ARTÍCULO

Spatial distribution, density and population structure of the Cortes geoduck, *Panopea globosa* in the Central Gulf of California

Distribución espacial, densidad y estructura poblacional de la almeja de sifón
Panopea globosa en la parte central del Golfo de California

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Resumen.- La almeja de sifón *Panopea globosa* es una especie de importancia comercial por su alta demanda en el mercado de Asia. El propósito de este estudio fue analizar el efecto de la concentración de clorofila, temperatura superficial del mar, turbidez y ciclo de mareas en la estimación de la densidad, distribución espacial, y estructura poblacional de la almeja *P. globosa* en la región central del Golfo de California usando datos de satélite y observaciones de campo. Los organismos fueron recolectados mediante buceo semi-autónomo, entre noviembre 2009 y enero 2011. Se recolectaron un total de 10.114 almejas con un peso promedio de 997 ± 212 g (80% ≥ 800 g), y una longitud promedio de 132 ± 12,5 mm (80% de los organismos recolectados estuvieron por arriba de 130 mm, que es la talla mínima legal de pesca). La densidad de *P. globosa* del área de estudio presentó diferencias significativas entre las 3 agregaciones identificadas con alta densidad, pero la densidad no estuvo correlacionada con ninguno de los factores ambientales considerados.

Palabras clave: Pesquería, manejo, Golfo de California, almeja de sifón

Abstract.- The geoduck clam *Panopea globosa* is a commercially important species because of its high market demand, particularly in Asia. The aim of this study was to analyze the effect of chlorophyll concentration, sea surface temperature, turbidity, and tidal cycle on density estimation, spatial distribution, and population structure of *P. globosa* in the central Gulf of California using remote sensing and field survey data. Specimen collections were conducted through semiautonomous diving from November 2009 to January 2011. A total of 10,114 clams were obtained with an average weight of 997 ± 212 g (80% ≥ 800 g), and an average length of 132 ± 12.5 mm (80% of all collected clams exceeded 130 mm, the minimum legal fishing size). *P. globosa* distribution displayed significant differences among the 3 patches of high density in the study area, but density was poorly correlated with the environmental factors.

Key words: Fishery, management, Gulf of California, geoduck

INTRODUCTION

The Cortes geoduck *Panopea globosa* (Dall, 1898) is one of two geoduck clam species in Mexican waters. *Panopea generosa* (Gould, 1850) ranges from southern Alaska to the western coast of the Baja California Peninsula (Goodwin & Pease 1991). A prospective fishery for both species was initiated in Mexico in the early 2000s, and the catch skyrocketed to 1325 ton in 2011 (CONAPESCA 2012). Presumably, the increased catch resulted from Asian market demand and other suppliers facing over-exploited resources. The current reported catch was over 2100 ton annually, comprising both *P. generosa* and *P. globosa*. However, *P. globosa* contributed to more than 85% of the total catch (Aragón-Noriega *et al.* 2012).

