Spatiotemporal variations in suitable areas for Japanese scallop aquaculture in the Dalian coastal area from 2003 to 2012

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ABSTRACT

The Japanese scallop (*Mizuhopecten yessoensis*) is an important commercial species in the Dalian coastal area. The present study employed a suitable aquaculture site-selection model (SASSM) and used satellite remote-sensing data to analyze the spatiotemporal distribution of suitable areas for Japanese scallop aquaculture in the Dalian coastal area from 2003 to 2012. The study area was divided into four marine zones. The results demonstrated that the suitability scores of scallop aquaculture areas were high in May and low in February. The Changhai County (Zone II) and Lushunkou areas (Zone III) exhibited high potential for Japanese scallop aquaculture development. The results of the suitability models were consistent with the existing scallop aquaculture in the study area. These zones, combined with climatic events [the winter East Asian Monsoon (EAM) and El Niño/La Niña–Southern Oscillation (ENSO) events], were used to examine the impact of climate variability on scallop aquaculture. Results suggest that the suitability scores in Zone III were more sensitive to changes in environmental factors (e.g., sea surface temperature, chlorophyll-a, and suspended sediment) and climate changes, whereas the correlations among these factors were not significant in Zone II. Adaptation to these changes should be considered when developing plans and management strategies for scallop aquaculture.

Keywords: Dalian coastal area, ENSO event, GIS-based model, Japanese scallop, Winter east Asian monsoon

1. Introduction

The Japanese scallop (*Mizuhopecten yessoensis*) is a cold-tolerant shellfish that is widely distributed among the northern islands of Japan, the northern part of the Korean Peninsula, the Russian Primorye, and the Sakhalin and Kurile islands (Ito, 1991). In 1982, the Japanese scallop was first introduced into China from Japan as an alternative species for aquaculture in northern China due to the species' large size, fast growth, and high market value (Li et al., 2007). Japanese scallops quickly became a popular species that was widely promoted and cultured in Liaoning and Shandong provinces. In 2005, the annual production of Dalian scallop aquaculture accounted for about 90% of the total national production (Liu et al., 2010a). By 2009, the annual production of Japanese scallops had reached about 260,000 tons in the Dalian coastal areas along the Northern Yellow Sea (Dalian Bureau of Statistics, 2010). According to interviews with local farmers, scallop aquaculture became the most profitable industry in the Dalian coastal area during 2002–2006, growing at an annual rate of 40%. However, after reaching a peak in 2006, Japanese scallop aquaculture began to be devastated by large-scale mortality beginning in 2007, resulting in severe economic losses. The death rate often reached 50–80%. However, what caused the massive mortality in Japanese scallops from the Dalian coastal area remains unclear.

Most scallop aquaculture sites are in coastal areas, which can be influenced by many factors, such as increased coastal pollution, high densities of scallops within the aquaculture, environmental degradation, climate change, and human activities. According to a field survey of Dalian coastal areas with water depths of 20 m or less, water temperatures ranging between 5°C and 20°C have occurred throughout the floating rafts used for scallop aquaculture. The raft spacing is only about 3 m, and substantial research has found that high culture densities in scallop aquaculture can affect growth and mortality rates (Cano et al., 2000; Fréchette and Daigle, 2002; Zhang et al., 2006). The hanging and bottom culture methods used for scallops have both been used with varying success due to variation in environmental variables, such as water temperature, water depth, suspended particulate matter concentration, and chlorophyll concentration, at different locations (Grant et al., 2003; Kleinman et al., 1996; Laing, 2002; Pelot and Cyrus, 1999). Currently, both methods are used in the Dalian coastal area; therefore, the selection of appropriate culture methods for different environments might affect the growth of scallops. Increases in coastal pollution (e.g., incidences of oil spills) from accelerated urban and industrial growth in China may lead many farmers to suspect that scallop mortality and ocean pollution are directly related.

Marine ecosystems are likely very sensitive to climatic changes, especially in the high northern and southern latitudes (Lassalle and Rochard, 2009). Fisheries everywhere are vulnerable to temperature change (Cheung et al., 2009, 2010), and Japanese scallops often experience temperatures ranging from 5°C to 20°C. Scallops are stressed at temperatures between 20°C and 23°C, although they do survive. Sea temperatures during years of mass mortality were usually higher than in normal years (DFO, 2011). A great deal of research has examined the effects of climatic fluctuations on aquaculture development (Cocharane et al., 2009; Horreo et al., 2010; Soheila and

Bahram, 2010; Taylor et al., 2008). The climate of China is influenced mainly by the East Asian monsoon (EAM), which is characterized by strong northerly winds during winter months and weak southerly winds in summer (Huang et al., 2007). Additionally, sea-surface temperature (SST) anomalies in the midlatitude western North Pacific depend on variation in monsoon intensity (Hanawa et al., 1989). The Yellow Sea Warm Current (YSWC) is believed to be part of the northward flow of the Tsushima Current (Niino and Emery, 1961) and to be the only mean flow that brings warm, saline water into the Yellow and Bohai seas (Uda, 1934). In summer, winds from the south drive northeastward flow along the Chinese coast, and the YSWC enters the Yellow Sea from only the upper layer because of the Yellow Sea cold water mass; it then turns northeastward to the Tsushima Current in deep layers (Cui et al., 2004). The YSWC is stronger in winter and very weak in summer (Xu et al., 2009). El Niño/La Niña–Southern Oscillation (ENSO) is the dominant, coupled (ocean–atmosphere) source of climate variability in the tropical Pacific, and it serves as the main source of interannual variability in the climate system. Climates over the northwestern Pacific and East Asia are also greatly affected by ENSO (Wang et al., 2000). ENSO affects the SST field in the East China Sea (ECS) with a 5–9-month delay (Kuo et al., 2011; Wang et al., 2001). The mature phase of ENSO often occurs in boreal winter and is normally accompanied by a weaker than normal winter monsoon along the East Asian coast (Ji et al., 1997; Tomita and Yasunari, 1996; Zhang et al., 1996). Therefore, we have reason to believe that the EAM and ENSO could affect scallop aquaculture in the Dalian coastal area.

The present study assessed various factors, such as environmental variables, human activities, and climate change, to comprehensively determine appropriate sites for the aquaculture of Japanese scallops. Conducting aquaculture in optimal areas will greatly reduce the risk of environmental impacts, promote overall profit, and minimize conflicts between aquaculture and other resources (Radiarta et al., 2008; Stead et al., 2002). Geographic information systems (GIS), remote sensing, and mapping provide useful tools in the development and management of marine aquaculture (Kapetsky and Anguilar-Manjarrez, 2007; Silva et al., 2011). Some research has already developed aquaculture and suitable aquaculture site-selection models (SASSMs) to identify suitable sites for Japanese scallop aquaculture in Funka Bay, Japan (Radiarta and Saitoh, 2009; Radiarta et al., 2008; Saitoh et al., 2011). Therefore, we applied this method to the study of Japanese scallop aquaculture in the Dalian coastal area because it is very similar to Funka Bay, in that it is located within a similar latitude and also uses the hanging culture method.

The objectives of this study were to continue the development of GIS-based models to identify the most suitable sites for Japanese scallop development in the Dalian coastal area and to examine the potential impact of climate change (EAM and ENSO) on scallop aquaculture development. Results could provide advisory information and a foundation for the sustainable development of scallop aquaculture in the Dalian coastal area.

2. Materials and methods

2.1. Study area

Dalian is one of the most heavily developed industrial areas of China, with a total area of 13,237 km^2 and a population of 6.17 million in 2010 (Dalian Bureau of Statistics, 2010). The city administers six districts, three county-level cities, and one county. Dalian includes 92 subdistricts and 69 towns/townships. The Ganjingzi, Zhongshan, Xigang, and Shahekou districts make up the main urban center. Changhai County is composed entirely of islands east of the peninsula. The city’s climate is a monsoon-influenced humid continental climate characterized by humid summers due to the EAM and cold, windy, dry winters that reflect the influence of the vast Siberian anticyclone. Average temperatures range from –3.6°C in January to 24.5°C in August. Annual precipitation averages 602 mm.

