Aquaculture 366–367 (2012) 105–114

Contents lists available at SciVerse ScienceDirect

Aquaculture

journal homepage: www.elsevier.com/locate/aqua-online

Interannual variation in commercial oyster (*Crassostrea gigas*) farming in the sea (Florianópolis, Brazil, 27°44′ S; 48°33′ W) in relation to temperature, chlorophyll *a* and associated oceanographic conditions

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ARTICLE INFO

Article history:
Received 13 July 2011
Received in revised form 8 September 2012
Accepted 11 September 2012
Available online 19 September 2012

Keywords:
Oyster
Crassostrea gigas
Chlorophyll
Temperature
El Niño
La Niña

ABSTRACT

Aquaculture of filter-feeding bivalve mollusks involves the fruitful conversion of marine particulate organic matter into premium protein of high nutritive value. Culture performance of bivalves is largely dependent on hydrological conditions and directly affected by *e.g.* temperature and chlorophyll levels. Accordingly, these parameters may be related with seasonality but also with oceanographic features combined with climate events. Yields of Pacific cupped oyster (*Crassostrea gigas*) reared at commercial procedures in suspended structures (long-lines) in a sheltered bay in Southern Brazil (Santa Catarina State, 27S 43′; 48 W 30′) were evaluated in relation to local environmental conditions: sea surface temperature, chlorophyll *a* concentration, and associate effects of cold fronts events and El Niño and La Niña periods. Outputs from four consecutive commercial crop years were analyzed (2005/06, 2006/07, 2007/08, 2008/09) in terms of oyster survival and development time during the following grow-out phases of the culture cycle: seed to juvenile, juvenile to adult, adult to marketable. Since culture management and genetics were standardized significant differences verified among crop performance could be mostly related to environmental effects. Time series of temperature and chlorophyll *a* (remote sensing data) from crop periods displayed significant seasonal and interannual variation. As expected, performance during initial grow-out stages (seed to juvenile) was critical for final crop yield. Temperature was the main factor affecting survival in these initial stages with a trend of negative correlation, though not statistically significant. On the other hand, oyster development rate was significantly and positively affected by chlorophyll *a* concentration. Chlorophyll *a* values could be increased by upwelled cold nutrient-rich South Atlantic Central Water (SACW, related to predominant Northern winds) though further dependent on occurrence of Southern winds (cold fronts) to assist seawater penetration into the sheltered farming area. Lower salinity nutrient-rich northward drifted waters from La Plata River discharge may also result in chlorophyll *a* rise in the farming area. The El Niño period (July 2006 to February 2007) coincided with lower chlorophyll *a* levels in the farming site that may be related to both decreased number of cold fronts as well as predominance of Northern winds that retain northward spreading of La Plata River discharge waters. In contrast, the La Niña period (August 2007 to June 2008) corresponded to higher chlorophyll *a* values in the farming area by both upwelling of SACW and penetration of La Plata River discharge water assisted by increased occurrence of Southern winds and cold fronts. The recognition of the potentially changing climate and effects upon the environment will be an important step in planning future development of bivalve aquaculture.

1. Introduction

The aquaculture of filter feeding shellfish takes advantage of natural water productivity, transforming primary productivity into high nutritional quality animal protein (Matsuura, 2001). To achieve the adequate growth bivalves primarily require a productive environment with adequate availability of phytoplankton and particulate organic matter (Silva, 1998), as well as a proper range in abiotic conditions as temperature and salinity. Therefore, these characteristics make them extremely dependent on the farming environment. The environmental characteristics of the farming site may not only define carrying capacity (Byron et al., 2011a), but also the economical feasibility in setting a suitable farming management (Brandini et al., 2000; Spencer, 2002). Specifically for farming marine open waters, the differences in culture performance according to farming site may

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http://dx.doi.org/10.1016/j.aquaculture.2012.09.011

highlight and reflect local environmental characteristics. Though initial attempts to consider farm-scale features linked with the ecological and economical optimization of culture practices have been reported (Ferreira et al., 2007), essential environmental features as food availability are not usually considered in commercial farm management. Moreover, there may be a lack of science consideration due to ineffective communication between scientists and stakeholders, farmers, managers and decision makers (Byron et al., 2011b). This may be highlighted if considered potential climate changes upon farming yields (De Silva, 2010; Everett and Garcia, 2005).

Under open aquaculture systems outputs from bivalve farming are closely related to the ability of species and management to cope with a fluctuating aquatic environment, subject to shifts in physical and biological water conditions according to inter-related factors including seasonality, coastline physiography, continental runoff, ocean dynamics, meso and large scale hydrological and climatic phenomena (Dame and Prins, 1998; Hollowed et al., 2009; Kobayashi et al., 1997). A deeper understanding on these hydrological characteristics and their possibly cyclical condition may assist better crop planning and management as well as the search for new suitable culture sites. Basic oceanographic assessment in farming sites such as water characteristics and dynamics may provide useful data to be further considered for a better understanding of crop success. In addition, the access to real time data bases on environmental features may be a self-learning tool to add to the peculiarities of managing a bivalve farm. The research on this topic appears to be few developed and has been found scarce in the literature though the obvious potential for application in farming filter-feeding species (Thomas et al., 2011).

The present survey examined possible relationships between oyster (*Crassostrea gigas*) performance and variation in water temperature and chlorophyll *a* concentration in the main Brazilian oyster farming region: South Bay, Santa Catarina Island and State. Although environmental characteristics play an important role in production and therefore may determine the success of a bivalve farm, information on how could this be related to the farming environment is still scarce. Oyster yields under commercial practices were presently assessed during a four-year crop period in relation to effects of temperature seasonal cycles and food availability. The occurrence of cold fronts as well as larger scale climatic events (El-Niño/La-Niña) and water enrichment processes were further considered in the interpretation of variations in food availability in the farming site.

