for chemical and biological
 470 methods for seawater analysis. Pergamon Press, New York.

471 Qiu, B. 2002. Large-scale variability in the midlatitude subtropical and subpolar North Pacific
 472 Ocean: Observations and causes. Journal of Physical Oceanography, 32: 353-375.

473 Radiarta, I N., Saitoh, S-I., and Yasui, H. 2011. Aquaculture site selection for Japanese kelp
 474 (*Laminaria japonica*) in southern Hokkaido, Japan, using satellite remote sensing and
 475 GIS-based models. ICES Journal of Marine Science, 68: 773-780.

476 Saaty, T.L. 1977. A scaling method for priorities in hierarchical structures. Journal of
 477 Mathematical Psychology, 15: 234-281.

478 Saitoh, S-I., Mugo, R., Radiarta, I N., Asaga, S., Takahashi, F., Hirawake, T., Ishikawa, Y.,
 479 Awaji, T., In, T., and Shima, S. 2011. Some operational uses of satellite remote sensing
 480 and marine GIS for sustainable fisheries and aquaculture. *ICES Journal of Marine Science*,
 481 68: 687-695.

482 Sasaki, H., Miyamura, T., Saitoh, S-I., and Ishizaka, J. 2005. Seasonal variation of absorption
 483 by particles and colored dissolved organic matter (CDOM) in Funka Bay, southwestern
 484 Hokkaido, Japan. *Estuarine, Coastal and Shelf Science*, 64: 447-458.

485 Sekine, Y. 1988. Anomalous southward intrusion of the Oyashio east of Japan: 1. Influence of
 486 the seasonal and interannual variations in the wind stress over the North Pacific, *Journal of*
 487 *Geophysical Research*, 93: 2247–2255.

488 Sugie, K., Kuma, K., Fujita, S., Nakayama, Y., and Ikeda, T., 2010. Nutrient and diatom
 489 dynamics during late winter and spring in the Oyashio region of the western subarctic
 490 Pacific Ocean. *Deep-Sea Research II*, 57: 1630-1642.

491 Switzer, A.C., Kamykowski, D., and Zentara, S.J. 2003. Mapping nitrate in the global ocean
 492 using remotely sensed sea surface temperature. *Journal of Geophysical Research*, 108,
 493 doi:10.1029/2000JC000444.

494 Takahashi, D., Nishida, Y., Kido, K., Nishina, K., and Miyake, H. 2005. Formation of the
 495 summertime anticyclonic eddy in Funka Bay, Hokkaido Japan. *Continental Shelf Research*,
 496 25: 1877-1893.

497 Tanno, T., Kuroda, H., Isoda, Y., and Aiki, T. 2005. Flow variations off Cape of Esan,
 498 northeast of Tsugaru Strait. *Bulletin of Fisheries Sciences, Hokkaido University*, 56: 33-41.
 499 (in Japanese)

- Tatebe, H., Yasuda, I. 2005. Interdecadal variations of the coastal Oyashio from the 1970s to the early 1990s. *Geophysical Research Letters*, 32: L10613, doi:10.1029/2005GL022605.
- Toylor, M.H., Wolff, M., Mendo, J., and Yamashiro, G. 2008. Changes in trophic flow structure of independence Bay (Peru) over an ENSO cycle. *Progress in Oceanography*, 79: 336-351.
- Traganza, E.D., Silva, V.M., Austin, D.M., Hanson, W.L., and Bronsink, S.H. 1983. Nutrient mapping and recurrence of coastal upwelling centers by satellite remote sensing: Its implication to primary production and the sediment record. In E.Suess, and J. Thiede (Eds.), *Coastal upwelling. Its sediment record. Part A* (pp.61-83). Plenum.
- Wilkinson, G.N. 1961. Statistical estimations in enzyme kinetics. *Biochemical Journal*, 80: 824-832.
- Yasuda, T., and Hanawa, K. 1997. Decadal changes in the mode waters in the midlatitude North Pacific. *Journal of Physical Oceanography*, 27: 858-870.
- Yotsukura, N. 2010. Production of kelp in Japan: various natural resources and the established aquaculture technique. *Seaweeds for human consumption, Bioactive Compounds, and Combating of Diseases: An international interdisciplinary symposium, Carlsberg Academy, Copenhagen, August 26-27, 2010.*
- Zhang, R., Sumi, A., and Kimoto, M. 1996. Impact of El Niño on the East Asian monsoon: A diagnostic study of the '86/87 and '91/92 events. *Journal of the Meteorological Society of Japan*, 74: 49-62.