Dalian, with a coastline of 1,906 km, is located west of the Yellow Sea and east of the Bohai Sea, roughly at the southernmost tip of the Liaodong peninsula (Fig. 1). Based on the characteristics of the coastal water and the administrative divisions of the city (Bao et al., 2010), we divided the Dalian coastal area (extending 15 km from land) into four zones (Table 1). Zone I consists of coastal water of Zhuanghe (ZH) and Pulandian (PLD), relatively close to the mainland. Zone II comprises Changhai County, which includes Changshandao (CSD), Haiyangxiang (HYX), Zhangzhidao (ZZD), and Guangluxiang (GLX). This region includes island waters, which are less affected by the mainland. Zone III is located in the Northern Yellow Sea and includes Jinzhou (JZYS), the main city (MCYS), and Lushunkou (LSKYS). The Yellow Sea is a marginal sea of the Pacific, with a smooth terrain and broad area. Because the inflow river carries overly abundant sediment, the color of the coastal water is yellow, hence the name. Zone IV is located along the coast of the Bohai Sea and includes Lushunkou (LSKBS), the main city (MCBS), Jinzhou (JZBS), and Wafangdian (WFD). The Bohai Sea is an inland sea of China and is surrounded by land; thus, it is strongly influenced by the continental climate and human activities (Hainbucher et al., 2004).

2.2. Environmental factors

The environmental factors we examined included the chlorophyll-a (Chl-a) concentration, suspended sediment concentration (SSC), SST, and bathymetry, which are very important in the physical and biological conditions of scallop cultures (Bacher et al., 2003). The Chl-a and SST data were derived as level-2 data using a Moderate Resolution Imaging Spectroradiometer (MODIS)-Aqua sensor at a 1-km resolution. Due to MODIS-Aqua Reprocessing 2012.0, an instrument recalibration that occurred on 1 May 2012, all daily data from January 2003 to May 2012 were obtained from the Ocean Color Web site (http://oceancolor.gsfc.nasa.gov) using the R2012.0 version. Monthly Chl-a and SST images were computed to reduce the effect of cloud cover. The remote-sensing, data-processing software used in this study included the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) Data Analysis System (SeaDAS) 6.4 and ERDAS Imagine 9.3.

Suspended sediment concentration can be affected by the Chl-a concentration and water pollution, which can vary among coastal regions that experience different environmental conditions. Therefore, we extracted K_d (490) from the MODIS and SeaWiFS instruments to calculate SSC, based on the following algorithm (Wang et al., 2005):

$$SSC = 1.43 \times K_d(490)^{-0.89},$$

where K_d (490) is the diffuse attenuation coefficient at 490 nm and serves as an indicator of water column turbidity. All of the daily K_d (490) data were downloaded as level-2 data, at a 1-km resolution, from the Ocean Color Web site, and monthly averages of K_d (490) images were computed using SeaDAS software.

Bathymetric data were derived from ETOPO1, which is a 1 arc-minute global relief model of the Earth's surface that integrates land topography and ocean bathymetry (Christopher and Barry, 2009). The bathymetric data were processed by ArcGIS 10.0

software, which was developed by the Environmental System Research Institute in the United States (ESRI).

2.3. Social factors

To choose an appropriate site for scallop aquaculture, one must not only consider environmental factors, but also take into account social economics and support facilities. Therefore, our study integrated factors related to social infrastructure, such as the distance to town, the distance to piers, and the distance to land-based facilities. Additionally, some regional constraints on scallop aquaculture were considered, such as harbor, township, industrial areas, and river mouth. The social infrastructure and constraint data were extracted from Advanced Land Observing Satellite (ALOS) AVNIR-2 images, which were acquired on 5 November 2009, 5 October 2010, and 7 December 2010. The ALOS data were downloaded at a 10-m resolution from the ALOS User Interface Gateway Web site (AUIG, https://auig.eoc.jaxa.jp/auigs/en/top/index.html) as level-1 B2G, geo-coded data. The distance analysis function of ArcGIS was used to measure distances for social infrastructure and constraint data.

2.4. GIS model

Fig. 2 shows the schematic framework of the SASSM for the Japanese scallop aquaculture. The SASSM was formed using three sub-models, including an environmental model (Chl-a, SSC, SST, and bathymetry), a social infrastructure model (distances to town, piers, and land-based facilities), and a constraints model (harbor, area of nearby towns, and river mouth). Parameter values were ranked on a scale from 1 (least suitable) to 8 (most suitable) following Radiarta et al. (2009). Parameter weights were determined by pairwise comparisons, according to the analytical hierarchy process for decision-making (Saaty, 1977). Each model was implemented using ModelBuilder in ArcGIS, and constructed using the weighted linear combination (WLC) method of multi-criteria evaluation (MCE), following the methods of Malczewski (2000). The final suitability map was created by combining the three sub-models. Suitability scores were ranked on a scale from 1 (least suitable) to 8 (most suitable).

2.5. Climate events index

The intensity of the winter monsoon is well represented by the Monsoon Index (MOI), which is defined as the difference in sea-level pressure (SLP) between Nemuro, Japan, and Irkutsk, Russia (Hanawa et al., 1988). The monthly SLP data sets used in the present study, at a 1.25° resolution, originated from the Japanese 25-year ReAnalysis (JRA-25), a long-term reanalysis cooperative research project conducted by the Japan Meteorological Agency (JMA) and the Central Research Institute of the Electric Power Industry (CRIEPI).

Oceanic Niño Index (ONI) values, defined as SST anomalies in the Niño 3.4 region (located at 5ºN to 5ºS and 120º to 170ºW) of the eastern and central equatorial Pacific Ocean, were based on the 1971–2000 base period. ONI data are published by the NOAA National Weather Service, Center for Climate Prediction, and are available at http://gcmd.nasa.gov/records/GCMD_NOAA_NWS_CPC_ONI.html.

2.6. Statistical analysis

The climate event indices (MOI and ONI) were integrated into the SASSM using a stepwise multiple regression analysis to determine the underlying causes of climate impact. Tests of statistical significance were based on *t*-tests at significance levels of $P < 0.01$ and 0.05. We analyzed the correlations among climate event indices (MOI and ONI), environmental factors (Chl-a, SSC, and SST), and suitability scores for all seasonal changes. Prior to analysis, all anomalous data were processed, with the exception of ONI. An anomaly was considered as a departure from average conditions. Measured monthly data for each factor were compared to the long-term average of that month, from 2003 to 2012. SPSS 13.0 software was used for statistical analyses.

3. Results

3.1. Seasonal variability of environmental factors

Oceanic satellite observations in the visible and near-infrared bands make it possible to obtain measurements on several variables related to ocean color, primarily Chl-a concentration, SSC, and SST. However, for coastal Case-2 waters containing more yellow substances and increased suspended matter, non-phytoplankton matter plays an important role in determining the optical properties of the water body. Therefore, the Chl-a concentration is generally high due to eutrophic waters (Xing et al., 2007). The previous study verified the satellite data in coastal regions (Radiarta et al., 2008), and the consistency of MODIS Chl-a and SST data with *in situ* data was about 70% and 90%, respectively. Therefore, satellite data can adequately reflect long-term trends in ocean color information.