Panopea globosa was first described by Keen (1971) based on empty shells found near San Felipe and Isla San Marcos in the upper Gulf of California. Hendrickx *et al.* (2005) included the species in a taxonomic checklist of macro-invertebrates, but no data was provided on species distribution. Former records restricted *P. globosa* distribution in the Gulf of California. However, Suárez-Moo *et al.* (2013) extended its range as far as Bahía Magdalena (24.6° N) on the western coast of the Baja California Peninsula, clearly outside the Gulf (Fig. 1). Interestingly, *P. generosa* and *P. globosa* have exhibited an overlapping distribution at Bahía Magdalena (Leyva-Valencia *et al.* 2012); however, the continued distribution of *P. globosa*
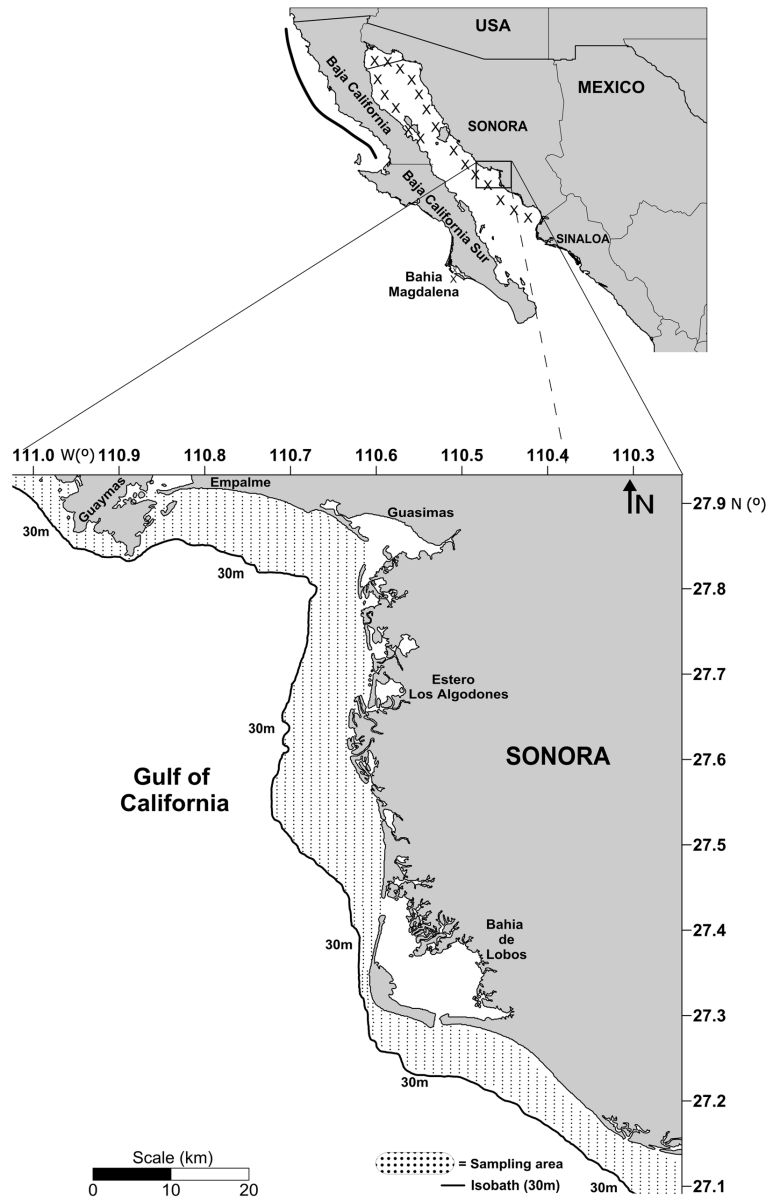
Figure 1. Study area showing the sampling grid. The distribution of *Panopea globosa* (crosses) and *P. generosa* (line) based on verified records in Mexican waters is shown / Área de estudio mostrando la malla de muestreo. Se indica la distribución de *Panopea globosa* (cruces) y *P. generosa* (línea) verificada con registros de pesca en aguas mexicanas

along the western coast of the Baja California peninsula northward from Bahía Magdalena still remains unknown.

The current knowledge available for *P. globosa* in the central Gulf of California (CGC) has been limited to reproductive traits (Aragón-Noriega *et al.* 2007, Arámbula-Pujol *et al.* 2008)

growth analyses (Cortez-Lucero *et al.* 2011, Cruz-Vásquez *et al.* 2012), and distribution and abundance (Cortez-Lucero *et al.* 2014). These 5 studies used data from the CGC where the geoduck fishery is still in its initial stages (Aragón-Noriega *et al.* 2012). The management plan (DOF 2012)[1] requires bed identification, *i.e.*, geographic localities, and density estimation

at each site to issue fishing permits. The Mexican fishery regulation requires that any entity requesting a fishing permit must provide density estimates. Therefore, the first step is to request a polygon where a specific natural resource is known to occur, as in the case of the geoduck clam. Once the authority has granted permission to explore the area, a third party, contracted by the entity requesting the fishing-permit, conducts density estimation surveys. The authority (Comisión Nacional de Acuacultura y Pesca - CONAPESCA)[2] subsequently grants the adequate fishing quota; for example, the quota might be 0.5% of the estimated virgin biomass if it is a preliminary (fomento) permit or 1.0% if it is a commercial permit. Therefore, the knowledge of density and spatial distribution in *P. globosa* is integral for management purposes. In addition, assessment of environmental effects on the species spatial distribution and population structure can enhance the understanding of the dynamics shaping these attributes over time. Moreover, if the quota is granted based on a density miscalculation, *e.g.*, overestimating abundance to obtain larger catches, the population might be over-exploited.

In an influential paper, Orensanz *et al.* (2004) warned geoduck commercial fisheries that the species might not be sustainable in the short-term. Geoducks have exhibited long life-history dynamics, and presently only short-term information is available. Furthermore, environmental factors might affect density estimations, as well as the species life cycle. In the Pacific Northwest (British Columbia, Canada, and Washington State, USA), Valero *et al.* (2004) explored correlations between *P. generosa* recruitment, large river discharges, and sea surface temperatures. Their results indicated river discharges were negatively and temperature positively correlated with recruitment, but *r*-values were scale-dependent. In the upper Gulf of California, Calderon-Aguilera *et al.* (2010a) reported the reproductive cycle of *P. globosa* was coupled with pulses of higher primary productivity. Observations suggested geoduck larvae recruitment was consistent with that predicted by Cushing's (1969) match/mismatch hypothesis, which states successful recruitment depends on the timing of food availability and larval production.