522 Table 1. Water sampling during the cruises (Apr. 2010 – Jan. 2012) on the T/S *Oshoro-Maru*
523 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

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

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.

Year	Suitability scores (%)								El niño/ La niña event *	Total-production (10 ³ tons)**
	1	2	3	4	5	6	7	8		
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

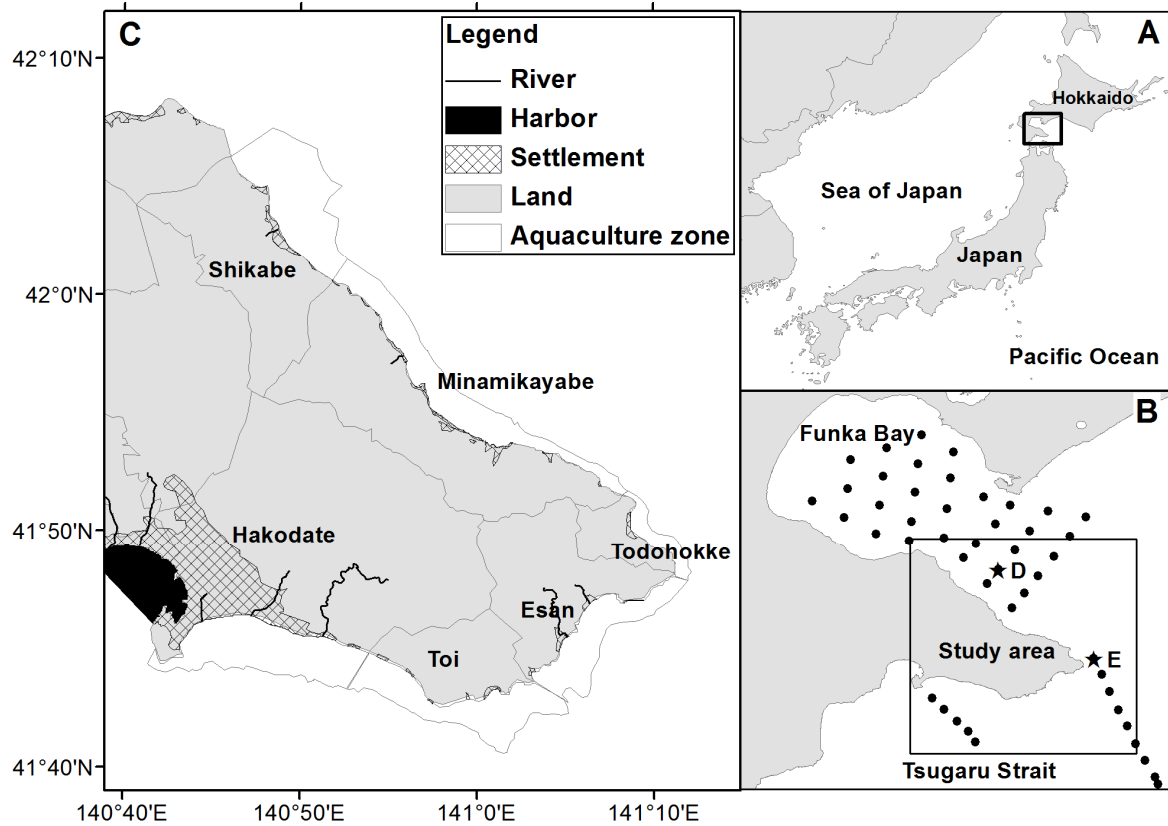


Figure 1. (a) Study area in southern Hokkaido, Japan. (b) Filled circles represent local sampling stations in Funka Bay and the Tsugaru Strait. The star marked D is ST.13, and the star marked E is SE.9. (c) Zones of marine aquaculture in southern Hokkaido, Japan.

