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Recruitment of catarina scallop (*Argopecten ventricosus*) larvae on artificial collectors off the NE coast of the Gulf of California

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Abstract

We evaluated recruitment of larvae of catarina scallop, *Argopecten ventricosus*, in the area of Puerto Peñasco, NE Gulf of California. We moored artificial collectors in six sites from June 2007 to August 2008 and replaced them every 2 months. We used monthly (July 2002–September 2011) sea surface temperature (SST, °C) and surface chlorophyll-*a* concentration (SSChl, mg m^{-3}) Aqua/MODIS satellite data to describe seasonal environmental behaviour study area. Also, we recorded bottom temperature at each site every 4 h, and every 2 months measured sea surface salinity, temperature and dissolved oxygen. We used a repeated measures ANOVA to evaluate differences in the number of recruited spat between main factors, and analysed the presence of multimodal spat shell size frequency distributions. Overall, spat recruitment was negatively correlated with seawater temperature and showed higher spat recruitment abundances throughout winter, which is the season with the highest surface chlorophyll *a* concentration. We estimated multimodal shell size frequency distributions characterized by more than one modal size. The natural collection of *A. ventricosus* spat on artificial collectors in the area can be successfully performed over a protracted period (November–December to May–June). Our results extend the area where collection of *A. ventricosus* spat can be successful.

Keywords: scallop, *Argopecten ventricosus*, collector, spat recruitment, Gulf of California

Introduction

The Gulf of California and the Pacific side of the Baja California Peninsula, Northwest Mexico (Fig. 1), are highly productive marine environments where industrial, small-scale fisheries and aquaculture activities take place (Cisneros-Mata 2010). In this region, the catarina scallop, *Argopecten ventricosus* (Sowerby II, 1842), is an economically important resource (Félix-Pico 2006; SAGARPA 2010). Of approximately 20 bivalve species harvested in the region, *A. ventricosus* landings accounted for 50% of the total captures from 1986 to 2001 (SAGARPA 2004). The species is harvested by small-scale hookah-diving fishers primarily for its adductor muscle (locally known as 'callo'), which is mainly exported to the USA (González-Anativia 2001; Félix-Pico 2006). The species is also cultured, but in much less quantity than harvested naturally. For instance, the largest record of landings of *A. ventricosus* totalled 15 800 Mt in 2008 (Fig. 2a) (FAO 2011), whereas aquaculture production peaked in 2001 with 127 Mt (Fig. 2b) (SAGARPA 2010; FAO 2011).

Despite its relevance, the production of both fisheries and aquaculture activities has been characterized by marked fluctuations over the last decades (Fig. 2) (Félix-Pico 2006; SAGARPA 2010).