2. Materials and methods

2.1. Study site

Oyster grow-out in suspended vertical devices (lantern nets) installed at the island side of the South Bay (Ribeirão da Ilha), Santa Catarina State, Brazil (27°44′ S; 48°33′ W), was considered for the survey (Fig. 1). The study site is located in the Southern portion of the channel (7 km width, 1 to 9 m depth) comprised between the continental border and the Santa Catarina Island, characterized by calm waters with some small river discharges and minimum tide variation (Cruz, 1998; Knopper et al., 2002). The bay may be reached by upwelled cold nutrient rich waters (16–17 °C, salinity 35.5‰) from South Atlantic Central Water (SACW) depending on the intensity and period of Northern winds (Silveira and Möller, 1998, 1999) possibly combined with cold front events which facilitate shelf water penetration into the South Bay farming area (Silveira et al., 2006a,b). The zone is also influenced by the La Plata River (34°54′ S; 57°00′ W) plume

Fig. 1. Oyster farming location (circled), Ribeirão da Ilha, Santa Catarina Island, Santa Catarina State, Brazil.

that may spread northward to Santa Catarina State coast (Piola et al., 2000) depending on winds predominant direction from La Plata River estuary (34°54′ S; 57°00′ W) (Möller et al., 2008; Piola et al., 2005). South Bay is few occupied with much less than 1% of the total area dedicated to bivalve aquaculture, thus the hydrological parameters determined may be mostly unaffected by farming self-residues.

2.2. Farm management

The long-line employed consisted of a cable which floats on the surface, supported by plastic buoys. Hanging from these cables toward the bottom are the oyster lanterns, typical culture equipment for the grow-out phase. Oyster production numbers at commercial level from different crop years (2005, 2006, 2007 and 2008) were obtained from Atlântico Sul Marine Farm (www.fazendamarinha.com.br). Data included initially stocked seed number, dates of long-line management along the farming cycles and oyster outputs at different farming ages. The farm comprises ca. 35 ha of suspended parallel long-lines with 100 meters length each and 10 meters distance between them, installed at average depth of 4.0 m (range: 2.5 to 6.0 m). Oysters were classified progressively in four different classes according to shell length increase in the course of farming: seed (>3 mm), juvenile (>3 cm), adult (>5 cm) and marketable (7–12 cm). Marketable oyster class is further divided to satisfy market needs in small (≤7 cm), medium (8–9 cm), large (10–11 cm) and extra large (≥12 cm) individuals. Different culture devices may be employed according to oyster size class (Fig. 2). Oyster seeds from same genetic origin were purchased from a local public hatchery (LMM, Federal University of Santa Catarina, Florianópolis) at sizes 3 and 5 mm mean shell length. Crops were yearly initiated with seed stocking in floating nursery boxes between March and April, however successive monthly stockings may also be done throughout a year. Although the number of seed stocked may have varied among assessed crop years, farming management was standardized since stocking density was maintained similar. Each simultaneous seed stocking comprised an allotment, and several allotments in a year will constitute the crop. For the present survey only one allotment of each yearly crop (March or April seed stocking) was considered and thus the terms 'allotment' and 'crop' may be presently used as synonyms.

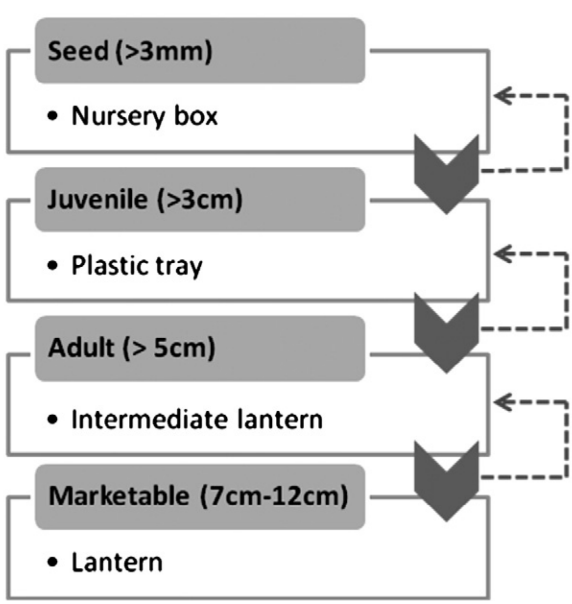

Fig. 2. Oyster culture steps and related farming equipment, according to oyster shell size in brackets. Dotted arrows show the possibility of oyster size class to return to the same culture device if the shell size is not adequate to the next step.

Farm management routine included growing devices taken out from the sea in intervals of 15 to 30 days with individuals separated by different sieve sets and sorting strategies. Individuals grown to the next size class were reallocated according to the rearing sequence (Fig. 2) and those which have not grown sufficiently to pass to the next step were returned to the same equipment back in the sea. Oyster transfer between growing devices is dependent on both culture density and oyster size. The density is set lower after each sorting management (when devices are taken out from the sea) as to allow for individual oyster growth inside lantern available volume. After reaching the last size class (marketable) oysters were visually sorted according to size in a selection table. At the assessed site, a crop regularly extends oyster outputs for up to 1.5 year since initial seed stocking. Four annual crops were assessed: 2005/06 stocked in April, and 2006/07, 2007/08 and 2008/09, stocked in March. Three to five millimeters seeds were stocked for the crops initiated in 2005, 2006 and 2008, and 5 mm seeds for the crop started in 2007. Data from these specific crops were selected due to standardized farm management protocol, and same seed genetic origin. Thus, differences among annual outputs were assumed to be mostly related to environmental effects. The asynchrony in oyster development under sea farming conditions generates several outputs of a certain size class in the course of the crop period. Oyster productive performance was determined during crops according to different rearing phases: seed to juvenile (referred as phase 1), juvenile to adult (phase 2) and adult to marketable (phase 3). Relative outputs of each size class were computed and expressed as survival (%) in relation to the initial oysters stocked in the phase. Final crop survival was calculated as the ratio between total marketable oyster output and the initially stocked seed number. Accordingly, phase–specific period for oyster development was also computed in the evaluation of productive performance. A Performance Index (*Pi*) was calculated for each respective rearing phase and final crop in order to balance for survival (%) in relation to development rate expressed as phase or crop time interval (months):

$$Pi = (\text{survival}/\text{phase or crop time interval}).$$

2.3. Environmental data

Daily sea surface temperature (SST) values were determined in a single local station (27°44′ S; 48°33′ W) within the farming area using a manual thermometer at 50 cm depth. Remote sensing temperature data in the farming area were obtained from ANTARES Project database (www.dsr.inpe.br/antares/) to be further compared to *in situ* determined temperature. Surface temperature (horizontal distribution) may sometimes vary according to displacement of different temperature water masses inside the bay. Temperature stratification in the water column may also occur especially at higher depths, in conditions of calm winds, and may be more pronounced in winter. Remote sensing temperature values may be considered an average of temperatures in the area. Remote sensing data were not available for each day of the survey period because of its dependence on clouds coverage. Available remote sensing data were regressed against *in situ* determined water temperature ($n = 182$) to check for prediction capacity in the farming area.