The objective of this study was to analyze spatial distribution, population structure and the effect of chlorophyll *a* concentration, sea surface temperature, turbidity, and tidal cycle on density estimation of *P. globosa* in the central Gulf of California, using remote sensing and field survey data.

MATERIALS AND METHODS

STUDY AREA AND SAMPLE COLLECTION

The Gulf of California experiences seasonally reverse circulation: cyclonic in summer and anticyclonic in winter (Soria *et al.* 2014).

The anticyclonic period lasts from November to April. Flow is northward on the peninsular and southward on the mainland coasts. This configuration produces upwelling along the continental margin enriching the waters, which was identified by satellite imagery (Lluch-Cota *et al.* 1999). The main difference between inner waters of the Gulf of California and the adjacent open Pacific is the presence of a high-salinity near surface water mass in the Gulf, which results in modifications by mixing surface water from the eastern tropical Pacific (Hammann *et al.* 1998). The study area comprised a portion of the CGC (27°56.6'N-111° 1.4'W to 27°5.4'N-110°14.6'W; Fig. 1). Hammann *et al.* (1998) described a major gyre system in the central Gulf; this gyre provides an ideal combination of factors for retention of geoduck larvae. Mean surface temperature varies from 17.5°C in January to 32°C in August. The study area sediments are of 3 main types: (i) fine sand, located in the northern section of the study area; (ii) loamy sand, distributed in the central part of the study area; and (iii) silt-clay, confined to the southern study area (Sánchez *et al.* 2009). It was restricted the fishing area to the 30 m isobath to assure diver safety, and because it is the maximum legal fishing depth (DOF 2012). It was first established a grid of 1000 x 500 m with outer coordinates at 27.9 N-111W and 27.1 N-110.3W from the shoreline with a 30 m depth. Dives were subsequently conducted, where each dive counted all geoducks in a transect perpendicular to the coast 2 m wide by 25 m long, which covered a 50 m^2 area (Fig. 1). Sampling the grid area resulted in 1791 dives conducted from November 2009 to January 2011 (Fig. 1).

In each point of the grid, commercial hookah divers harvested individual clams using a stinger (a high-flow hydraulic tool employed to uncover buried clams). Water was pumped into bottom sediments causing liquefaction of the substrate to facilitate clam extraction. After extraction from the sediment, the clams were transported to the laboratory in coolers, and they were processed immediately upon arrival. The collected organisms were tagged and weighed while alive, and their bodies were subsequently removed from the shells. After drying, shell length (the straight-line distance between the anterior and posterior shell margins) was measured to the nearest 0.1 mm using calipers.

Density was defined through the systematic sampling approach, and subsequent density estimates, which were expressed as geoduck number per diving hour (Catch Per Unit Effort-CPUE) were obtained from commercial divers. CPUE results were used for further comparisons with environmental variability. Length and weight data were also acquired from commercial catch.

WEIGHT-LENGTH RELATIONSHIP

The weight-length function, $W = aL^b$, was fitted to the data, where W is the total wet weight in g; L is shell length in mm; a is intercept (the initial growth coefficient or condition factor); and b is the allometric coefficient. In addition, a t-test was used to determine if the b-value was significantly different from isometric growth ($b = 3$; Zar 1999).

SPATIAL DISTRIBUTION

Geoduck spatial distribution in the study area was estimated using the following 3 grid methods: (i) inverse distance to a power; (ii) minimum curvature; and (iii) point Kriging. All approaches were included in Surfer[3]. Kriging was selected because it resulted in better fit and least variance. This technique employs statistical functions of 2 points that describe an increase or decrease in correlation between samples, which are separated to determine a heterogeneous grid value from known neighbors' values. We used default values for the variogram model and tested residual distributions.