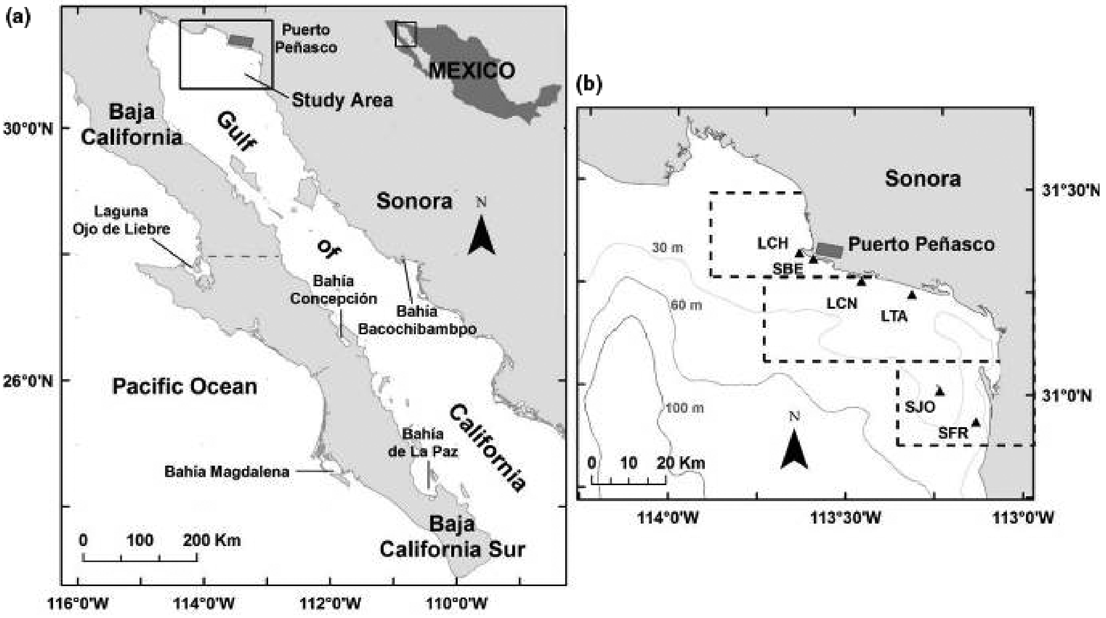

Figure 1 (a) The Gulf of California and the Baja California Peninsula, Mexico. (b) The study area near Puerto Peñasco showing spat collection sites (black triangles) for catarina scallop, *Argopecten ventricosus.* In dotted lines, three subregions used in the text: The NW region contains the sampling sites La Cholla (LCH) and Sandy Beach (SBE). The Central region includes sampling sites Las Conchas (LCN) and Los Tanques (LTA). The SE region includes sampling sites San Jorge Island (SJO) and San Francisquito (SFR).

Because of the stochastic nature of the fishery's captures of *A. ventricosus* (a common phenomenon also seen in other scallops fisheries elsewhere) (Félix-Pico 2006; Orensanz, Parma, Turk & Valero 2006), aquaculture of this species could be an appropriate strategy to complement fisheries' landings or even increase the natural production of scallops (Rangel-Dávalos 1990; Uriarte, Rupp & Abarca 2001; Félix-Pico 2006). Furthermore, the development of aquaculture and conservation initiatives (e.g. stock enhancement and repopulation programmes) relies greatly on the availability of larvae produced either under hatchery conditions or collected from natural environments (Pouliot, Bourget & Frechette 1995; Arnold, Marelli, Bray & Harrison 1998; Narvarte, Félix-Pico & Ysla-Chee 2001; Uriarte *et al.* 2001; Félix-Pico 2006).

Argopecten ventricosus inhabits fine and coarse sandy bottoms along both sides of the Baja California Peninsula and from the east coast of the Gulf of California to the Peruvian coast (Peña 2001). *A. ventricosus* is a functional hermaphrodite species and broadcast spawner that can reach 90 mm of maximal shell height (Peña 2001). The sexual maturity, when 50% of the scallops exhibit mature gonads, occurs at an age less than 4 months (mean shell height = 20 mm) (Cruz, Rodriguez-Jaramilllo & Ibarra 2000). Scallops at maturing and spawning stages can be present all year-round; however, the reproductive patterns vary according to local environmental conditions (Baqueiro-Cárdenas & Aranda 2000; Luna-González, Cáceres-Martínez, Zúñiga-Pacheco, López-López & Ceballos-Vázquez 2000). Depending on rearing temperatures and food availability, spawned scallops can mature and spawn again in less than 4 weeks (Monsalvo-Spencer, Maeda-Martínez & Reynoso-Granados 1997; Félix-Pico 2006). Under hatchery conditions, scallop larvae can reach the pediveliger stage within 9–18 days depending on water quality parameters (Uriarte *et al.* 2001; Félix-Pico 2006). At sea, artificial substrates (like plastic meshes, plastic plates, and ropes), have been used successfully to collect spat (post-larvae) with marked variations between locations and seasons (Maeda-Martínez, Reynoso-Granados, Sólis-Marín, Leija-Tristán, Aurioles-Gamboa, Salinas-Zavala, Luch-Cota & Ormart 1993; Félix-Pico *et al.* 1997; Félix-Pico 2006). Several techniques have been applied to culture *A. ventricosus* for commercial harvest and these techniques vary according to local conditions. These methods include both bottom and