Fig. 3 presents the seasonal cycle of monthly Chl-a concentrations, SSC, and SST in the Dalian coastal area, for the four marine zones from 2003 to 2012. The Chl-a concentration was the highest in September–October and the lowest in June–July for every year (Fig. 3a). The monthly average Chl-a concentration in Zone I was lowest in June 2006 (1.3 mg m^{-3}) and highest in September 2006 (10.9 mg m^{-3}). Another peak also appeared in February–March, with the highest concentration occurring in Zone I in February 2011 (10.2 mg m^{-3}); this result was consistent with Zou (2005). Changes in long-term, mean SSC were inversely correlated with Chl-a (Fig. 3b). The annual peak in SSC took place in July. Maximum SSC occurred in Zone III in July 2004 (9.1 g m^{-3}), and the lowest SSC values were found in September 2006, with a minimum in Zone I (2.6 g m^{-3}). The time series of monthly SST exhibited relatively regular sinusoidal variation for all four zones (Fig. 3c). The seasonal pattern of SST for all zones exhibited a minimum in February (0.2–3.5°C) and a maximum in August (21.5–24.6°C).

3.2. Spatial variability of environmental factors

Spatial patterns in the variability of Chl-a, SSC, and SST during the 10 study years are shown in Fig. 4. High Chl-a concentrations occurred within the Dalian coastal area, especially in ZH and JZBS (>10 mg m^{-3}), but values gradually decreased with increasing distance from land (Fig. 4a). Low Chl-a concentrations occurred within the Bohai Sea Strait and the Northern Yellow Sea, likely due to discharges of freshwater containing abundant nutrient matter along the coastal shore, which enhanced phytoplankton growth (Liu et al., 2010b). Spatial changes in SSC were opposite those in Chl-a (Fig. 4b). Spatial changes in SSC gradually increased with increased distance from land, with especially high values (>5.5 g m^{-3}) in the Yellow Sea region, which may be related to offshore pollution. Annual averages of SST were high in summer (July–September; 16–24°C) and low in winter (January–March; 0–4°C; Fig. 4c).

3.3. Suitability maps of the sub-models

The suitability maps of the different sub-models generated for Japanese scallop aquaculture in the Dalian coastal area are shown in Fig. 5. In the SASSM, Chl-a concentration, SSC, SST, and bathymetry were the criteria used to evaluate the environmental model. According to the different concentration values of each factor in each month, we produced 113 environmental model maps (from January 2003 to May 2012). To reflect the overall distribution of the Dalian coastal area, the environmental model for May 2009 was used as an example (Fig. 5a).

In the social infrastructure model, distances to towns, piers, and land-based facilities were taken into account for the criteria settings (Fig. 5b). Approximately 10% of the study area was assigned the highest score of 8 (most suitable), whereas about 58% of the area scored 1 or 2; these latter areas were located far from land-based facilities and infrastructure.

The constraints model contained limit information (Fig. 5c), including harbor areas (Port of Dalian), areas near the river mouth, areas near townships and industry, tourism zones, and artificial facilities along the coast. Together, these areas covered about 7% of the Dalian coastal area.

3.4. Spatial and seasonal variations in the final models

Based on the SASSM, all of the final monthly suitable maps were generated during 2003–2012. To reflect the spatial and seasonal variations among final models over the course of 1 year of scallop culture, we generated final monthly mean maps from 2003 to 2012 (Fig. 6). We can see that suitable areas increased in May and November, which coincided with the two peak scallop growth times during the season. The most suitable area had scores of 7 and 8 and included about 10% of the potential area, whereas 84% of the area was classified as having intermediate scores (4–6), and about 4% of the region was identified as having the lowest scores (1–3). Based on the spatial distribution, the most suitable areas (scores above 7) were widely distributed in the coastal waters of CSD, GLX, ZZD, and LSK, most of which lie along the Yellow Sea. These results were also consistent with the current Japanese scallop aquaculture areas in Dalian, as Changhai Country (Zone II) is the largest Japanese scallop aquaculture base in China. Furthermore, the coastal waters of LSK (Zone III) are located at the confluence of the Bohai Sea and Yellow Sea, where a large amount of wild Japanese scallop seeding occurs (Chang et al., 2007).

3.5. Seasonal changes in suitability scores for the four marine zones

The time series of average suitability scores for the four marine zones during 2003–2012 are shown in Fig. 7. The results indicate that the average suitability scores in Zones II and III (5.0 and 5.4, respectively) were higher than those in Zones I and IV (4.7 and 4.4, respectively). Among these values, the mean suitability scores in Zone III were the highest, but exhibited the largest fluctuations. The seasonal changes in the suitability scores of Zone II were more stable. Overall, the patterns of seasonal variation indicated that the amount of suitable area was lower in January and increased significantly in April–May. Suitable areas maintained high scores during May–August. Because the spawning period of Japanese scallops begins in April–May in the Dalian coastal area (Chang et al., 2007), the suitability level in May will strongly affect the growth of scallops. Furthermore, based on the observed seasonal changes in each zone, we suspect that to maintain stable scallop aquaculture throughout the entire year, the values of scores in winter will also be important.

3.6. Climate events index variation

Climate change is a complex phenomenon influenced by many factors. Dalian is located in the middle and high latitudes, and both regions are subject to the effects of warm equatorial waters and monsoons; therefore, the two indices of winter MOI and ONI were used to explore the impact of climate change on the optimal areas of Japanese scallop aquaculture in the Dalian coastal area. The MOI is an index used to measure the winter EAM in East Asia (Yasuda and Hanawa, 1999). In this study, we hypothesized that cold surges from Siberia to Japan may affect the sea surface conditions around the Dalian coastal area. When the MOI increases, strong northerly winds generally prevail over the Yellow Sea during winter months (from December to February; Naimie et al., 2001). From the monthly time series of MOI anomalies during 2003–2012 (Fig. 7), winter MOI was strong in 2006 and 2011.

NOAA considers El Niño conditions to be present when the ONI is at least +0.5. These conditions will result in hot and dry, and even arid conditions in the northern part of China. Conversely, NOAA declares that La Niña conditions exist when the ONI is below –0.5, which may cause increased rainfall and falling temperatures in Northern China (Wang et al., 2000). We sorted El Niño and La Niña episodes into three categories: strong (>±1.5), moderate (±1.0–1.4), and weak (±0.5–0.9), based on ONI values (Stachelski and Czyzyk, 2008). From the monthly time series of ONI during 2003–2012 (Fig. 7), a strong El Niño took place during 2009–2010, and a moderate La Niña occurred during 2008–2009 and 2010–2011.

4. Discussion

4.1. SASSM development

This study employed a GIS-based model and used satellite remote-sensing data to develop a SASSM for Japanese scallop aquaculture in the Dalian coastal area. Environmental factors, such as SSC and bathymetry data, and social factors that were relevant to the Dalian coastal areas were incorporated into the model. Comparing the SASSM applied to Funka Bay, Japan (Radiarta et al., 2008), and to the Dalian coastal areas in this study, the results were comparable and highly consistent with current, *in situ* scallop culture operations. Therefore, this method could be applied to other regions to develop sustainable management strategies for scallop culture.

However, the SASSM in this study was not stereotypical and many areas exist in which the accuracy of the model could be improved. In the environmental model, additional factors that influence scallop growth and survival, such as salinity, dissolved oxygen, and freshwater discharge, could be included in the SASSM. Improvements in the social infrastructure model could be made by including more site-specific data, such as pollution discharge, tourist area, and military restricted zones. Moreover, continued improvements in GIS software and satellite remote-sensing technology will also improve the accuracy of the SASSM. Additionally, the SASSM could be applied to other coastal aquaculture species such as kelp and oyster.

A major limitation of the SASSM was the satellite remote-sensing data, which only accounts for changes in surface waters. While hanging cultures of scallops are kept at a depth of 5-20 m from the surface, the environmental conditions at this depth were different from those at the surface. Therefore, in the future, we will incorporate a numerical model, such as four-dimensional variational data assimilation system (4D-VAR; Ishikawa et al., 2009), to develop a three-dimensional SASSM for scallop aquaculture.