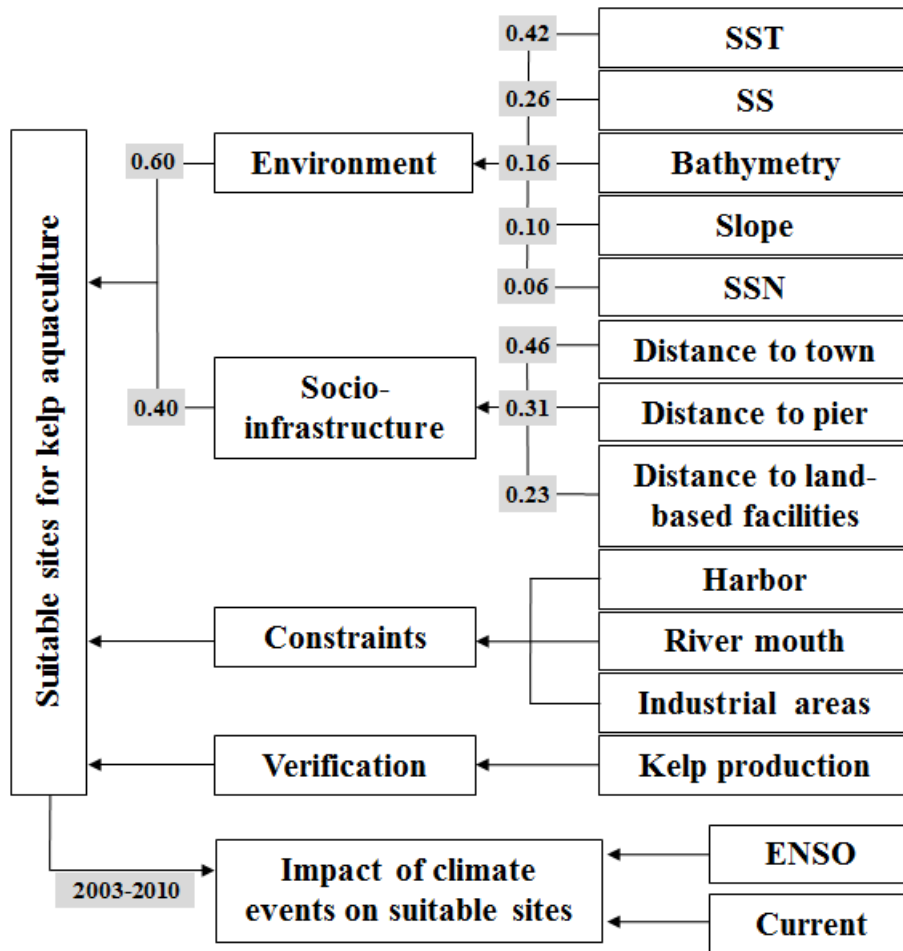


Figure 2. Hierarchical scheme and parameter weights of the SASSM for Japanese kelp in southern Hokkaido, Japan.

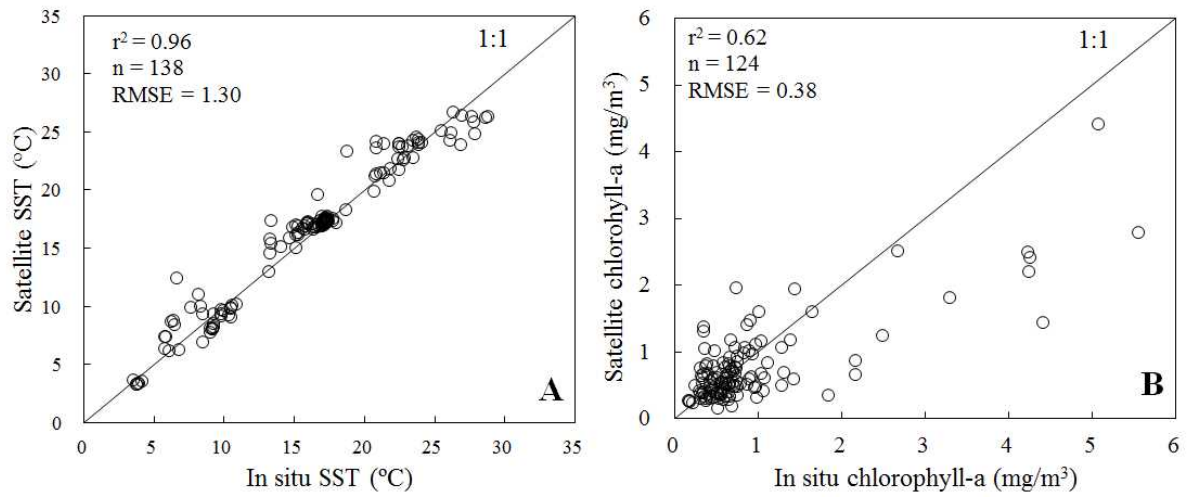


Figure 3. Variation in (a) SST and (b) Chl-*a* between *in situ* and satellite data in southern Hokkaido, Japan.