ENVIRONMENTAL VARIABILITY

Variability in Chl-a concentration was examined using monthly ocean color images from October 2010 to December 2011. The images were obtained from SeaWiFS sensors and were compounded monthly with a resolution of 1 km per pixel[4]. Sea surface temperatures (SSTs) were obtained from NOAA_OI_SST_V2 data (Reynolds *et al.* 2002) provided by NOAA/OAR/ESRL PSD[5]. It was developed density overlays covering the entire study area, which showed the 3 highest density patches, in addition to density levels of other sampling sites (Fig. 2). MODIS-Aqua Level 1A data were obtained from the NASA Goddard Space Flight Center processed to a Level 2 format using NASA's SeaWiFS Data Analysis System (SeaDAS version 5.1.6) software, following Lahet & Stramski (2010). Turbidity was estimated from satellite imagery (MODIS-Terra, available from NASA Level 1 and Atmosphere Archive and Distribution System)[6] with a spatial resolution of 1000, 500, and 250 m for each sampling date. Geographic and atmospheric correction was performed using
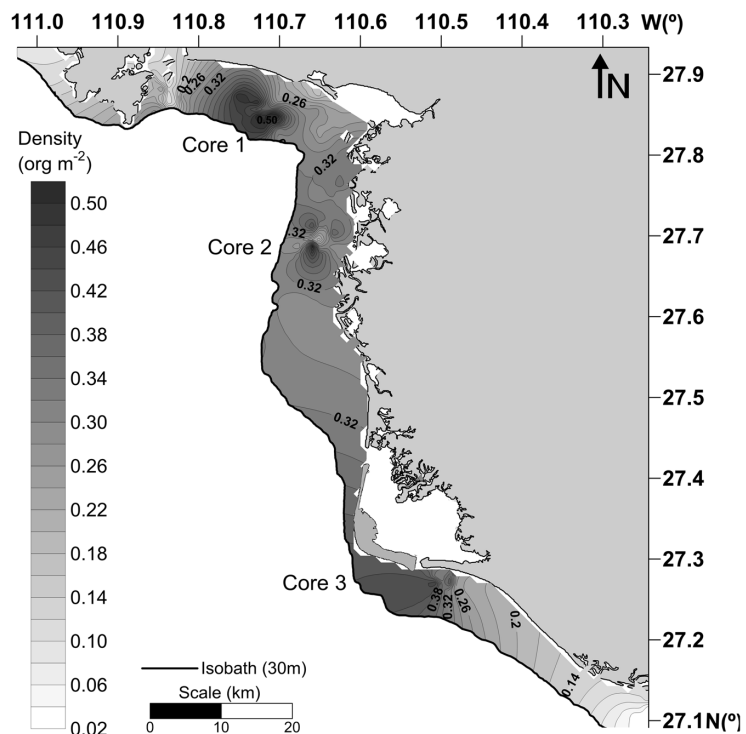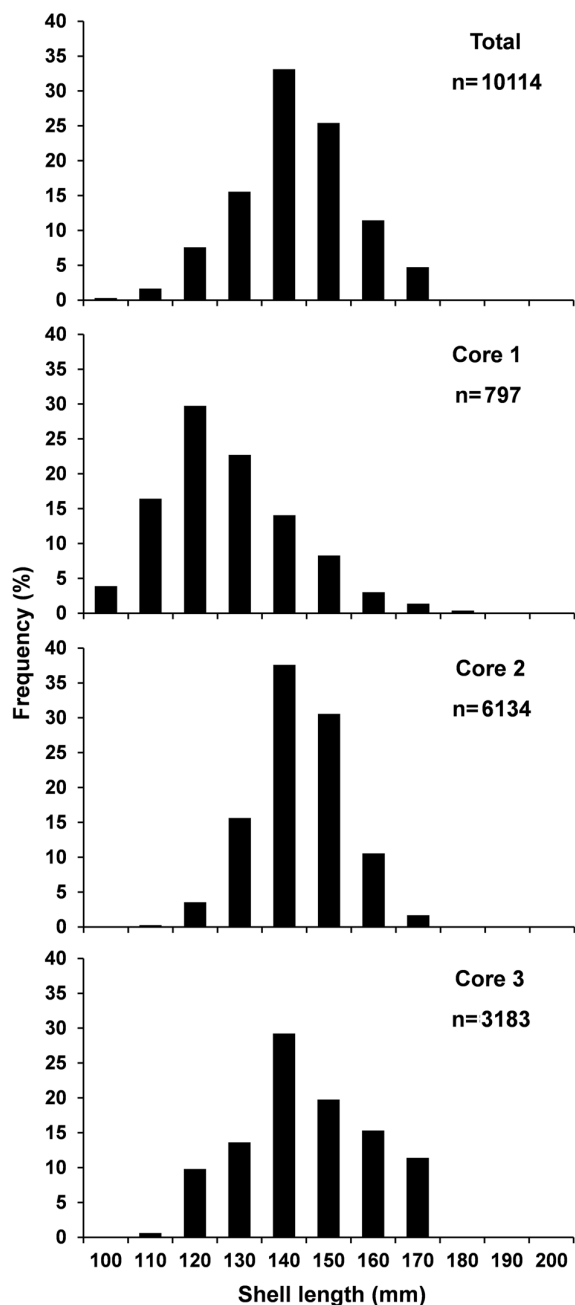

Figure 2. Density distribution of the geoduck *Panopea globosa* (org·m⁻²) in the central Gulf of California obtained by the Kriging ordinary method. The 3 denser beds (cores) are depicted / Distribución y densidad de la almeja de sifón *Panopea globosa* (org·m⁻²) en la parte central del Golfo de California, obtenida con el método de Kriging ordinario. Se resaltan los 3 bancos de alta densidad

[3]Golden Software, LLC. Surfer version 9 <http://www.goldensoftware.com/products/surfer>
[4]<http://www.science.oregonstate.edu/ocean.productivity>

[5]<http://www.esrl.noaa.gov/psd>
[6]<http://ladsweb.nascom.nasa.gov/data/search.html>

Figure 3. Length frequency distribution of *Panopea globosa* from the central Gulf of California at the 3 cores with the highest density / Frecuencias de longitud de la almeja de sifón *Panopea globosa* de la parte central del Golfo de California en los 3 bancos de alta densidad

the algorithm developed by J. Descloitres, NASA Goddard Space Flight Center. Tides were measured using data available in the MAR V 1.0 2011 program supported by CICESE[7]. This program applies *in situ* sea-level data from tidal gauges, and calculates tide height at a specific locality. It was selected a core zone 1, and followed fishing activities at three different times associated with different tide phases. A Pearson's correlation was used to measure the linear correlation (dependence) between an environmental variable and CPUE (*i.e.*, proxy for geoduck density).