4.2. Comparisons of environmental factors and suitable scores in the four zones

Based on the different characteristics of these four zones, we generated mean values for environmental factors (Chl-a, SSC, and SST) and suitable scores for every month, in each zone, during 2003–2012. The mean values of Chl-a in Zones I and IV were much higher than those in Zones II and III (Fig. 8a). Average values of SSC were high in Zones II and III (6.0 g m^{-3} and 5.6 g m^{-3}, respectively), but low in Zones I and IV (3.9 g m^{-3} and 4.0 g m^{-3}, respectively; Fig. 8b). The average values of SST in every month were similar, but Zones I and IV had the lowest value in winter (Fig. 8c). The average suitability scores in Zones II and III (5.0 and 5.4, respectively) were higher than those in Zones I and IV (4.7 and 4.4, respectively; Fig. 8d). Among these values, the mean suitability scores in Zone III were the highest, but exhibited the largest fluctuations. A comparison of these four zones revealed that the concentrations of Chl-a and SSC in Zones I and IV differed from those of Zones II and III, likely because the main rivers of the region are distributed in ZH, PLD, and WFD, which occur in Zones I and IV; therefore, levels of pollution and suspended matter are much higher in these riverine zones than in other regions. Furthermore, Zone I was not very suitable for this species, even though many Japanese scallop aquaculture fields are distributed in the coastal waters of ZH. The apparent low suitability of this zone may be one reason that production is low in this region.

4.3. Correlation among climate events, environmental factors, and suitability scores

This study divided the Dalian coastal area into four zones based on their different characteristics and marine conditions. Additionally, we used climate event indices (MOI and ONI) to explore the impact of climate change on optimal areas for Japanese scallop aquaculture. Table 2 presents the correlations among environmental factors, suitable scores, and climate event indices for the different zones. Chl-a and SSC anomalies were significantly negatively correlated (–0.72 to –0.94, $P < 0.01$) in all zones. In Zone I, the correlation between SSC and score anomalies was also significant (0.29, $P < 0.05$), suggesting that SSC has become an important factor in this region. In Zone II, the correlations among factors were weak (except the correlation between Chl-a and SSC), which may explain why the seasonal changes in suitability scores were stable in Zone II. However, in Zone III, the suitability scores were correlated with Chl-a (–0.35, $P < 0.01$), SSC (0.24, $P < 0.05$), and SST (0.29, $P < 0.05$), suggesting that changes in the suitability area are susceptible to environmental factors in Zone III. Climate events can also directly influence sea temperatures. Our results indicate that the correlation between SST and score anomalies in Zones III and IV were –0.31 ($P < 0.05$) and –0.29 ($P < 0.05$), respectively. ENSO events may exert stronger effects more often in Zones III and IV than in the other two zones. For the entire seasonal analysis, the suitability scores in Zone III were more sensitive to changes in environmental factors and climate events indices (MOI and ONI), whereas the correlations among these factors were not significant in Zone II. Therefore, even if the suitability scores of Zone III are higher, Zone II is the most suitable for Japanese scallop aquaculture.

4.4. Impact of climate events on the suitability of an area

Because the EAM strongly affects East Asia in winter and ENSO events affect the Yellow Sea (Kuo et al., 2011), we combined MOI in January and ENSO events from the previous year to evaluate areas of different suitability levels in May of each year. When MOI was strong in winter, we found that the most suitable areas (scores 7 and 8) for scallop aquaculture were more abundant than in other years, such as 2006 and 2011 (Table 3). In particular, the most suitable areas in Zone III increased to 10.6% and 8.4%, in 2006 and 2011, respectively. This pattern was likely because during winter, northerly winds prevail, and shelf shallow sea convective mixing and eddy mixing are strongest; thus, deep-water nutrients brought to the surface result in plankton blooms (Naimie et al., 2001), which can provide food for scallop breeding in the spring. Beginning in May, northeasterly winds disappear, and the weak southeastward wind results in the YSWC entering the Yellow Sea from only the upper layer (Cui et al., 2004), and ocean conditions are stabilized.

By evaluating the suitable areas in El Niño years, we found that suitable sites for scallop aquaculture changed considerably relative to other years, with the percentage of the most suitable areas (scores 7 and 8) being significantly lower in El Niño years than in other years (Table 3). In particular, during June 2009–April 2010, a strong El Niño episode occurred, and the most suitable areas (scores 7 and 8) decreased to 1.7%, 4.0%, 4.9%, and 1.3% in Zones I, II, III, and IV, respectively. This phenomenon has also been confirmed by Japanese researchers; e.g., Baba et al. (2009) found that years of low spat density and low growth in the Japanese scallop corresponded with El Niño years. The ENSO events could affect the changes in sea temperature through oceanic and atmospheric circulation in this region (Chen et al., 2013).

In the last 10 years, the abnormal climate has also led to large changes in the suitability of the Dalian coastal area. This phenomenon may be one factor driving the large-scale mortality of Japanese scallops. Therefore, climate conditions must be considered for the future development of marine aquaculture.

5. Conclusions

Our results suggest that the GIS-based model is an effective tool for identifying the most suitable areas for Japanese scallop development. The final results revealed that the suitability scores of scallop aquaculture areas were high in May and low in February. From the spatial distribution maps, the coastal waters of Changhai County (Zone II) and LSKYS (Zone III) had the highest potential for scallop aquaculture development. However, the suitability scores in Zone III were more sensitive to changes in environmental factors and climate events indices (MOI and ONI), whereas Zone II was more stable. With reference to winter EAM and ENSO events, our results indicate that climate events have an impact on the environmental conditions of the Dalian coastal area through effects on SST and wind. For example, when the MOI was strong in winter, suitable areas in May were more abundant than in other years. However, after moderate and strong El Niño years, suitable areas for scallop aquaculture within the Dalian coastal area were less abundant than in other years.

Overall, our analyses suggest several recommendations for the aquaculture of Japanese scallops in the Dalian coastal area. First, it is important to establish standard criteria, scientific management, and informed distribution of aquaculture sites and reduce culture densities of scallops. Second, in years with strong climate change, the use of the hanging culture method for aquaculture should be reduced and the use of bottom cultures should be increased to reduce the effects of climate change at the surface of the marine environment on the output of scallop aquaculture. Third, a disaster compensation system should be established to reduce the impact of sudden natural or anthropogenic disasters on scallop aquaculture. Fourth, it is necessary to implement the Japanese total allowable scallop culture (TASC) system (Hirota and Kosaka, 2010), shift control from the total amount of aquaculture to total production, and encourage the production of high-value and large-sized scallops to increase the income of farmers. Fifth, the pollution of rivers and offshore areas of the Dalian coastal area must be controlled.

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Table 1

Regional division codes for the Dalian coastal area.

Zone	ID	Name	Water area (km^2)	GIS-code
I	1	Zhuanghe	1765.64	ZH
	2	Pulandian	302.19	PLD
II	3	Changshandao	1384.68	CSD
	4	Haiyangxiang	1018.59	HYX
	5	Zhangzhidao	1006.45	ZZD
	6	Guangluxiang	659.96	GLX
III	7	Jinzhouyellowsea	919.39	JZYS
	8	Main city(yellow sea side)	582.15	MCYS
	9	Lushunkou(yellow sea side)	458.04	LSKYS
IV	10	Lushunkou(bohai sea side)	1016.73	LSKBS
	11	Main city(bohai sea side)	795.29	MCBS
	12	Jinzhou(bohai sea side)	360.16	JZBS
	13	Wafangdian	1662.50	WFD

Table 2

Pearson's correlation coefficients among environmental factors, suitability scores, and climate events, for the different zones in the Dalian coastal area during 2003–2012.