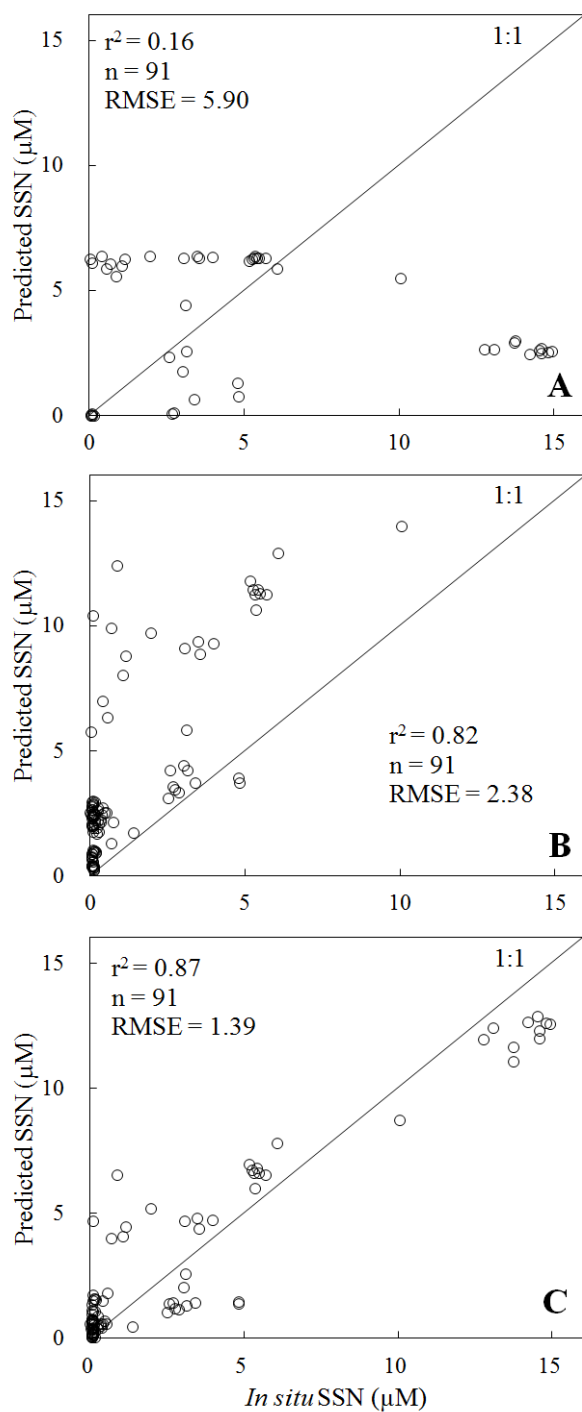


Figure 4. Relationship between shipboard- and satellite-estimated SSN using Goes *et al.*'s (1999) algorithm (a) $NO_3 = -3.33 + 2.16(T) - 0.12(T)^2$, (b) $NO_3 = 25.22 - 1.96(T) + 0.04(T)^2 - 1.21(Chl-a) - 0.05(Chl-a)^2$, (c) newly developed SSN predictive algorithm for Funka Bay $SSN = 18.302 - 1.629(T) + 0.036(T)^2 - 2.045(Chl-a) + 0.041(Chl-a)^2$