Chlorophyll *a* was also assessed by remote sensing outputs of ocean color (ANTARES Project: www.dsr.inpe.br/antares/). However, chlorophyll *a* values estimated from satellite images is usually overestimated in shallow waters or water bodies with large continental sediment runoff and gelbstoff (colored dissolved organic matter) (Martinez et al., 2005). A linear regression between available remote sensing values and reported *in situ* chlorophyll *a* concentration in the bay area ($n = 24$) (Ferreira et al., 2004; Parizotto, 2009; Rupp, 2007) was calculated to take into account this bias. In the reference surveys, methods reported for chlorophyll *a* determination showed consistent for analysis in different environments (Dos Santos et al., 2003; Murray et al., 1986; Rivera et al., 2005), so even though these references used different techniques for chlorophyll *a* determination, data could be considered comparable. Time series for chlorophyll *a* levels in the farming area during crop periods (y) were obtained after applying the linear model for available remote sensing data (x).

Predominant wind direction and occurrence of cold fronts in the farming area, as well as El Niño/ La Niña events in the crop time series (2005 to 2009), were evaluated to check for possible effects upon natural productivity, as represented by seawater chlorophyll *a* levels. Predominant wind directions were monthly compiled from the Santa Catarina State Agricultural Research and Rural Extension Agency (ciram.epagri.rct-sc.br). Monthly cold fronts occurrence was obtained from the weather bulletins released by Brazil Weather and Climate Studies Center, National Institute for Space Research (INPE: www.inpe.br). Data on El Niño/La Niña (Oceanic Niño Index, ONI) were obtained from United States National Oceanic and Atmospheric Administration (NOAA: www.cpc.noaa.gov/). ONI values were obtained for the 3.4 Pacific Ocean region so that positive (≥ 0.5 °C) or negative (≤ -0.5 °C) deviations were indicative of El Niño or La Niña periods, respectively. El Niño/ La Niña were also considered as possible environmental factors upon the farming site because they may affect La Plata River plume dislocation along Southern Brazilian coast. During El Niño periods, even though the elevated precipitation and increased discharge in the zone, the NE prevailing winds would displace the plume offshore; whereas during La Niña periods the SE winds may enable increased plume penetration into the sheltered farming area (South Bay of Santa Catarina Island) (Piola et al., 2005).

During cold front events southerly winds may push waters inside the South Bay and thus affect chlorophyll *a* concentration (Silveira et al., 2006a,b). To assess this hypothesis chlorophyll *a* variation (ΔChl *a*) in the South Bay was calculated as the difference between chlorophyll *a* concentration (mg.m^{-3}) during cold fronts (Chl a_{CF}) events and chlorophyll *a* concentration (mg.m^{-3}) in adjacent days (Chl $a_{B/A}$: immediately before or after cold fronts, depending on available data), accordingly to meteorological data assessed. The ΔChl *a* values were than related to the El Niño and La Niña periods and possible effects upon oyster crop performance were checked.

Crop performance in the different rearing phases (*i.e.* seed to juvenile, juvenile to adult, adult to marketable) was compared to hydrological features. Survival and duration of rearing phases were regressed with mean water temperature or chlorophyll *a* levels in the farming area.

2.4. Statistical analysis

The relationships between remote sensing data and *in situ* measurements for temperature and chlorophyll *a* were evaluated by linear regression models. Similar analysis was employed to study the relationships between these environmental variables and oyster performance. Pearson correlation tested the significance of relationships found in regressions, as denoted by the determination coefficient (R^2) and P value.

3. Results

3.1. Crop output

During the crop years assessed, oysters at the juvenile size class could be obtained from 30 to 240 days after initial seed stocking (Fig. 3). However, most seeded individuals attained juvenile size at 60–120 farming days. Adults and marketable individuals were achieved after 60 to 450 and 150 to 510 days after seed stocking, respectively. On the other hand, the majority of seeded individuals reached juvenile and marketable sizes at 90–180 and 150–270 days, respectively. Crop outputs as denoted by survival were different among each other throughout the crop period showing a considerable variation according to crop years in the different size classes. The juvenile class showed the most homogenous survival rate *per* month among crops evaluated as denoted by the coefficient of variation in comparison with variation in adult and marketable size classes. The high variation in oyster outputs from different years, under standardized management protocols, confirmed the hypothesis of a significant environmental effect upon crop outputs. First marketable sized oysters could be obtained within 5 months from seed stocking although last crop fraction could extend to as long as 18 months to be harvested.

3.2. Oyster performance

The juvenile to adult development (phase 2) had comparative higher crop survivals and Performance Index (*Pi*) (Table 1, Fig. 4), showing survival played an important role upon oyster performance. Final survival was higher in crop 2008/09 (43.1%), followed by 2005/

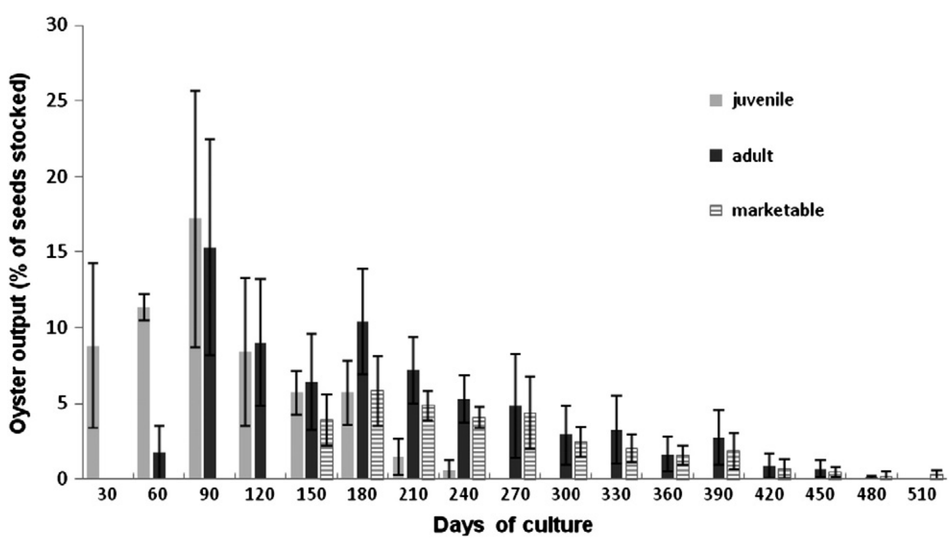

Fig. 3. Oyster (*Crassostrea gigas*) output as percentage of seeds stocked in different size classes (juvenile, adult, marketable) along the culture cycle. Values expressed as mean (error bars = standard deviation) for output of size classes from crops 2005/06, 2006/07, 2007/08 and 2008/09.