RESULTS

Kriging spatial interpolation output for the population distribution and density surveys are shown in Fig. 2. The figure depicts the interpolated geoduck density throughout the entire study zone. Three main core density areas (area in km^2) were identified, with the highest density at each core approximately 0.5 geoducks m^{-2}. Fine and loamy sands were predominant at cores 1 (8 km^2) and 2 (5 km^2), and silt-clay was the primary substrate at core 3 (11 km^2). All 3 core areas were ~ 20 ± 5 m in depth.

A total of 10114 geoduck samples were analyzed from throughout the entire study zone and the study period. Geoduck shell length-frequency distribution ranged from 100 to 180 mm (Fig. 3), and the mode was 120 mm in core 1 and 140 mm in cores 2 and 3. Total weight ranged from 460 to 2000 g (Fig. 4), and the mode varied from 800 g in core 1 to 1000 g in cores 2 and 3. The weight-length relationship indicated negative allometric growth for each core (Fig. 5; *t*-test, $P < 0.05$).

Chl-*a* values recorded from October 2010 to January 2011 fluctuated in each of the 3 core areas. Values in cores 1 and 2 varied from 3 to 7 mg m^{-3}, while in core 3, they varied from 2 to 7 mg m^{-3} (Fig. 6a). The sea surface temperature (SST) showed a sharp decline from 28°C in October 2010 to 10°C in January 2011 in each of the 3 cores analyzed (Fig. 6b). Turbidity fluctuated from 40 to 160 units. The CGC showed a mixed semi-diurnal tidal cycle; therefore, the zone presented 2 uneven tides per day, or one high and one low tide per day in some cases. The amplitude tidal range was only 600 mm to -595 mm (Fig. 7).

Geoduck density obtained from commercial activities, using CPUE as an index of relative abundance, showed a positive relationship with Chl-*a* and turbidity but a negative relationship with SST (Figs. 6a, b, and c). The other environmental variable examined was tidal phase. The results showed the lowest geoduck density was recorded when divers collected clams from a tidal height of 400 mm to -200 mm, and the highest one was obtained when divers performed collections above a 600 mm tidal height (Fig. 7).

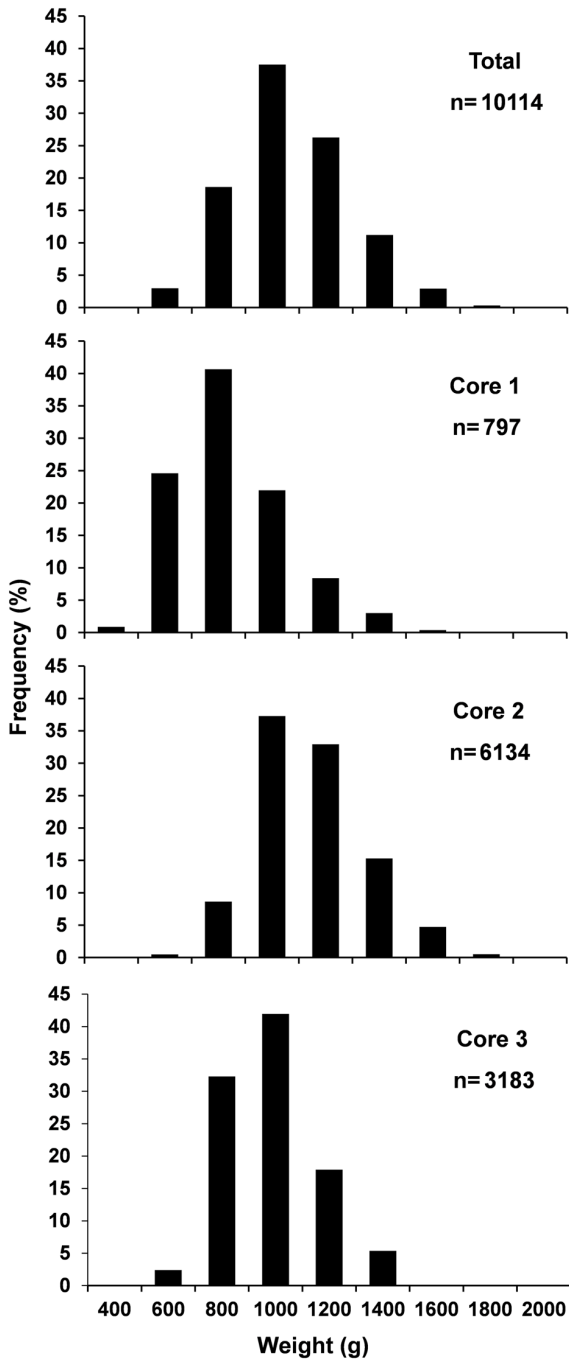
[7]<http://oceanografia.cicese.mx/predmar>