Zone I	Chl-α	SST	SSC	Score
Chl-α	1.00			
SST	0.02	1.00		
SSC	-0.72**	-0.02	1.00	
Score	0.01	0.03	0.29*	1.00
MOI	-0.01	-0.03	0.01	0.02
ONI	0.10	-0.15	-0.06	0.05
Zone II	**Chl-α**	**SST**	**SSC**	**Score**
Chl-α	1.00			
SST	0.09	1.00		
SSC	-0.92**	-0.02	1.00	
Score	0.08	0.19	-0.03	1.00
MOI	0.06	-0.10	0.01	0.06
ONI	0.06	-0.13	-0.08	0.11
Zone III	**Chl-α**	**SST**	**SSC**	**Score**
Chl-α	1.00			
SST	0.11	1.00		
SSC	-0.87**	0.01	1.00	
Score	-0.35**	0.29*	0.24*	1.00
MOI	0.02	-0.05	-0.01	-0.01
ONI	0.12	-0.31*	-0.18	0.02
Zone IV	**Chl-α**	**SST**	**SSC**	**Score**
Chl-α	1.00			
SST	0.04	1.00		
SSC	0.94**	0.03	1.00	
Score	0.16	0.04	0.11	1.00
MOI	-0.04	-0.02	0.01	0.15
ONI	-0.02	-0.29*	-0.05	-0.07

*Correlation is significant at the 0.05 level.
**Correlation is significant at the 0.01 level.

Table 3. Different suitability levels (expressed as a percentage of the total potential area) for Japanese scallops in May of each year in the Dalian coastal area, combined with the East Asia monsoon (EAM) of that year and El Niño/La Niña–Southern Oscillation (ENSO) events occurring during the previous year.

Year				**Suitability scores (%)**						ENSO **
Zone I	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**MOI***	**Pre. Year**
May 2004	0.0	0.0	1.2	9.6	81.5	6.3	1.5	0.0	Weak	Normal
May 2005	0.0	0.0	0.2	1.6	78.3	16.1	3.8	0.0	Middle	Weak El
May 2006	0.0	0.0	0.4	2.2	76.6	16.3	4.5	0.0	Strong	Weak La
May 2007	0.1	0.3	2.1	9.6	80.4	6.5	1.1	0.0	Weak	Moderate El
May 2008	0.2	0.7	1.7	1.3	74.4	17.0	4.7	0.0	Middle	Moderate La
May 2009	0.1	0.0	1.0	6.2	77.9	11.5	3.3	0.0	Weak	Weak La
May 2010	0.0	0.0	0.6	2.5	82.3	12.9	1.6	0.1	Weak	Strong El
May 2011	0.0	0.0	0.5	3.0	84.3	9.7	2.3	0.0	Strong	Moderate La
May 2012	0.0	0.0	1.5	9.3	75.4	10.3	3.4	0.0	Middle	Weak La
Year				**Suitability scores (%)**						
Zone II	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**		
May 2004	0.0	0.0	0.1	3.5	85.4	7.4	3.1	0.4	Weak	Normal
May 2005	0.0	0.0	0.0	0.1	77.9	16.8	4.0	1.1	Middle	Weak El
May 2006	0.0	0.0	0.0	0.2	76.2	16.8	5.9	0.8	Strong	Weak La
May 2007	0.0	0.0	0.3	4.3	83.4	8.4	3.0	0.6	Weak	Moderate El
May 2008	0.0	0.0	0.8	0.8	73.6	18.1	5.2	1.4	Middle	Moderate La
May 2009	0.0	0.0	0.2	2.7	79.7	12.2	4.0	1.3	Weak	Weak La
May 2010	0.0	0.0	0.1	2.6	78.9	14.4	3.8	0.2	Weak	Strong El
May 2011	0.0	0.0	0.1	0.2	73.8	18.2	6.8	0.8	Strong	Moderate La
May 2012	0.0	0.0	0.0	3.4	77.4	13.8	4.9	0.5	Middle	Weak La
Year				**Suitability scores (%)**						
Zone III	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**		
May 2004	0.0	0.0	0.0	0.1	84.2	9.9	4.8	0.9	Weak	Normal
May 2005	0.0	0.0	0.0	0.0	80.7	11.0	7.0	1.3	Middle	Weak El
May 2006	0.0	0.0	0.0	0.0	79.0	10.3	9.3	1.3	Strong	Weak La
May 2007	0.0	0.0	0.2	1.7	84.6	8.5	4.8	0.2	Weak	Moderate El
May 2008	0.0	0.0	0.0	0.1	78.7	11.9	7.4	1.9	Middle	Moderate La
May 2009	0.0	0.0	0.0	0.1	81.2	10.4	7.0	1.4	Weak	Weak La
May 2010	0.0	0.0	0.0	0.1	84.4	10.6	4.7	0.2	Weak	Strong El
May 2011	0.0	0.0	0.0	0.0	79.7	11.8	7.5	0.9	Strong	Moderate La
May 2012	0.0	0.0	0.0	0.1	82.1	10.5	6.7	0.6	Middle	Weak La
Year				**Suitability scores (%)**						
Zone IV	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**		
May 2004	0.0	0.0	0.6	2.3	81.6	9.3	5.2	1.0	Weak	Normal
May 2005	0.0	0.0	0.7	2.0	78.5	14.8	3.8	0.3	Middle	Weak El
May 2006	0.0	0.0	0.1	0.9	78.3	14.4	5.2	1.1	Strong	Weak La
May 2007	0.0	0.1	2.9	6.7	84.5	4.3	1.3	0.3	Weak	Moderate El
May 2008	0.0	0.1	1.2	5.6	74.2	15.1	3.7	0.1	Middle	Moderate La
May 2009	0.0	0.0	1.1	3.0	77.7	15.2	2.6	0.5	Weak	Weak La
May 2010	0.0	0.0	1.2	10.5	80.7	6.4	1.2	0.1	Weak	Strong El
May 2011	0.0	0.0	0.4	2.7	79.0	13.7	3.9	0.2	Strong	Moderate La
May 2012	0.0	0.0	0.9	5.1	78.4	12.8	2.7	0.1	Middle	Weak La

*MOI: winter Monsoon Index;   **ENSO: El Niño/La Niña-Southern Oscillation

Figure captions.

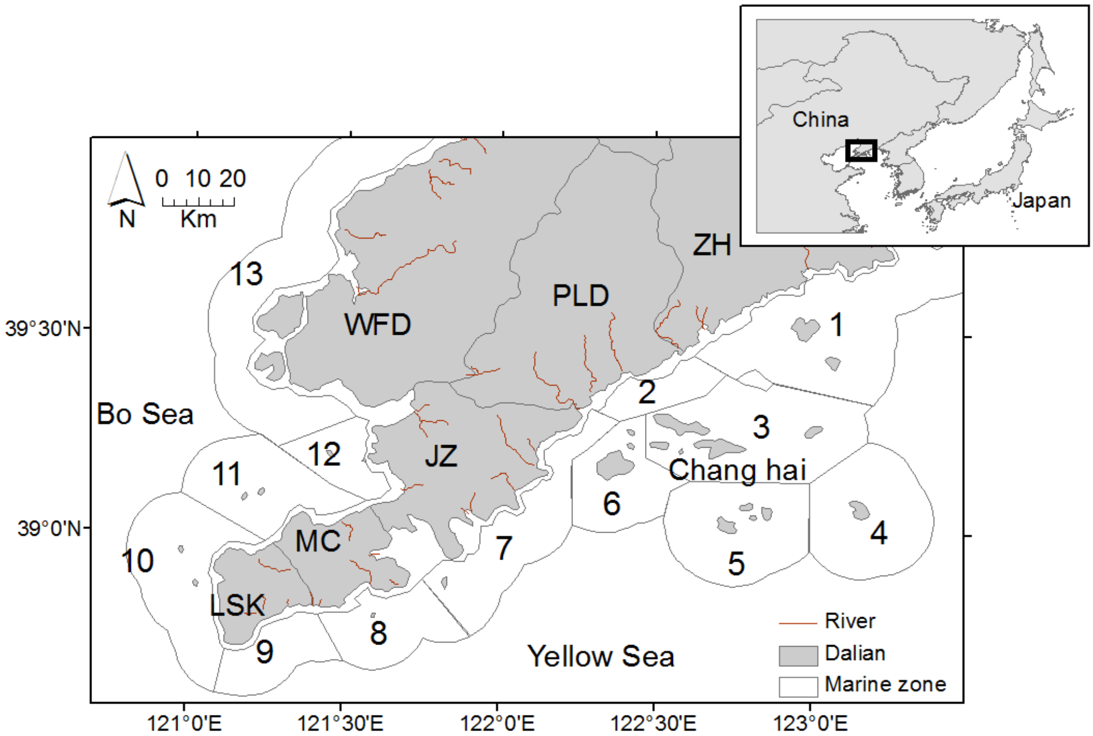

Fig. 1. Study area and regional divisions (see Table 1).