Table 1
Production details of Pacific cupped oyster (*Crassostrea gigas*) farmed in the sea in suspended long-lines during four year crops in South Bay, Santa Catarina Island, Brazil (27°44′ S; 48°33′ W). Oyster seeds yearly stocked in March or April. Culture phases are identified according to oyster development in size classes: phase 1 = seed (>3 mm) to juvenile (>3 cm), phase 2 = juvenile to adult (>5 cm), phase 3 = adult to marketable (7 to 12 cm). Farm management included individual sorting in intervals of 15 to 30 days. Further details in Materials and methods.

Crop year	Initial number of seeds stocked	Number of juveniles produced	Number of adults produced	Final number of marketables produced	Survival (%)				Time to harvest (months)			
					Phase 1	Phase 2	Phase 3	Final	Phase 1	Phase 2	Phase 3	Final
2005/06	1,227,964	526,300	461,520	341,988	42.8	87.6	74.1	27.8	8	7	13	18
2006/07	1,896,435	604,800	481,680	367,931	31.8	79.6	76.4	19.4	6	8	12	17
2007/08	2,148,680	788,200	785,520	588,564	36.6	99.6	74.9	27.4	5	6	8	13
2008/09	913,980	611,100	536,760	394,410	66.8	87.8	73.5	43.2	6	6	10	15

06 and 2007/08 (27.8 and 27.4%, respectively) and last by 2006/07, with even reduced values (19.4%) (Table 1). Oyster grew faster in 2007/08 and crop exhibited the lowest rearing period in all phases, whereas the 2005/06 was overall the crop that took the longest development. Final *Pi* was lower in crops 2005/06 and 2006/07 mainly because of longer culture period while in crops 2007/08 and 2008/09 elevated *Pi* values were related to both elevated survival followed by shorter farming period. Final crop survival and *Pi* showed significantly affected by performance in the seed-juvenile rearing phase (Table 2). When final crop survival was correlated with phase survival, and final crop *Pi* was correlated with phase *Pi*, significant correlation was only verified for the seed-juvenile period (phase 1), with $R^2 = 0.96$, $P = 0.02$ and $R^2 = 0.93$, $P = 0.04$, respectively.

3.3. Chlorophyll a and temperature: in situ and remote sensing assessment

Remote sensing temperature data showed highly correlated to *in situ* values and proved to be a useful and accessible tool for sea surface temperature (SST) determination at least in the study site ($n = 182$, $R^2 = 0.92$, $SE = 0.99$ and $P < 0.01$) (Fig. 5). As the residuals of prediction were relatively low (up to 6%) with 2.7% on average, remote sensing data showed a high predictive capacity of *in situ* determined seawater temperature. The relationship between satellite predicted and *in situ* determined chlorophyll *a* concentration also showed significant ($n = 24$, $R^2 = 0.66$, $SE = 1.12$, $P < 0.01$). The linear model described ($y = 1.8647x + 4.2043$) was used to estimate chlorophyll *a* levels in the farming area at crop periods (Fig. 6). Satellite values were applied to the model in order to be corrected for expected overestimation, and thus values within the range reported for coastal waters in this geographic area could be used to describe time series of chlorophyll *a* levels.

Seasonal features in SST were clearly showed in crop time series. Maximum monthly mean value of SST was obtained in March (25.9 ± 1.1 °C) whereas the lowest value varied between July (19.5 ± 1.8 °C) and August (19.5 ± 1.4 °C) (Silveira et al., 2008a). Colder months showed higher SST variation among winters (Fig. 7a). The year of 2007 showed the highest monthly mean temperature in March (27.1 °C) and also lowest monthly mean temperature in July (16.2 °C). Mean ± s.d. of SST was 21.8 ± 3.3; 22.3 ± 3.7, 22.1 ± 4.4, and 22.1 ± 2.8 °C for the whole farming period in crops 2005/06, 2006/07, 2007/08 and 2008/09, respectively.

On the other hand, available chlorophyll *a* levels showed no apparent annual pattern in the present time series with values ranging from 0.4 (April 29th 2007) to 11.8 $mg.m^{-3}$ (May 21st 2008) (Fig. 7b). This is rather expected as chlorophyll *a* concentration may be affected by different factors rather than seasonality, especially in the coastal zone. From the available remote sensing data set, the occurrence of elevated chlorophyll *a* concentration (>5 $mg.m^{-3}$) was higher in 2007 and 2008 ($n = 15$), and to a lesser extent in 2006 ($n = 11$) and 2005 ($n = 4$). Mean ± s.d. of chlorophyll *a* levels was 2.75 ± 2.0, 3.14 ± 2.5, 3.97 ± 2.9 and 3.9 ± 3.0 $mg.m^{-3}$ for the crops 2005/06, 2006/07, 2007/08 and 2008/09, respectively.

3.4. Environmental effects upon oyster performance

Seeds were stocked in periods of relatively elevated seawater temperatures and chlorophyll *a* levels (Fig. 7a, b), except for the 2005/06 crop when seed stocking temperature was <22 °C. High SST during *C. gigas* seed stocking and in the following rearing months may have resulted in reduced survival in the seed-juvenile rearing phase (31.8–36.6%), as observed in crops 2006/007 and 2007/08 (Table 1, Fig. 7a). The highest survival at the seed-juvenile phase (66.9%) was verified in the 2008/09 crop. The importance of survival from seed to juvenile oyster in relation to total crop output was previously highlighted in Section 3.2. Chlorophyll *a* levels at seed stocking were apparently not related to survival at seed-juvenile phase, since decreased survival in 2007/08 occurred even at relatively elevated chlorophyll *a* concentration (Fig. 7b). Temperature seems to have a stronger effect upon survival of early stages of *C. gigas* farmed in this sub-tropical area. Though not significantly, mean temperature indicated a trend to be negatively related to crop survival especially in