Figure 4. Weight frequency distribution of *Panopea globosa* from the central Gulf of California at the 3 cores with the highest density / Frecuencias de peso de la almeja de sifón *Panopea globosa* de la parte central del Golfo de California en los 3 bancos de alta densidad
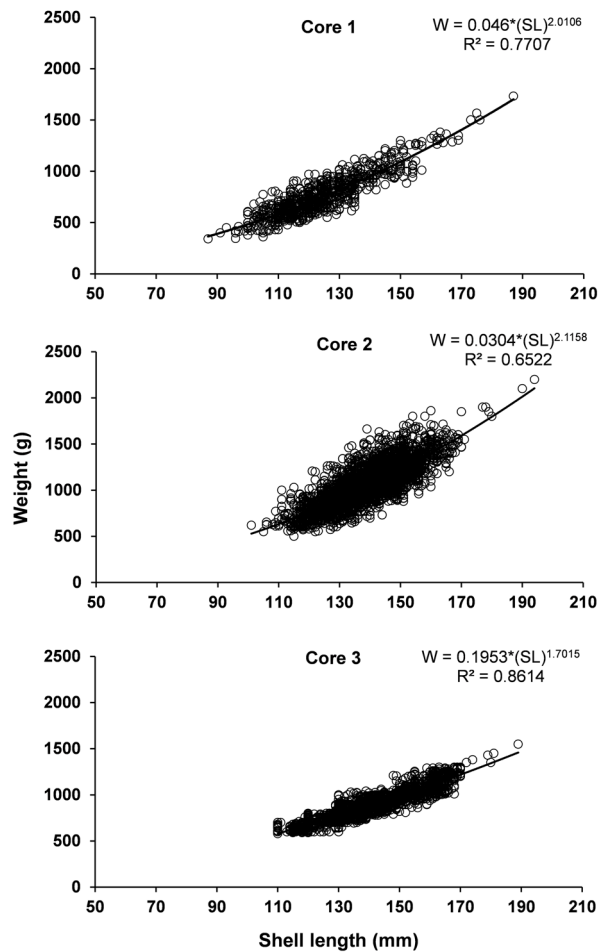

Figure 5. Shell length-total weight relationship for *Panopea globosa* from the central Gulf of California at the 3 cores with the highest density / Relación longitud-peso de la almeja de sifón *Panopea globosa* de la parte central del Golfo de California en los 3 bancos de alta densidad
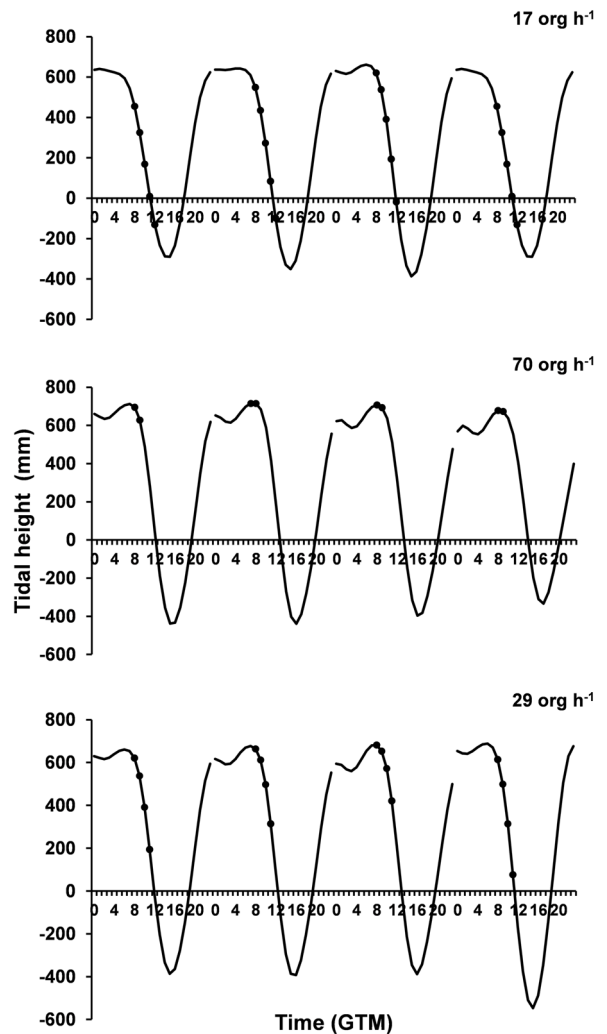
DISCUSSION