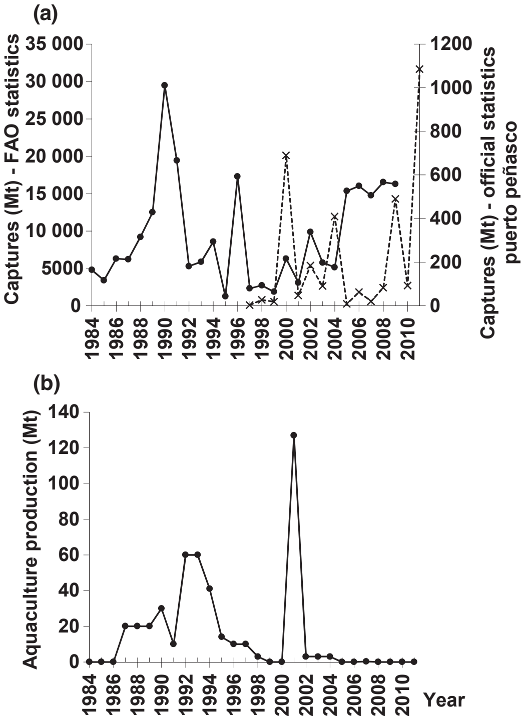

Figure 2 Catarina scallop *Argopecten ventricosus*. (a) Annual fishery captures for Northwest Mexico (solid line) (Source FAO, 2010) and Official captures declared at the regional office of CONAPESCA in Puerto Peñasco (dashed line), Mexico. (b) Annual aquaculture production for Northwest Mexico (Source FAO, 2010). Values are expressed in Mt of whole animal weight.

suspension culture techniques (Maeda-Martínez, Lombeida, Freites, Lodeiros & Sicard 2001; Félix-Pico 2006). Independently of the culture techniques, catarina scallops can reach commercial size (shell height ≈60 mm) in less than 1 year (Maeda-Martínez, Omart, Mendez, Acosta & Sicard 2000; Avendaño, Cantillanez, Le Pennec, Lodeiros & Freites 2001; Félix-Pico 2006).

Whereas commercial fisheries and aquaculture activities along both margins of the Baja California Peninsula are well documented (Narvarte *et al.* 2001; Félix-Pico 2006), the status of fishery and aquaculture initiatives along the east coast of the Northern Gulf of California are less documented, or information is constrained to a few sites (Félix-Pico 2006; SAGARPA 2010). Puerto Peñasco is an important fishing town on the northeastern side of the Gulf of California, where the species represents an important economic influx for local fishers when it is available in the natural environment (Martinez-Tovar, pers. obs). However, landings of this scallop species have also fluctuated markedly over recent years in this region (Fig. 2a), with the most recent and intense fishing pulses observed in 2004, 2009, and 2011. In spite of the species importance, there are no records of aquaculture initiatives for *A. ventricosus* or information on the natural availability of scallop spat (and the natural factors affecting it) for the area of Puerto Peñasco.

To understand the spatial and temporal availability of larvae along a geographical area around Puerto Peñasco, we deployed artificial collectors (Netlon nets) from June 2007 to August 2008. The aim of this study was to provide basic information on the natural availability of *A. ventricosus* spat (optimum site locations, timing, depth variances, and intensity of settlement), needed for the development of sustainable aquaculture and conservation initiatives (e.g. stock enhancement and repopulation programmes) in this important fishing area in the Northern Gulf of California.