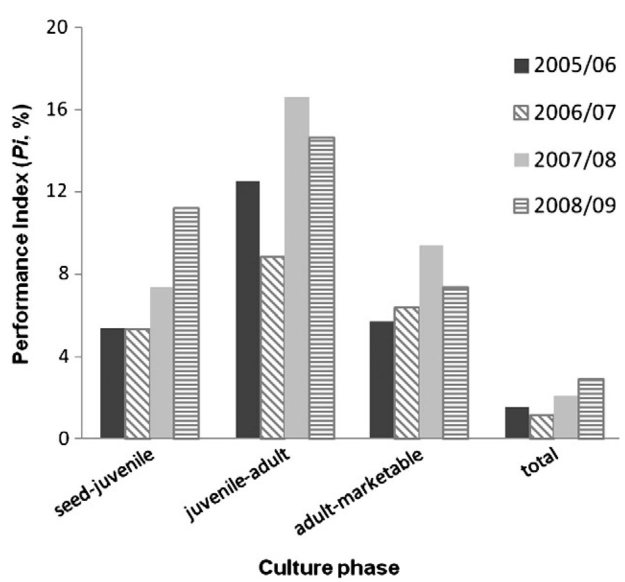

Fig. 4. Performance Index (*Pi*, %) related to each different culture phases and crop years. *Pi* = (survival/phase or crop interval).

Table 2
Values of R^2 and P from correlations ($n = 4$) between final survival and phase survivals and final Performance Index (*Pi*) and phase *Pi*s. Significant correlations are underlined ($P \leq 0.05$).

	R^2	P
Final survival × survival seed-juvenile phase	0.96	0.02
Final survival × survival juvenile-adult phase	0.17	0.58
Final survival × survival adult-marketable phase	0.18	0.57
Final *Pi* × *Pi* seed-juvenile phase	0.93	0.04
Final *Pi* × *Pi* juvenile-adult phase	0.57	0.24
Final *Pi* × *Pi* adult-marketable phase	0.24	0.51

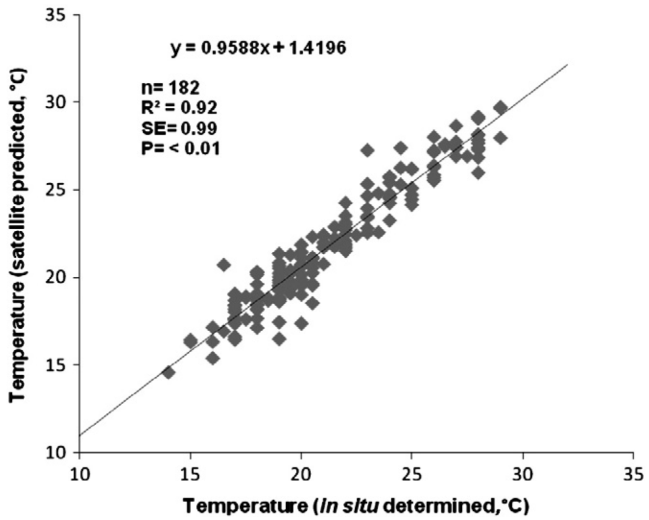

Fig. 5. Regression between satellite predicted and *in situ* determined sea surface temperature values in a fixed station in the farming area, South Bay, Santa Catarina Island, Brazil.

the phase seed-juvenile and possibly at juvenile-adult, with mean temperature in the rearing phase ranging between 20.0 and 21.3 °C, and 19.6 and 20.9 °C, respectively (Fig. 8a).The survival in the adult-marketable grow-out phase seemed not affected by temperature at 22.0–23.1 °C interval. Survival of early oyster stages could be also affected by temperature variation in the rearing phase since a negative trend (not statistically significant) was verified if regressing seed-juvenile survival *versus* the variance of phase temperature ($R^2 = 0.42$, data not shown). The development rate of farmed oyster, as assessed by phase interval (months) in different rearing phases, showed not related to mean phase temperature under these ranges (data not shown). On the other hand, chlorophyll *a* influenced the development rate of *C. gigas* under the assessed farming conditions with significant effects upon the time spent in each rearing phase (Fig. 8b). The negative relationship observed between phase duration and mean chlorophyll *a* concentration was highly significant in the assessed crops for the seed-juvenile and adult-marketable phases; at ranges of 2.37 and 3.33, and 2.87 and 4.26 mg.m^{-3} mean chlorophyll *a* levels, respectively. Though not significant, oyster development and mean chlorophyll *a* also showed a trend of negative correlation in the juvenile-adult phase, under ranges of 2.14 and 3.35 mg.m^{-3}. Oyster survival showed no relationship with mean phase chlorophyll *a* concentration at determined intervals (data not shown).

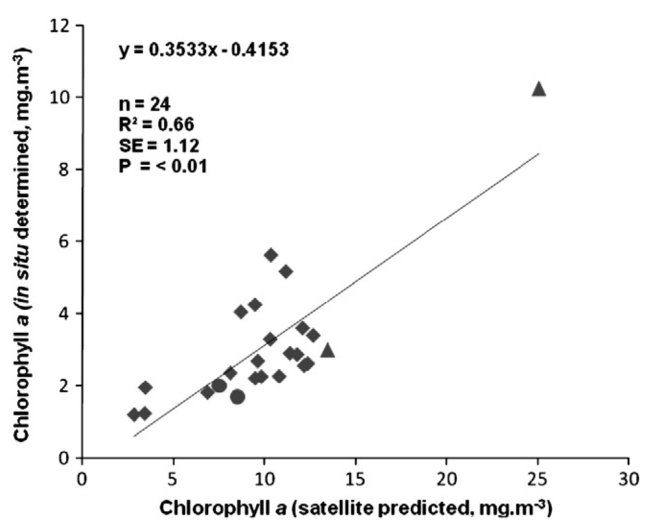

Fig. 6. Regression between satellite predicted and *in situ* determined (Ferreira et al., 2004, diamond; Rupp, 2007, circle; Parizotto, 2009, triangle) seawater chlorophyll *a* values in the farming area and adjacencies, Santa Catarina Island, Brazil.

In the course of the crop years northern winds were predominant in the majority (≥2/3) of assessed months. However, each crop year showed a distinctive pattern of predominant wind direction in the farming area. In 2005, east wind predominated in September and October, and south winds in December. South, east, west and southeast winds predominated in 2006 in February, April, May and November, respectively. Southern and southeastern winds were verified contrasting with predominant northern winds in May and November, 2007, respectively. The highest predominance of southern winds was registered in 2008, with southeast and south predominant in February, March, April and December. According to the ONI values El Niño was registered in the following periods: December 2004 to March 2005 and July 2006 to February 2007. The La Niña period corresponded to August 2007 to June 2008. With the exception of November 2006, the El Niño period corresponded to predominant northern wind direction in the farming area. On the other hand, four out of the eleven months period covered by La Niña had predominant south and southeastern winds.