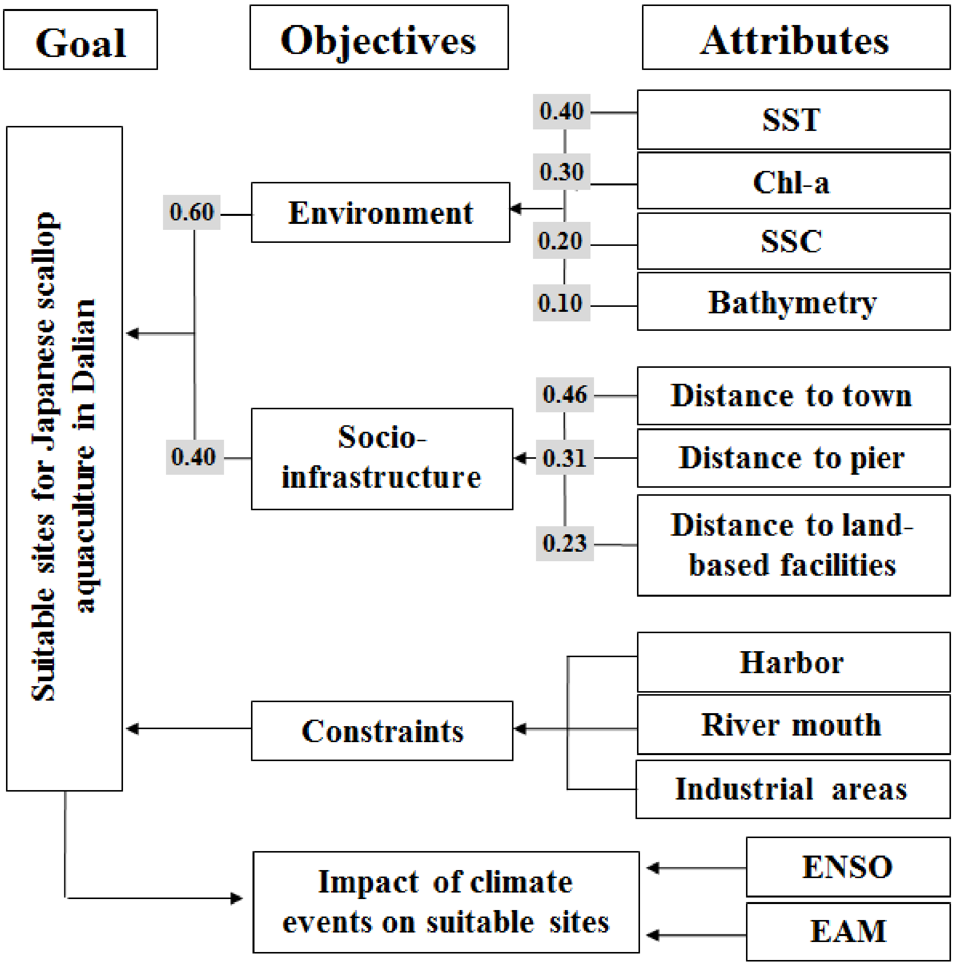

Fig. 2. Schematic diagram of the suitable aquaculture site-selection model (SASSM).

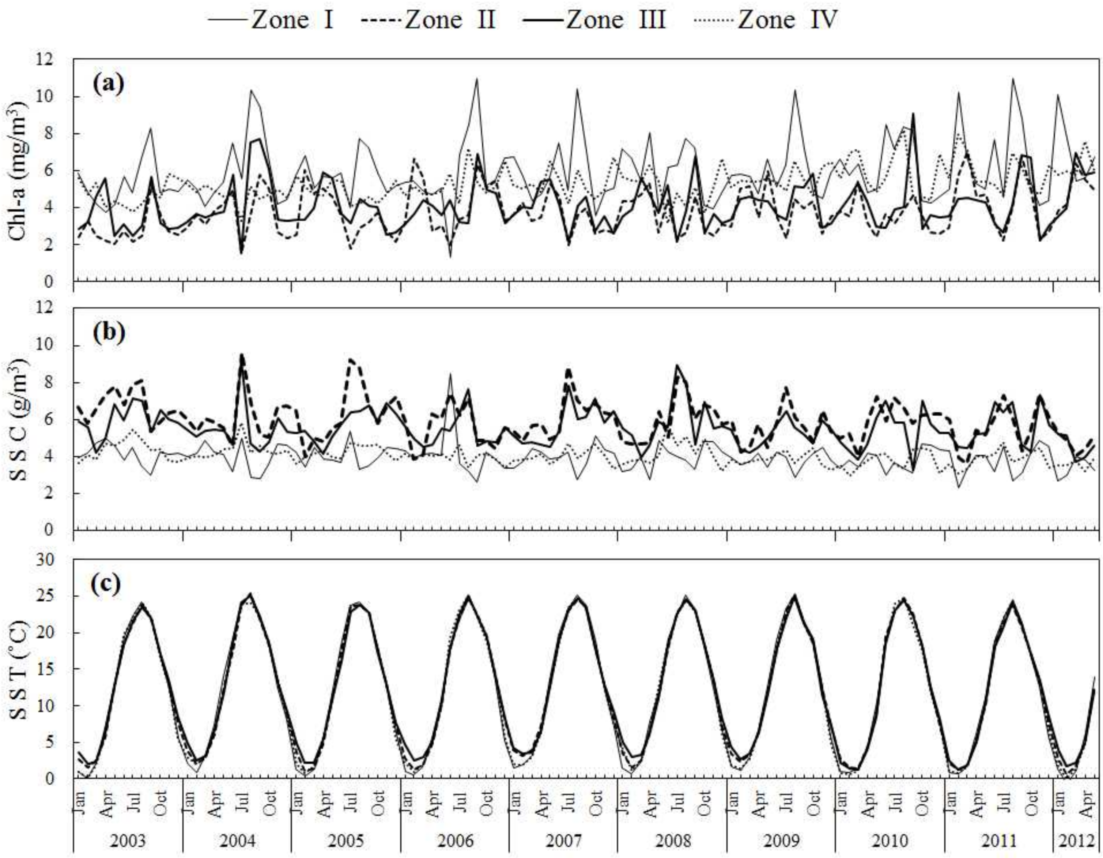

Fig. 3. Time series of monthly (a) chlorophyll-a (Chl-a) concentration, (b) suspended sediment concentration (SSC), and (c) sea surface temperature (SST) for the four marine zones of the Dalian coastal area from 2003 to 2012.