Materials and methods

Temporal and spatial variation of larvae abundance

We estimated recruitment of *A. ventricosus* spat on artificial collectors deployed in six sites along a geographical area around Puerto Peñasco, covering ~75 km of coast. These sites included La Cholla (31°20′N–113°38′W), Sandy Beach (31°19′N–113°36′W) in the NW sector, Las Conchas (31°16′N–113°26′W) and Los Tanques (31°14′N–113°19′W) in the Central region, San Jorge Island (31°0′N–113°14′W) and San Francisquito (30°55′N–113°7′W) (Fig. 1b) in the SE region. At each site, we deployed three vertical lines, each one consisting of a polyethylene rope (Ø = 0.8 cm) tied at one end to a screw-type anchor (length = 75 cm), and the other end to a polystyrene buoy (buoyancy = 5 kg) (Fig. 3). We tied collectors to the rope at 1, 3, 5 and 7 m starting from the anchor. Each collector was made of polyethylene Netlon® (200 × 40 cm; mesh opening = 7 × 12 cm) which in turn was enclosed inside a plastic-bag (60 × 40 cm; mesh opening = 0.8 × 1 cm) (Fig. 3). This outer bag played the important role of retaining detached spat, especially at sites with strong currents and rough sea conditions (Shumway & Parsons 2006). We deployed the first batch of collectors on June 22, 2007, and replaced them with new ones every

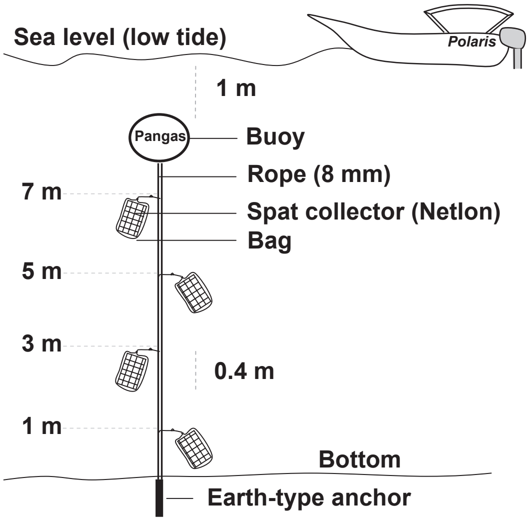

Figure 3 Diagram of vertical line collecting unit used at each spat collection site.

2 months to prevent excessive fouling on the collectors. Hereafter a month corresponds to the cumulative recruitment of spats produced over the 2 months before the replacement date. We ended the field collection of spats on 24 August 2008.

Environmental variables

To describe the seasonal environmental behaviour of the spat sampling area and of the entire Upper Gulf, we used monthly (July 2002–September 2011) sea surface temperature (SST, °C) and surface chlorophyll-*a* concentration (SSChl, mg m^{-3}) Aqua/MODIS satellite data (http://oceancolor.gsfc.nasa.gov). The data resolution was 4 × 4 km, but averages were made over the areas marked in Fig. 1, as representative of (a) the northwest region, (b) the central region and (c) the southeast region. We take chlorophyll concentration as a rough proxy of primary productivity.

Additionally, bottom water temperature (°C) was recorded every 4 h at each site with temperature loggers (Maxim-Dallas; ibutton 1-Wire model DS1922L). On each field trip, we used a hand-held sensor (Yellow Spring Incorporated, YSI 85, Yellow Springs, OH, USA) to measure sea surface water salinity (g L^{-1}), dissolved oxygen (%) and temperature.