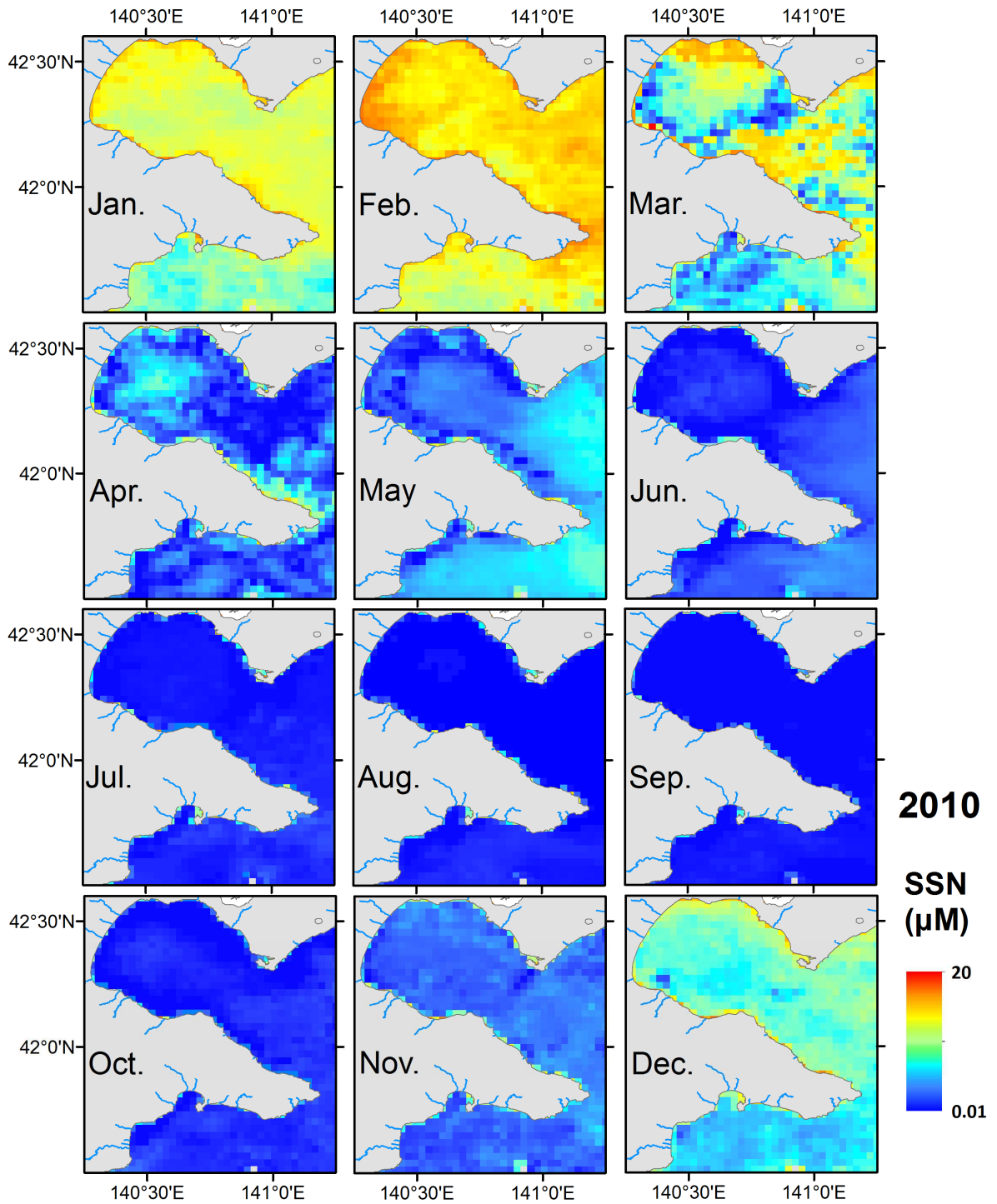


Figure 5. Monthly images of predicted SSN (μM) during Jan. 2010 to Dec. 2010 in the waters of Southern Hokkaido, Japan.