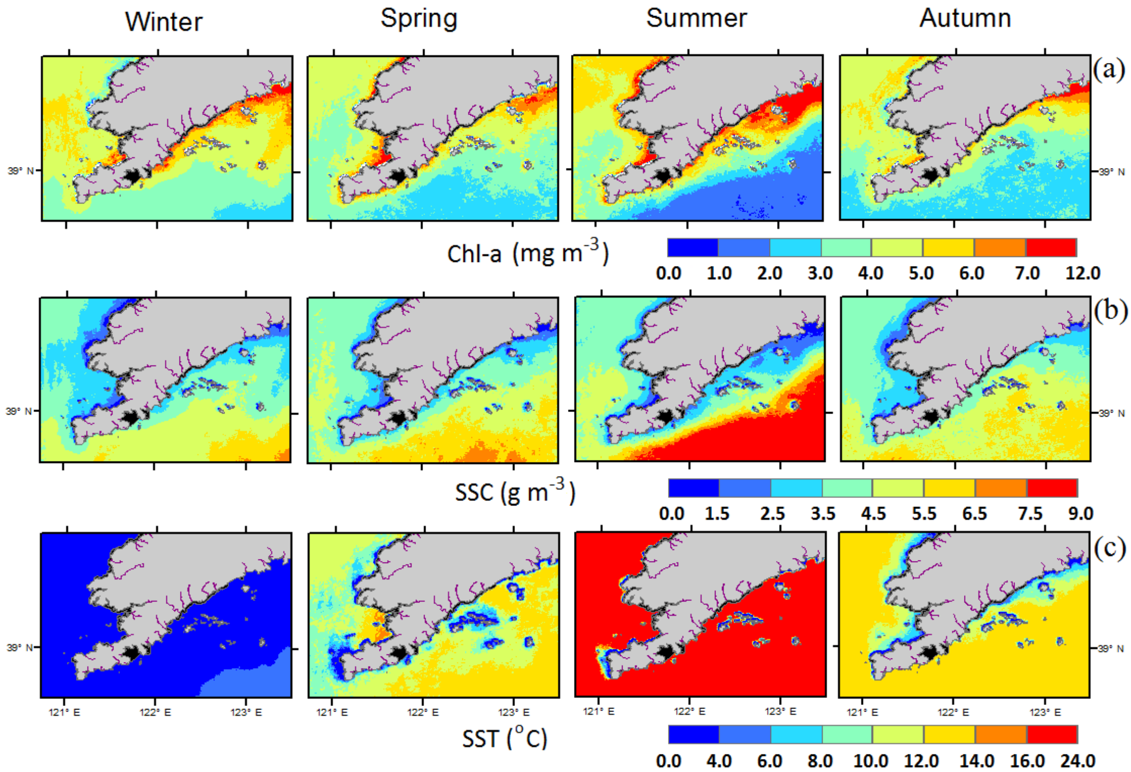

Fig. 4. Spatial distribution of the variability in seasonal averages of (a) chlorophyll-a (Chl-a), (b) suspended sediment concentration (SSC), and (c) sea surface temperature (SST) in the Dalian coastal area from 2003 to 2012.

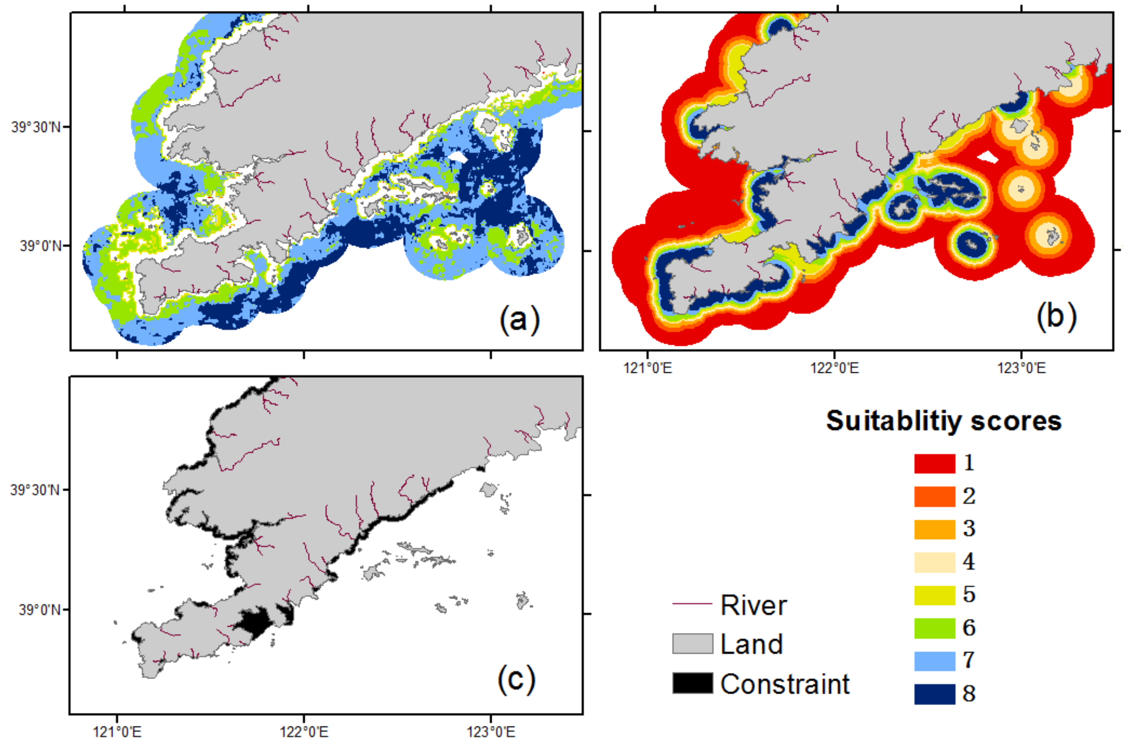

Fig. 5. Suitability maps for sub-models and the final model of Japanese scallop aquaculture in the Dalian coastal area. (a) Environmental model (May 2009), (b) social infrastructure model, and (c) constraints model.

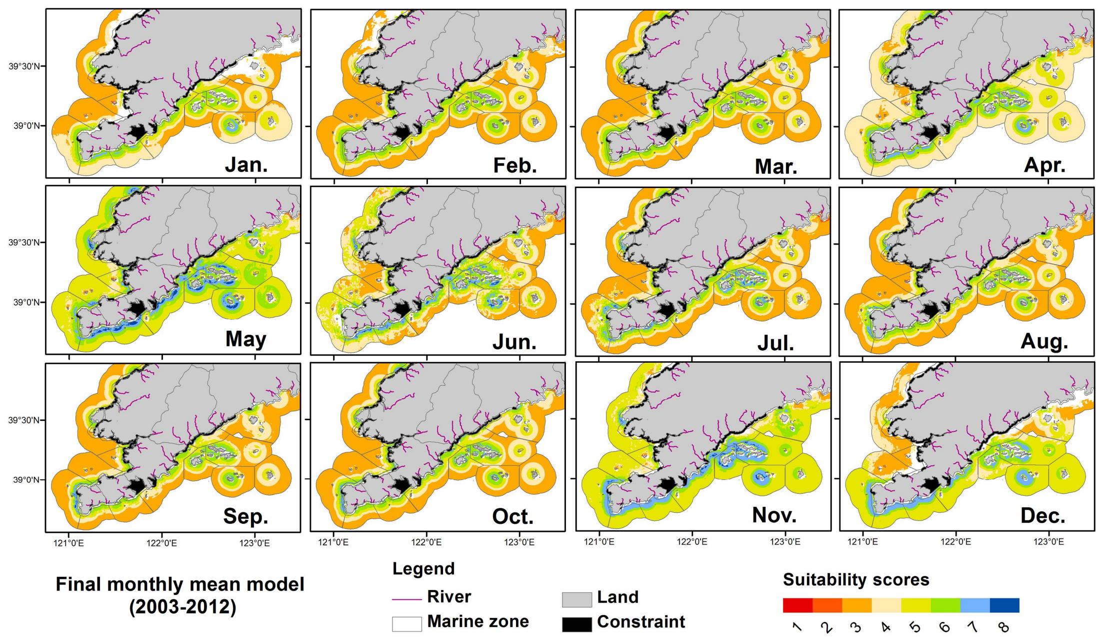

Fig. 6. Final monthly mean suitability maps for Japanese scallop aquaculture in the Dalian coastal area from 2003 to 2012.