Laboratory procedure and statistical analyses

We detached spat by washing and sieving each collector through a 250-μm nylon mesh. We transferred spat to a plastic pan to be counted and measured. We used the program Image ProPlus 4.0 (Media Cybernetics, MD, USA) to measure shell height (distance from the umbo to the opposite shell margin) based on digital images. We used a repeated measures analysis of variance (longitudinal study) to test significant differences in the number of recruited spat between months, sites and depths. We applied a natural logarithmic transformation [i.e. $\ln(x + 1)$] to the numbers of spat per collector to meet normality and homogeneity of variances. As the main factors as well as their interactions were significant, we performed individual one-way ANOVAS to compare spat recruitment at different depths for each site and month separately. When significant differences in depth were observed, we performed a *post hoc* Tukey test. We visually examined spat shell size frequency distributions at each site and month and observed multimodality in most cases. To simplify the representation and interpretation of the data, we performed the analysis pooling all depths together. We assumed that these distributions were actually the mixture of more than one normal distributions (i.e. presence of multiple spat cohorts). We used the package 'mixtools' (Benaglia, Chauveau, Hunter & Young 2009) in 'R' software v2.10.1 for Mac® (R Development Core Team 2009) to fit mixture distributions to the size dataset at each site and month. We fitted mixture distributions with 2–4 components, and chose the mixture distribution with the lowest negative log-likelihood. We estimated mean, standard deviation and proportion for each component of the modelled mixture distributions. In all statistical tests, we considered differences being significant when $\alpha < 0.05$.

Results

Environmental water parameters

The monthly time series of SST and SSChl for the various selected areas (Fig. 4) show that both variables have a strong annual signal, but they are around 6 month out of phase: maximum SST is in August–September (~31°C) and minimum in January–February (~15°C), while SSChl is minimum in June–September (~1.5 mg m^{-3}) and maximum in January–March (~3.5 mg m^{-3}). Furthermore, the time series (2002–2011) shows that there are changes between years, especially in winter SST (e.g. uncommonly warm in 2003 and 2010,

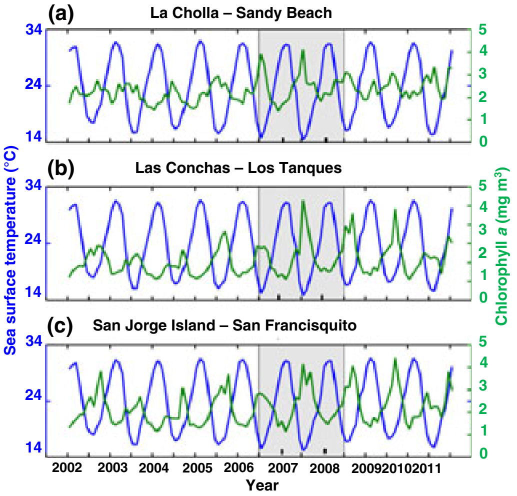

Figure 4 Monthly sea surface temperature (°C) and chlorophyll *a* concentration (mg m^{-3}) of the study area, from MODIS satellites: (a) Northwest region: La Cholla and Sandy Beach, (b) Central region: Las Conchas and Los Tanques, and (c) Northwest region: San Jorge Island and San Francisquito. Grey areas in each panel indicate the spat-sampling years (2007–2008). Source: Aqua/MODIS; http://oceancolor.gsfc.nasa.gov.

uncommonly cold in 2008), while in winter chlorophyll peaks were smaller in 2003–2005 than in 2006–2010 (Fig. 4). During the spat-sampling years (Figs 4 and 5), the chlorophyll winter maximum was higher in 2008 than in 2007, while the summer minimum was lower in 2008 than in 2007. In summer, the NW sector is warmer and contains less SSChl than the Central and SE sectors, which is due to the shallowness of the former, comprising mostly Adair Bay. For the same reason, the NW is cooler and contains more SSChl than the other two sectors in winter (Fig. 5).

The marked seasonal signal in SST was also present in the sea bottom temperature observations (Fig. 6). Across all sites, sea bottom temperature reached the lowest mean values in January (temperature range = 14.4–15.3°C) and the highest mean values in August (range = 30.3–31.3°C) (Fig. 6). Furthermore, in August, San Jorge Island and San Francisquito showed lower monthly mean (Fig. 6) bottom temperature values (30.3 and 30.9°C respectively) than the other sites (range = 31.2–31.3°C). Similarly, in January, San Jorge Island showed the highest monthly mean bottom temperature (15.3°C) in comparison with the other sites (range 14.4–14.9°C). The lowest temperature (11.3°C) was recorded at La Cholla in January 2008 and the highest (32.6°C) at Los Tanques in September 2007 (Fig. 6). We observed maximum salinity values (>35.5 g L^{-1}) throughout summer and slightly lower values in winter (<35 g L^{-1}). Dissolved oxygen levels remained >80% throughout the year with highest saturation values in summer and winter months (Table 1).