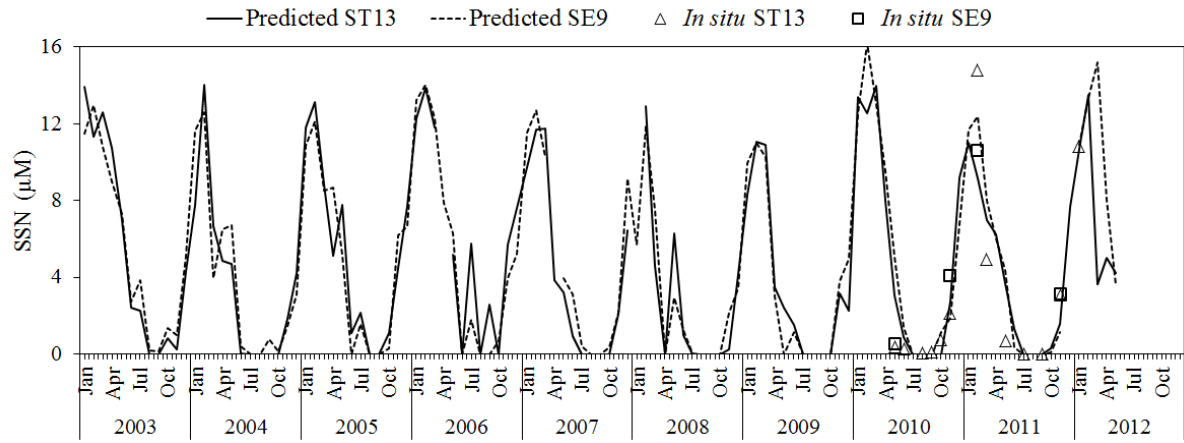


Figure 6. Seasonal variability and variation in *in situ* and satellite-predicted SSN (μM) at stations ST.13 and SE.9 during Jan. 2003 to May 2012 in southern Hokkaido, Japan.

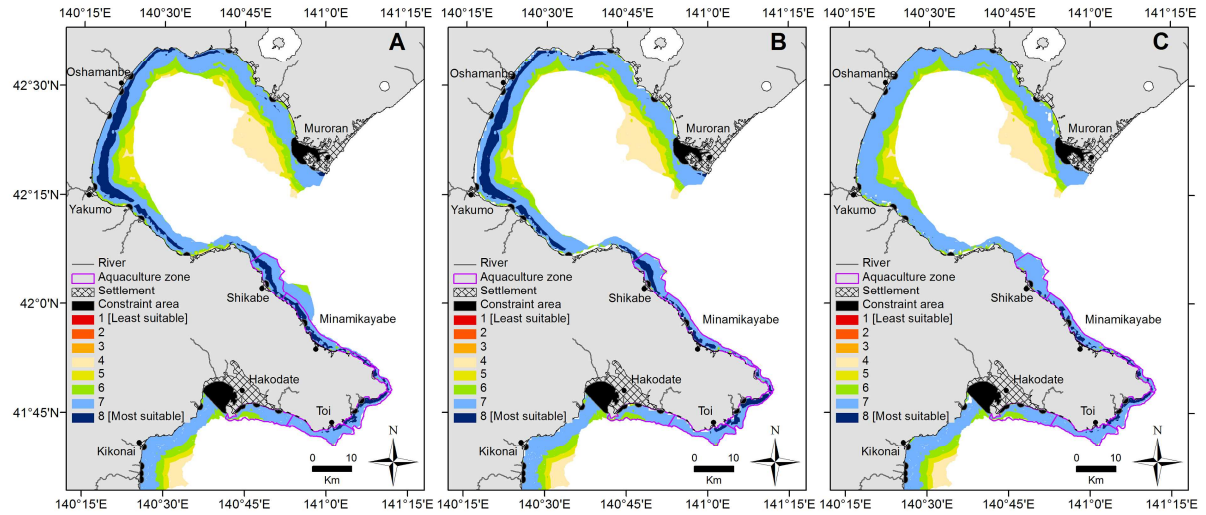


Figure 7. Suitability sites maps for Japanese kelp aquaculture in 2010 using (a) the previous model, (b) the SASSM with improved bathymetry, (c) the SASSM with improved bathymetry and SSN.