A unimodal size structure in *P. globosa* was documented in the central and upper Gulf of California. The first study (Aragón-Noriega *et al.* 2007) reported a mean shell length (SL) of 203 mm. Subsequently, a 93 mm modal size and mean 109.8 mm SL were estimated (Cortez-Lucero *et al.* 2011, Cruz-Vásquez *et al.* 2012). Results from the upper Gulf of California showed average *P. globosa* SL varied between 140 and 150 mm on the west coast (Calderon-Aguilera *et al.* 2010b), and mean 160.3 mm on the east coast (Pérez-Valencia & Aragón-Noriega 2012). In our study, the unimodal length-distribution patterns were similar in each of the three core areas evaluated. This unimodal size structure suggested a poor recruitment pulse and lower mortality in the adult stage.
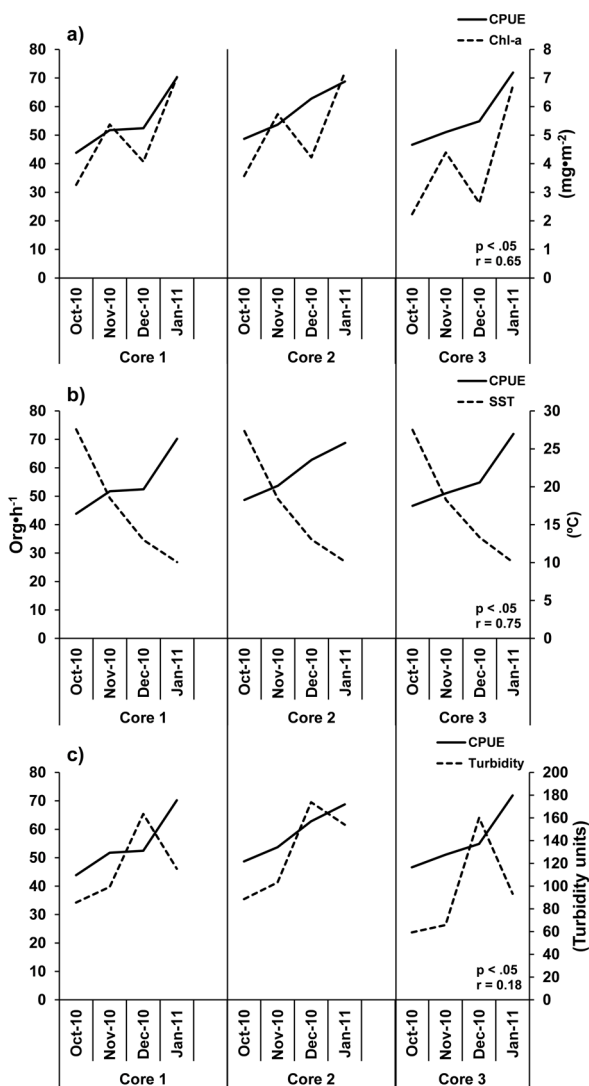
Figure 6. Temporal density variation and environmental parameters in each core; (a) Chl-*a*, (b) SST and (c) turbidity. The CPUE (org·h⁻¹) is superimposed on each graph / Variación temporal de la densidad y variables ambientales en cada banco; a) Chl-*a*, b) TSM y c) turbidez. En cada gráfica se ha superpuesto la CPUE (org·h⁻¹)

Figure 7. Relationship of *Panopea globosa* CPUE (org·h⁻¹) and tide height in the study area. CPUE data from commercial divers; Tide height from MAR V1.0 2011 program (available at: http://oceanografia.cicese.mx/predmar) / Relación de la CPUE (org·h⁻¹) de *Panopea globosa* con la altura de la marea en el área de estudio. La CPUE fue obtenida del buceo comercial; la altura de la marea del programa MAR V1.0 2011 (disponible en: http://oceanografia.cicese.mx/predmar)

The length-weight relationship and *b*-values detected in our study were congruent with results reported in other geoducks, *i.e.*, Calderon-Aguilera *et al.* (2010b) for *P. generosa* in the northwestern Mexican Pacific and Andersen (1971) in Washington State coastal waters. The *b* < 3 value determined in our study was consistent with geoduck shape. The *b* < 3 value suggested large specimens depicted a more elongated body shape or small specimens were in better nutritional condition at the time of sampling.