Spat recruitment

A total of 308 590 spat recruited throughout the study period. When all sites were pooled together, spat recruitment varied markedly between bimonthly periods. For instance, collectors retrieved in August (2007 and 2008) and October showed either low or null recruitment, whereas during winter and spring, recruitment was considerably higher (Fig. 7). After excluding the lowest-recruitment bimonthly periods, spat recruitment differed significantly between periods (repeated measures three-way ANOVA; $F_{1,62} = 14.65$, $P < 0.001$). In addition, spat recruitment at each site was significantly different in each period (repeated measures three-way ANOVA; $F_{5,62} = 20.39$, $P < 0.001$).

Spat recruitment throughout the study area showed highly variable patterns between sites (Fig. 7). In most sites, high spat recruitments were observed in those collectors retrieved in February (winter) when sea surface and bottom temperatures were at their lowest values and chlorophyll *a* concentration was at its highest (Figs 5 and 6). In addition, spat recruitment extended until August, when sea water temperature was increasing. At the northernmost site of La Cholla, we observed similar spat recruitment values between February (mean = 1410 spat collector^{-1}, SD = 431.1) and June (mean = 1601.7 spat collector^{-1}, SD = 705.8), whereas nearby Sandy Beach showed a single peak in April (mean = 1900.4 spat collector^{-1}, SD = 485.1) followed by a lower peak in June (mean = 1173.7 spat collector^{-1}, SD = 391.4) (Fig. 5). For the central site of Las Conchas, we estimated spat recruitment peaks in February (mean = 1848.3 spat collector^{-1}, SD = 681.2) and April (mean = 1603.8 spat collector^{-1}, SD = 470.8). For Los Tanques, we observed a single peak in February (mean = 1404.3 spat collector^{-1}; SD = 455.6) (Fig. 7). San Jorge Island showed the highest spat recruitment peak in February (mean = 2233.5 spat collector^{-1}, SD = 657.8) and lower values in June (mean = 1269; SD = 593.2 spat collector^{-1}) and December (mean