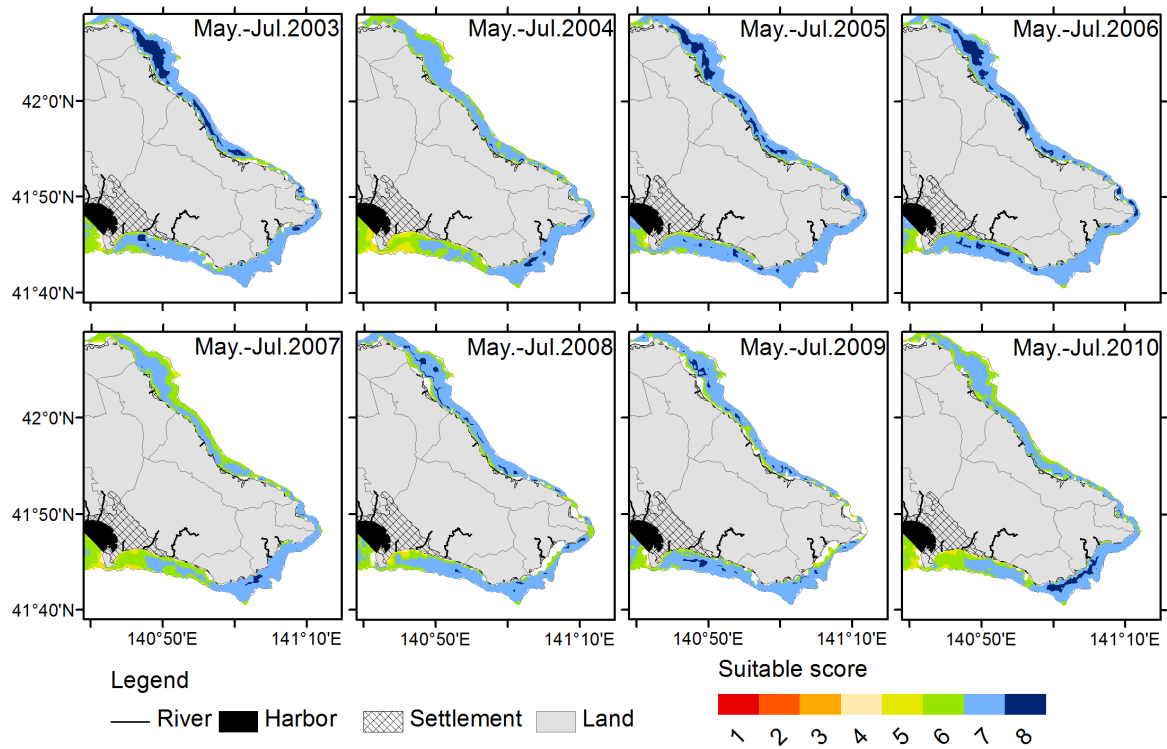


Figure 8. SASSM maps for Japanese kelp during the growing season (May–July) in southern Hokkaido, 2003 to 2010.

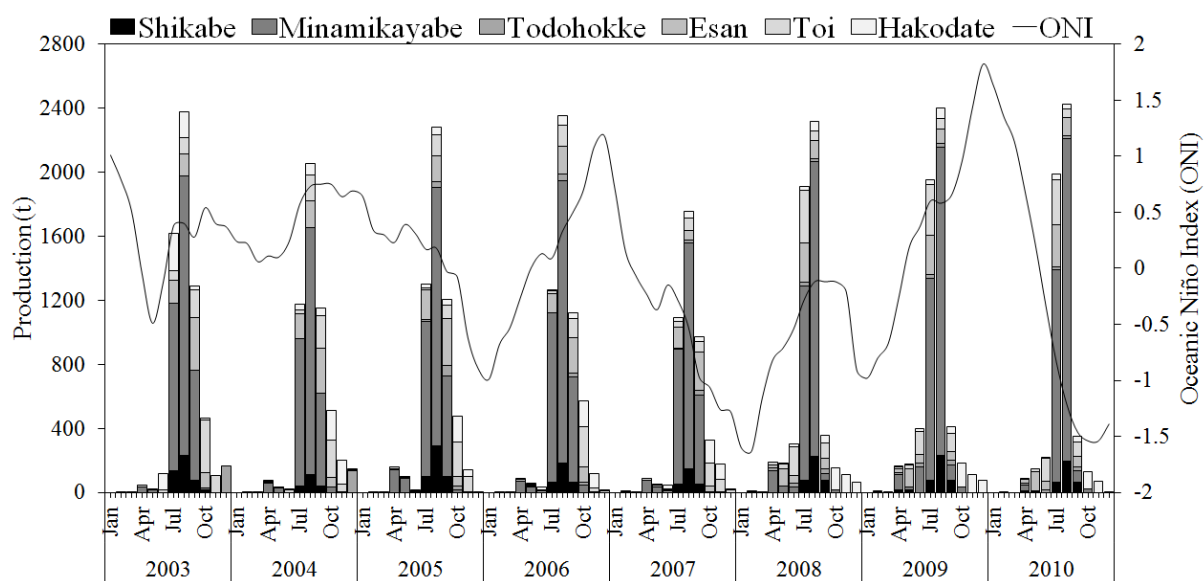


Figure 9. Monthly production of Japanese kelp and ONI in southern Hokkaido (2003–2010).