In a previous study conducted in the area Cortez-Lucero *et al.* (2014) discussed on the possible effect of larval density and bed connectivity, food supply, substrate, and hydrographic conditions. They argue that larval dispersal is most influenced by hydrography because the pelagic phase is relatively long (up to 25 days); therefore, currents determine larval aggregations, which affect settlement and recruitment. Also, the pediveliger larvae of some bivalves, *e.g.*, pectinids settle when they reach 180-200 µm long (Uriarte *et al.* 2002). However, if larvae drift

and settle in non-suitable substrate, they will die. Becker *et al.* (2012) reported some low-swimming capacity larvae take advantage of currents, depending on depth. Therefore, larval stage duration is critical for successful settlement. The larval stage lasts from 16-47 days in *P. generosa* (Becker *et al.* 2012). However, larval dispersion behavior and distribution is unknown in *P. globosa*. *Panopea generosa* is considered the most studied geoduck species. Becker e*t al.* (2012) indicated their study is one of the very few that focused on *P. generosa* larval behavior, and the results found no correlation between larval abundance and any physical variable.

In some areas with aggregated populations, Naidu & Anderson (1984) described self-sustainable populations due to oceanographic features causing water circulation, resulting in a mechanism for larvae retention in the same area as the spawning stock populations. In the central Gulf of California (our study area), Hammann *et al.* (1998) characterized a major gyre system providing an ideal combination of factors for larvae retention. Geoducks are sessile species that live buried in the seafloor, and this characteristic could influence the larval settling process. It is possible pediveliger larvae transported by sea currents aggregate at the bottom, where they seek similar substrates for fixation and posterior metamorphosis. Thus, geoducks are recruited in patches, and individuals that remain close to adults are also close enough to each other to ensure reproduction.

In our study, we found significantly different densities among beds 1, 2, and 3 ($P < 0.05$). We did not collect sediment samples. However, Sánchez *et al.* (2009) characterized the following three main sediment types from the study area: (i) core 1 - fine sand, located in the northern section of the study area; (ii) core 2 - loamy sand, distributed in the central part of the study area; and (iii) core 3 - silt-clay, confined to the southern study area. Goodwin & Pease (1991) described the spatial distribution of *P. generosa* in 6 areas from Puget Sound, Washington. Their results showed significant differences in clam density among different sediments with 1.2 clams m^{-2} in silty, 2.0 clams m^{-2} in silt-sandy, and 2.1 clams m^{-2} in sandy sediments; they concluded *P. generosa* exhibited increased density in sandy-silt and sand substrates.

Density assessment plays an important role in managing Geoduck fisheries in Mexico because its exploitation should be performed by beds. Mexican authorities have a mandatory management program in geoduck fishery that a bed is a regulated area with defined geographical limits whose density is suitable for fisheries. Thus, a method to estimate density was established. The method must be applied in all the areas, and it must be identical or similar. The density estimation method is an adaptation of the one developed in Washington for the geoduck clam (Brandbury *et al.* 2000). However, Brandbury *et al.* (2000) reported that

density estimation could be biased by turbidity, oceanographic currents, or temperature. Our results suggest that the tide phase should be taken into account as a factor affecting geoduck observation. As density plays an important role not only in defining the bed area (or bed geographic limits) but also the quota assigned, it is necessary to focus on the environmental factors that could affect geoduck counts. The authorities in Mexican fisheries have emphasized on identifying density variability to allow the sustainable exploitation of geoduck in Mexican fishing areas. For these reasons, our study is useful to determine the factors affecting density estimations.

Continuous improvements should be made in density estimations as the results of field surveys, as those of our study, to better define bed areas and capture quota. Density estimates should be modified according to those determined by the quotas if the intention is achieving a sustainable fishery.

Higher geoduck production might show increased density or individual mean weight; however, we found a strong positive correlation between geoduck density (expressed as CPUE) with Chl-*a* and temperature and a weak positive correlation with turbidity. It must be emphasized that this analysis was rather simplistic because many other compounding factors, such as pre-recruitment mortality, cohort strength, and age structure might be deterministic factors in the observed density and size distribution. Based on our observations and reviews of other studies, water depth and substrate type seem much better physical variables to correlate with distribution data even though we did not detect correlations.

One caveat of our study is we should have aged all specimens to cross-correlate primary productivity and recruitment. A lag between primary productivity and recruitment might be expected. Another caveat to our study is the absence of a show factor assessment as in Bradbury *et al.* (2000). Therefore, turbidity and tide effects on density estimates were confounding because we did not have comparative surveys. Moreover, divers themselves cause turbidity by sediment disturbance. Nevertheless, we are confident in the estimated geoduck densities due to the large number of dives (1791) and the robust grid method used for sampling.

In summary, *P. globosa* in the Central Gulf of California exhibits a patchy distribution with densities up to 0.5 ind·m^{-2}. However, this distribution was poorly correlated with Chl-*a*, sea temperature, turbidity, and tide cycles at the time of sampling. Moreover, we do not have enough information to rule out a time-lagged relationship. Therefore, the next steps for this research must be to correlate water depth and substrate type with distribution data and ageing of organisms.

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