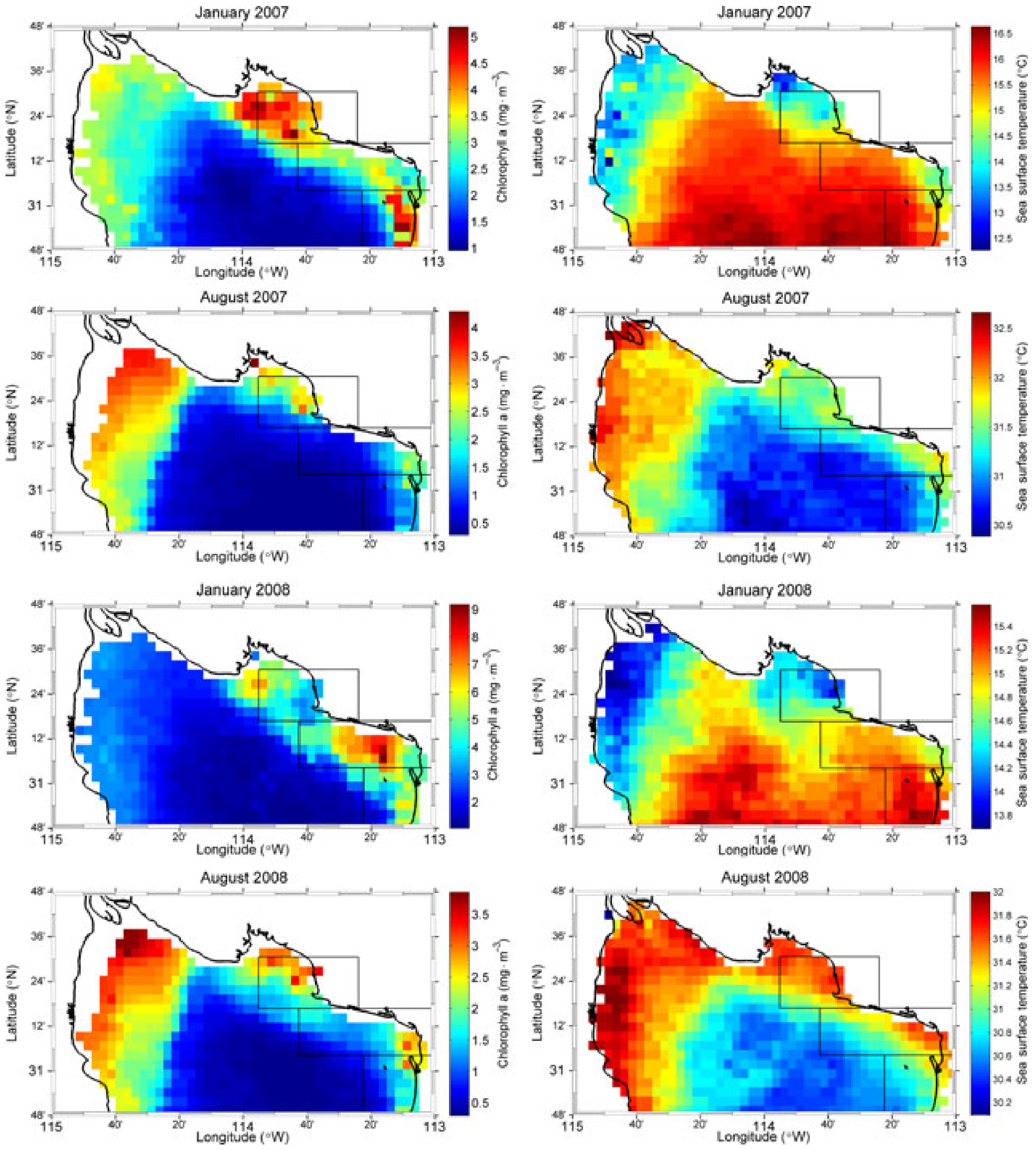

Figure 5 Satellite data (Aqua/MODIS) of monthly sea surface temperature and chlorophyll *a* concentration in the northern Gulf of California. Black boxes indicate selected areas along the spat-collection area: (a) Northwest region: La Cholla and Sandy Beach, (b) Central region: Las Conchas and Los Tanques, and (c) Northeast region: San Jorge Island and San Francisquito. Note: Colour scales not kept constant along the year to help visualize spatial contrasts.

= 1321.3 spat collector ^{1}, SD = 738.7). The southernmost site of San Francisquito showed a single recruitment peak in February (mean = 2555.4 spat collector^{-1}; SD = 842.9) (Fig. 7), the largest of the set.

Spat recruitment in the study area also showed different patterns according to site and sampling depth (Fig. 8). For example, as regards collectors retrieved in December at San Jorge Island and San Francisquito, we found lower spat recruitment abundances near the bottom than at the upper collectors (Fig. 8a), while spat recruitment did not differ between depths at each site (Fig. 8a). Contrary to this pattern, in February, spat recruitment tended to be higher near the bottom than near the surface in La Cholla, Las Conchas, Los Tanques and San Jorge Island (Fig. 8b). In April, an inverse relationship between depth and spat recruitment was observed between Las Conchas, with higher spat recruitment near the bottom than near the