Available data on the variation in seawater chlorophyll *a* concentrations after the passage of cold fronts did not show a defined pattern over the assessed time series (Fig. 9). From March 2005 until mid-2007 cold fronts showed not to provide a high increase in chlorophyll *a* concentration in the farming area. The period included an El Niño event between July 2006 and February 2007. In contrast, from August 2007 to June 2008, period of La Niña occurrence, cold fronts resulted in increased chlorophyll *a* concentration in South Bay, Santa Catarina Island. A relatively elevated survival rate in the seed-juvenile rearing phase from crop 2008/09 coincided with apparently positive effects of cold fronts upon chlorophyll *a* levels during La Niña strong influence period between July 2007 and July 2008. Accordingly, lower survival in seed-juvenile may have coincided with negative or poorly positive effects of cold front passage in the remaining crops, especially 2006/07 and 2007/08 (Fig. 9).

4. Discussion

Performance of farmed bivalves in the ocean is highly dependent on environmental characteristics as well as exposed to environmental changes, which highlights a certain degree of vulnerability. Understanding how crops may respond to the environmental variables under realistic farming practices may assist the adoption of new strategies for present and future conditions (Subasinghe et al., 2009). The assessment of oyster response to changing environmental conditions and effects of El Niño and La Niña over short terms may be a starting point to foretell crop success as well as potential long-terms effects of changing climate upon farming outputs (Pollack et al., 2011). In the present 2005–2009 field survey four single allotments (first allotments of the crop) from each yearly commercial crop were chosen due to its unique characteristics: (1) management followed a similar protocol therefore differences between crops management were minimized; (2) oysters were taken from the sea as soon as marketable size was achieved to supply the market, thus they were not stocked back in the sea for future trade which could elevate mortality; and (3) oysters were obtained from the same hatchery and lineage thus genetic interference is believed to be minimized. Oysters (*C. gigas*) farmed under South Bay of Santa Catarina Island environmental regime showed faster growth than reported in higher latitudes, and were able to achieve the marketable size within 5 months compared to as long as 2 years achieved under higher latitudes (Gosling, 2004).

Although variations in ecological parameters may occur in a different frequency than in the present sampling, monthly averages are often used as a representation of environmental features in farming site. Bivalves may immediately respond to medium shift (*e.g.* valve

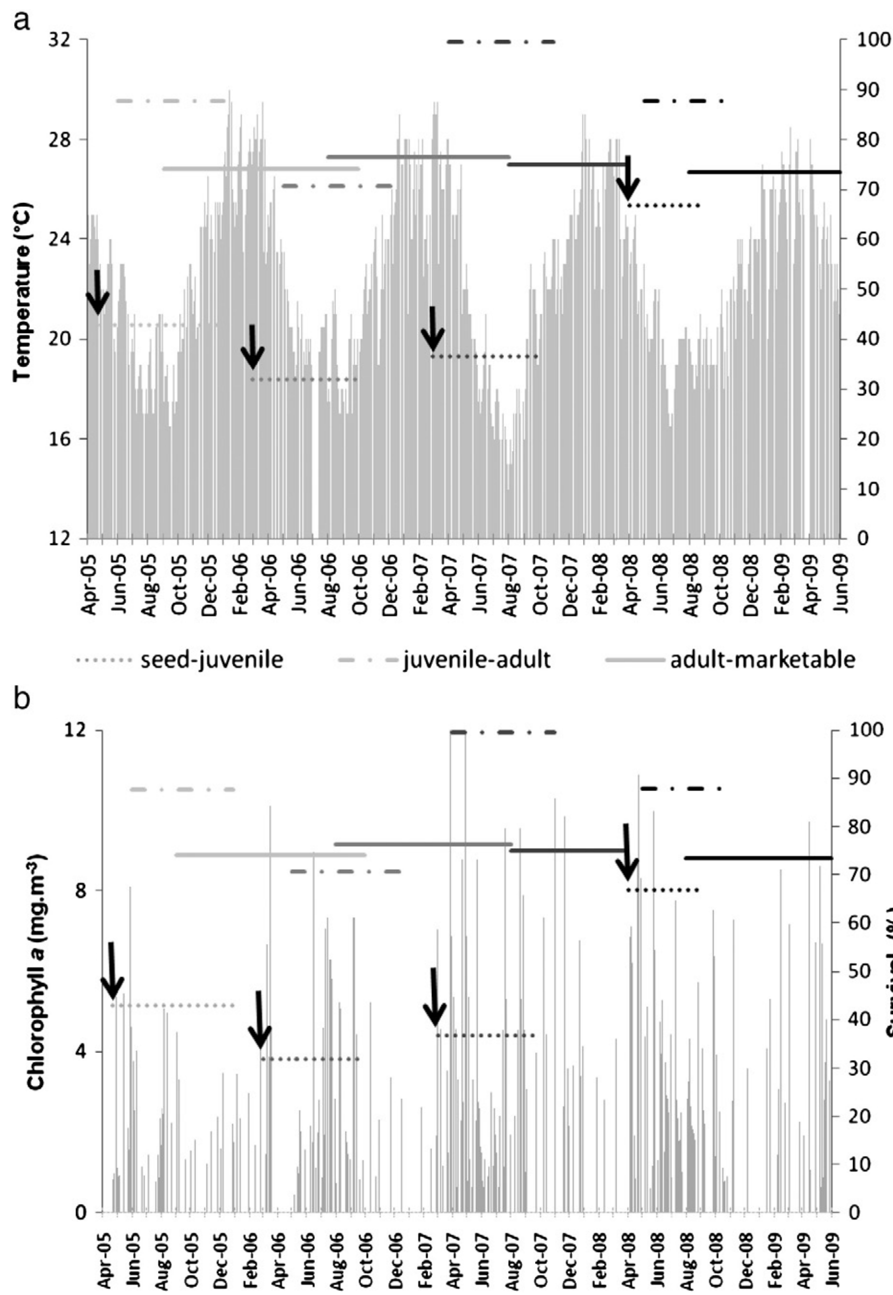

Fig. 7. Temperature (a) and chlorophyll *a* (b) variation in the four oyster (*Crassostrea gigas*) crops (2005/06, 2006/07, 2007/08 and 2008/09) and comparison with survival in the different culture phases in South Bay, Santa Catarina Island, Brazil. Horizontal lines: total survival in relation to individual stocked and time interval of each culture phase. Black arrows indicate the time of seed stocking for each crop. Further details in Materials and methods.