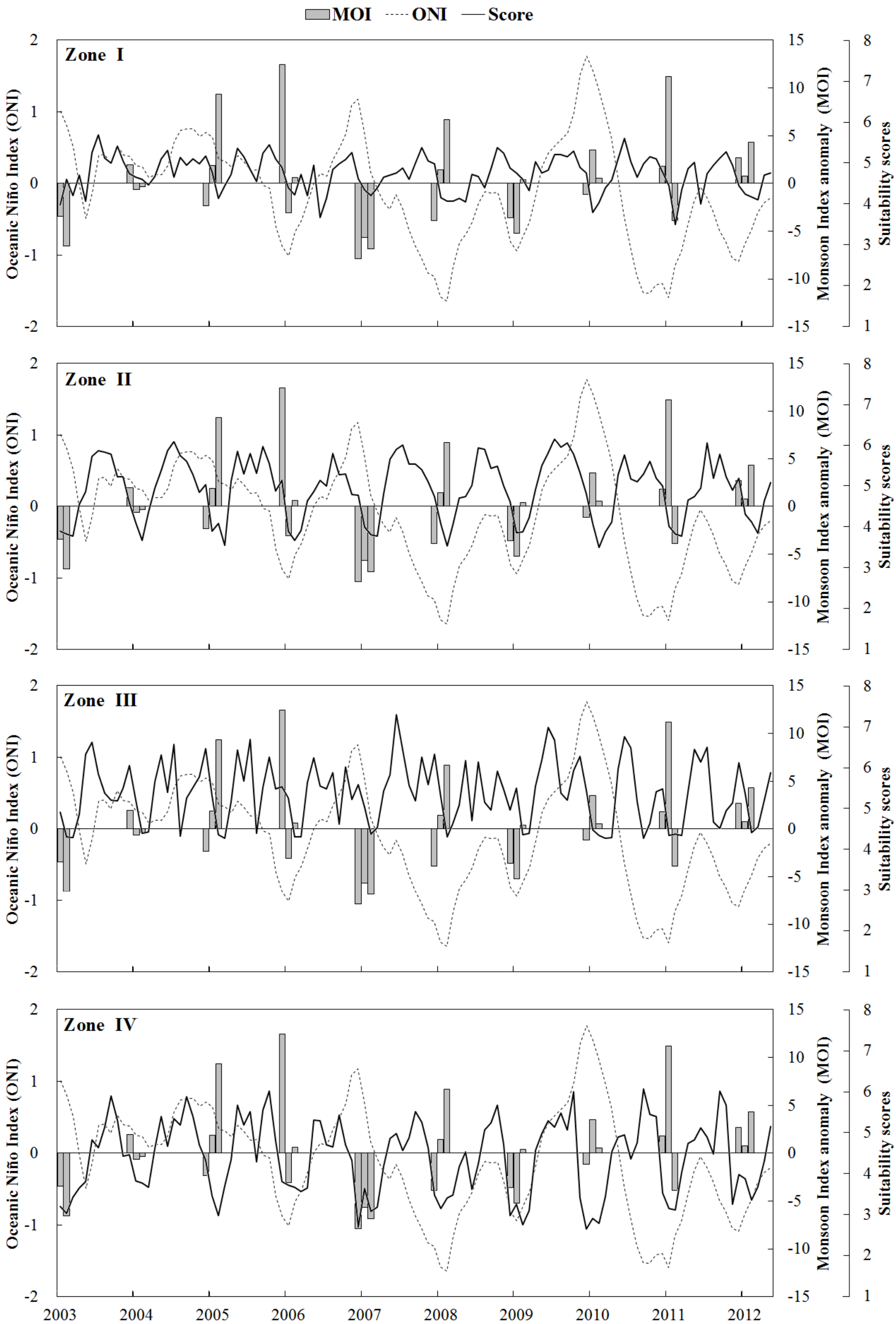

Fig. 7. Time series of the suitability score, winter Monsoon Index (MOI) anomalies, and Oceanic Niño Index (ONI) in the four marine zones of the Dalian coastal area. The anomalies were calculated relative to the monthly means for 2003–2012.

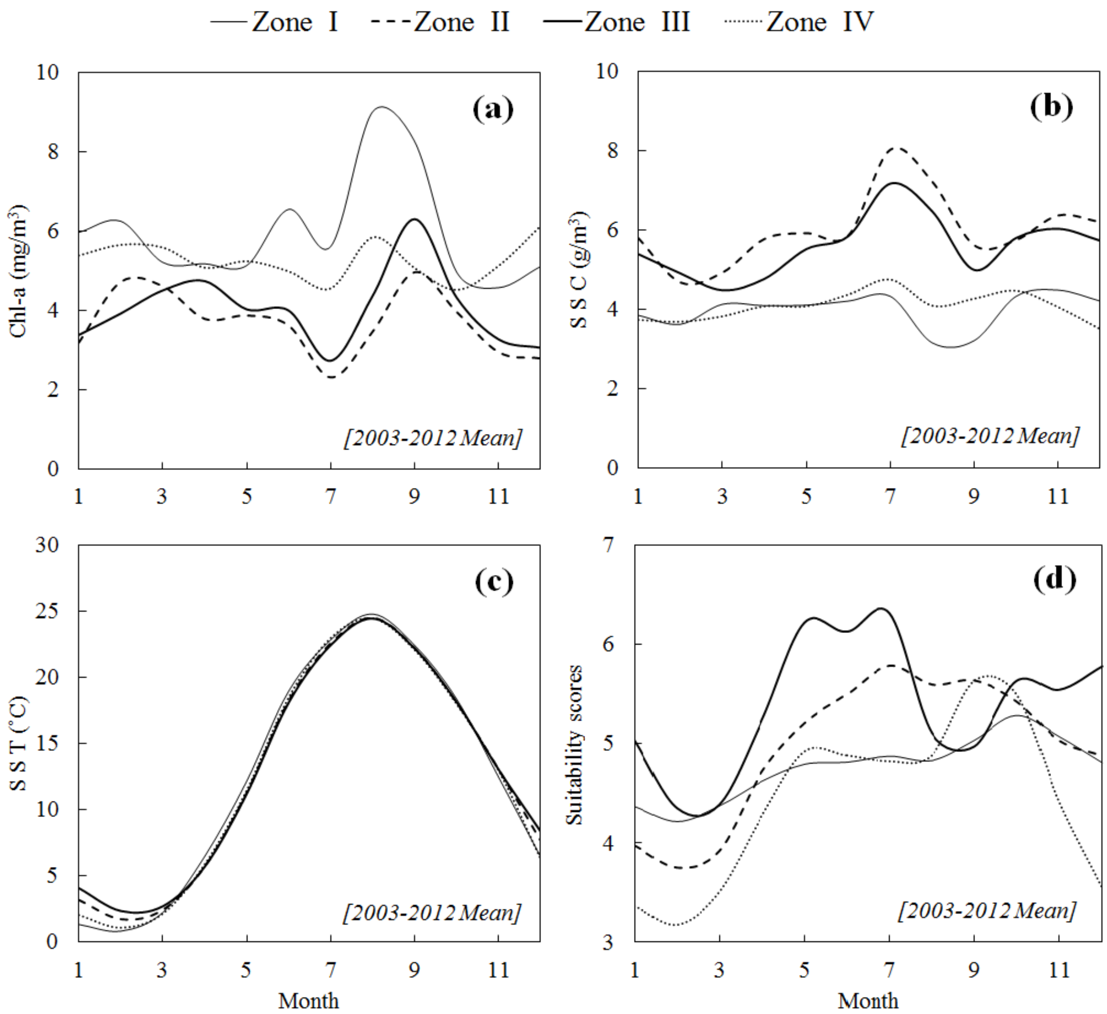

Fig. 8. Seasonal changes in the monthly mean values of (a) chlorophyll-a (Chl-a) concentration, (b) suspended sediment concentration (SSC), (c) sea surface temperature (SST), and (d) suitability scores in each marine zone in the Dalian coastal area from 2003 to 2012.