gape, Yonge, 1960; Dharmaraj, 1983; Wilson et al., 2005; and alteration in filtration rates, Riisgard et al., 2003; Pascoe et al., 2009), and the cumulative of effects of environmental stresses, energy expenditures and savings may correspond to farming performance of a stocked population over a significant period of time. Accordingly, pooled data of environmental variables over defined periods or farming phases may be useful for comparison with oyster growth and survival since performance indices may often vary after relatively longer exposure to favorable or unfavorable conditions. This may be also related to oyster capability to acclimatize to small variations in the farming environment (Gosling, 2004; Yonge, 1960). Growth and survival data under farmed oyster populations may be only possible to obtain with successive measurements of performance in a similar-age defined stock. The assessment of oyster-environment relationships has been reported for different habitats and farming zones given the importance of environmental factors to bivalve development (Brown, 1988; Brown and Hartwick, 1988).

Elevated temperatures have been suggested as a negative factor in oyster survival causing, especially in summer, the so-called summer mass mortalities (Goulletquer et al., 1998; Malhan et al., 2009). On the other hand, it may be attributed to multi-factorial effects, such as the combination of low water quality and elevated temperatures (Dégremont et al., 2007; Malhan et al., 2009; Soletchnik et al., 2005; Wolff, 2007). In addition, high temperatures are also likely to facilitate pathogen infections in oyster early life stages (Burge et al., 2007; Gagnaire et al., 2006). *C. gigas* seeded during relatively elevated temperatures may thus be underperformed in comparison to those stocked in relatively lower temperatures periods, emphasizing the importance of careful selection of seeding time (Burge et al., 2007). Oyster in phases 2 and 3 may be not as affected by temperature

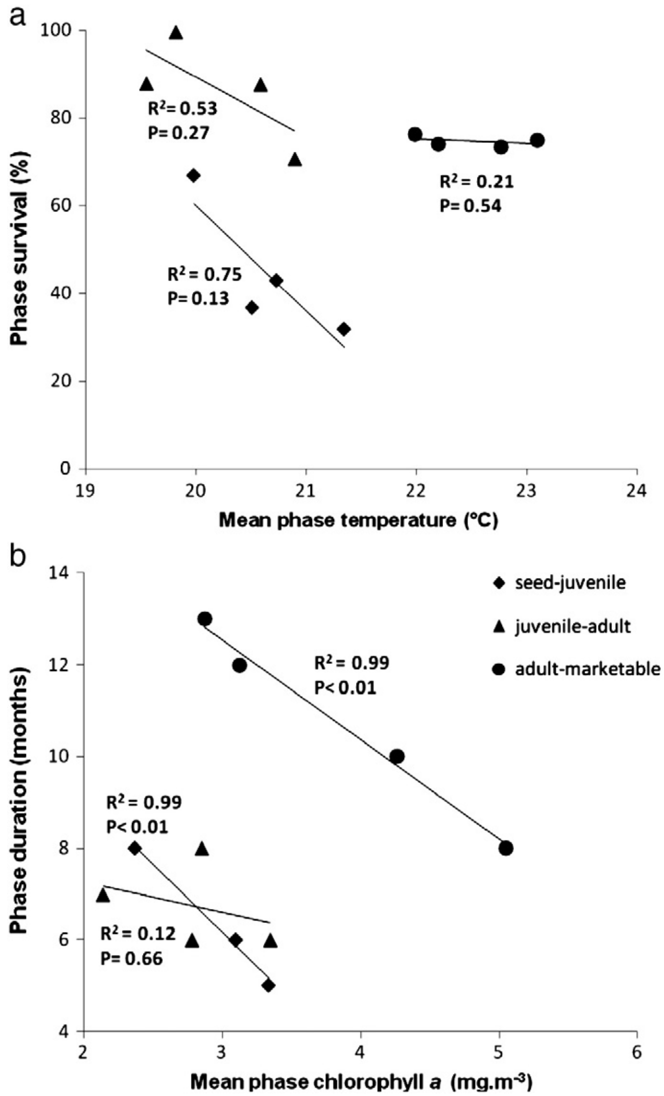

Fig. 8. The relationship between survival and temperature (a) and phase duration and chlorophyll *a* (b) in different culture phases of oyster (*Crassostrea gigas*) farmed in South Bay, Santa Catarina Island, Brazil.

possibly because successive selection of more temperature resistant individuals from the end of phase 1 to the next phases. This may have resulted in non-significant difference in phase 3 survivals among crops, and survival of adult-marketable individuals showed not affected by the determined environmental factors. Food availability may be considered the main responsible factor for bivalve growth (Gosling, 2004; Ren and Ross, 2001; Ren et al., 2010) despite some evidence of no correlation among these factors were also reported (Gangnery et al., 2003). A large variety of primary producers is often accessible in bivalve diet, such as benthic and planktonic microalgae. Though *C. gigas* is reported an opportunistic filter-feeder, phytoplankton is recognized as the main contributor of dietary nutrients (Leal et al., 2008). On the other hand, the estimation of net food contribution from chlorophyll *a* also depends on particle size range and retention efficiency in the prediction of oyster growth rates (Hyun et al., 2001). Present survey involving a large number of individuals showed chlorophyll *a* levels as a significant representative of food effects upon oyster development rate. Since the study did not aim to suggest a predictive model for oyster growth, presented relationships could assist in the interpretation of environmental effects upon individuals farmed under commercial conditions.

Present data indicated no significant effect of temperature upon oyster growth, as also verified in previous studies (Gangnery et al., 2003; Spencer, 2002). Crops, from higher to lower final performance (*Pi*), followed this order: 2008/09, 2005/06, 2007/08 and 2006/07. In the course of the farming period the combination of seawater temperature and chlorophyll *a* enabled for some preliminary suggestions regarding effects of these parameters upon oyster yields. Under farming conditions of moderate temperature and high mean chlorophyll *a*, the 2008/09 crop showed the best survival:development ratio. In 2007/08, initial phases experienced elevated water temperatures that may have negatively affected total survival of early oyster stages. Though lower temperatures in initial farming stages (42% survival), the reduced chlorophyll *a* levels was possibly a negative effect in the 2005/06 crop that resulted in longer development rate. The combination of increased temperature and reduced chlorophyll *a* may have resulted in lower Pi in the 2006/07 crop. These preliminary conclusions should be further tested for a better understanding of environmental effects upon oyster performance under practical conditions.

Water enrichment processes may have also affected food availability in the farming area. The predominance of sandy bottoms in the assessed site suggests intermediate circulation related to cold fronts could positively influence food availability in the farming area after mixing events (Gallucci and Netto, 2004). Three to four cold fronts in an 8 day interval could be verified in the farming site, especially in winter, although long-term cold fronts are mainly registered during summer (Rodrigues et al., 2004). In the surveyed area the warm sector which precedes the cold front the wind blows from NE, but as cold front approaches (cold front = boundary of cold air mass advances over a warm mass) the wind rotates counterclockwise to NW and then blows from south returning to NE direction after the cold front passage (Gallucci and Netto, 2004). Cold fronts could elevate the chlorophyll *a* concentration by *e.g.* promoting re-suspension of organic material which could reincorporate nutrients and photosynthetically active particulate organic matter (microphytobentos) into the water column. In the present study, however, cold fronts did not seem to induce a direct chlorophyll *a* rise in the farming site. On the other hand, cold fronts may assist for the entrance of shelf water masses in the sheltered farming area, supposedly resulting in further water fertilization. Though upwelling of the nutrient-rich South Atlantic Central Water (SACW) in the south of Santa Catarina Island is mostly dependent on the intensity and duration of NE winds (Silveira and Möller, 1998, 1999), the entrance of these water mass into the sheltered South Bay farming area would rely on Southern winds related to cold front events, as preliminarily observed *in situ* (Silveira et al., 2006a,b).Chlorophyll *a* levels showed poorly increased with cold fronts in 2005 and 2006 oyster crops. In these years, coastal upwelling, possibly due to its complexity, may have not occurred resulting in limited enriched water contribution into the South Bay. Though El Niño periods (July 2006 to February 2007) were reported to favor upwelling of SACW in south Santa Catarina Island due to predominance of NE winds, the complete upwelling might not occur since enriched colder water not ever reach surface layers (Silveira and Möller, 1998, 1999). On the other hand, during winter/spring 2007 the cold front matched with increased chlorophyll *a* concentration in the farming site, coinciding with La Plata River Plume detected in the area through severe salinity drops, low rainfall and predominance of Southerly winds, as well as by intense settlement of *Mytilus edulis platensis* mussel, autochthonous species from further southern areas of Brazil and Argentina coast (Couto et al., 2008; Silveira et al., 2008a,b). The same pattern may have occurred during winter/spring 2008 as the conditions (La Niña period and cold fronts) were similar. Although the cold front assessment was characterized by punctual events it suggested a possible relationship between crop survival and chlorophyll *a* fluctuations by cold fronts, at least in seed-juvenile and juvenile-adult oyster farming phases. Notwithstanding, the dependency of several factors for upwelling leads to an uncertainty toward

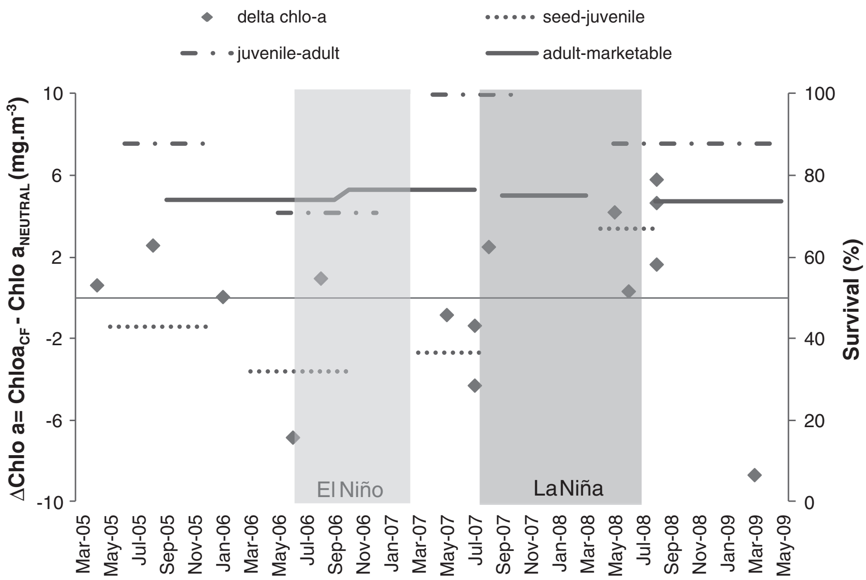

Fig. 9. Chlorophyll *a* variation (Δ Chlo *a*) related to cold front events in the four oyster (*Crassostrea gigas*) crop time series, and comparison with survival in the different culture phases in South Bay, Santa Catarina Island, Brazil. Diamond: Δ Chlo *a* values. Horizontal lines: total survival in culture phase period. Chlo a_{CF}: chlorophyll *a* seawater concentration during cold front events. Chlo $a_{NEUTRAL}$: chlorophyll *a* seawater concentration in adjacent days of cold front events. Further details in Materials and methods.

the SACW water entrance in the Bay, and may indicate why chlorophyll *a* levels did not show to increase with cold fronts during the El Niño period (Fig. 9).

5. Conclusion

Important environmental features seem to affect oyster farming in Southern Brazil, two main effects were presently assessed: seawater temperature and chlorophyll *a*. The former showed to mainly affect survival, and was negatively related to yield. Chlorophyll *a* levels seems to affect growth rate and showed a high correlation with development time. These hydrological features seem (inter) related to the entrance of different water masses in the farming area that may be further affected by El Niño and La Niña events, influencing winds, and possibly the local impact of large scale climate processes.

In a warmer weather condition ocean productivity is likely to decline in lower latitudes and increase in higher ones (FAO, 2010). Accordingly, farming the allochthonous temperate species *C. gigas* may be constrained by both temperature and food availability. In the future maybe the choice for more suitable species for the local climate or the necessity of seed stocking during the colder months might be an alternative to maintain oyster aquaculture. The topic requires more studies for further decisions and foundations.

Acknowledgments

This survey was sponsored by Capes, FAPESP and CNPq, Brazilian graduate and research funding agencies. Thanks are extended to Fabio Brognoli for assisting for a better understanding of commercial oyster farming practices. The critical input from Prof. Jaime Ferreira (UFSC) and Prof. Maria Gasalla (USP) is appreciated.

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