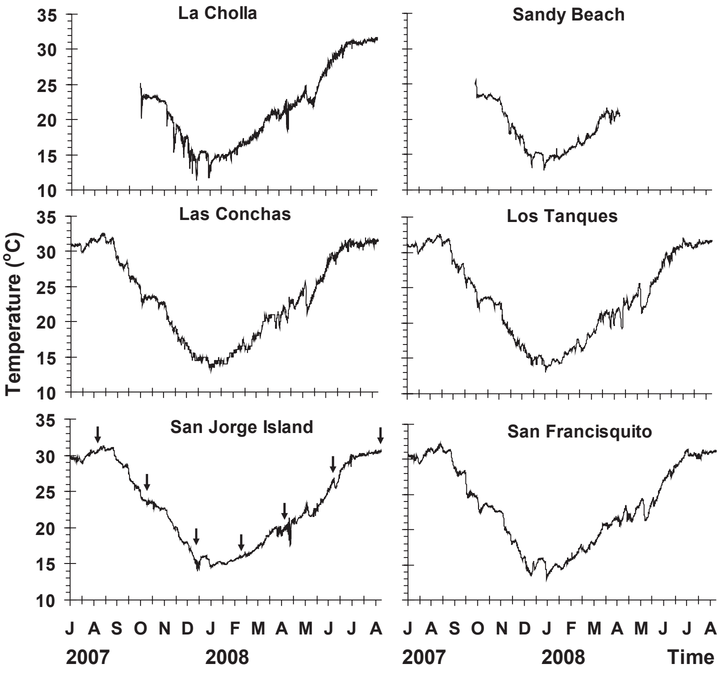

Figure 6 Sea bottom water temperature recorded every 4 h at each spat collection site along the Puerto Peñasco area from 23 July 2007 to 24 August 2008. The set of arrows in San Jorge Island panel represent the moment when collectors were replaced, which is also representative of the other sites. We ended the field collection of spat on 24 August 2008.

Table 1 Sea water salinity, dissolved oxygen and temperature recorded at each collection site in the study area of Puerto Peñasco

	La Cholla	Sandy Beach	Las Conchas	Los Tanques	San Jorge Island	San Francisquito
Salinity (g L^{-1})						
06/22/07	35.43	35.53	36.00	35.80	35.20	35.58
08/17/07	35.38	35.56	35.44	35.46	35.00	35.10
10/19/07	35.68	35.58	35.62	35.36	35.30	35.18
12/18/07	35.20	35.07	35.07	35.10	34.88	34.67
02/28/08	34.77	34.85	34.93	34.92	34.48	34.35
04/25/08	35.17	34.73	34.80	35.22	34.30	34.52
06/27/08	34.85	34.90	ND	34.40	35.20	35.50
08/25/08	35.40	ND	35.40	35.50	35.00	35.40
Dissolved oxygen (%)						
06/22/07	90.28	97.35	97.20	98.03	92.73	93.55
08/17/07	89.92	115.60	110.20	112.30	100.26	105.50
10/19/07	88.64	89.10	90.34	95.56	85.50	92.08
12/18/07	98.72	95.98	94.48	98.47	94.03	99.05
02/28/08	102.58	104.82	96.07	102.60	110.57	101.43
04/25/08	89.33	82.10	67.00	90.35	97.73	100.00
06/27/08	95.53	95.20	ND	104.87	94.20	94.10
08/25/08	89.70	ND	109.70	113.40	95.80	88.60
Temperature (°C)						
06/22/07	26.93	27.00	26.86	26.83	25.40	26.40
08/17/07	31.16	31.24	31.10	31.90	30.32	31.40
10/19/07	24.14	24.80	24.84	25.26	25.44	24.55
12/18/07	16.95	17.38	16.92	16.67	17.83	15.90
02/28/08	16.63	16.70	17.17	16.68	15.97	16.83
04/25/08	21.63	20.40	19.93	22.00	20.90	21.23
06/27/08	28.47	28.40	ND	30.75	25.64	28.03
08/25/08	31.45	ND	31.48	31.51	30.54	31.13

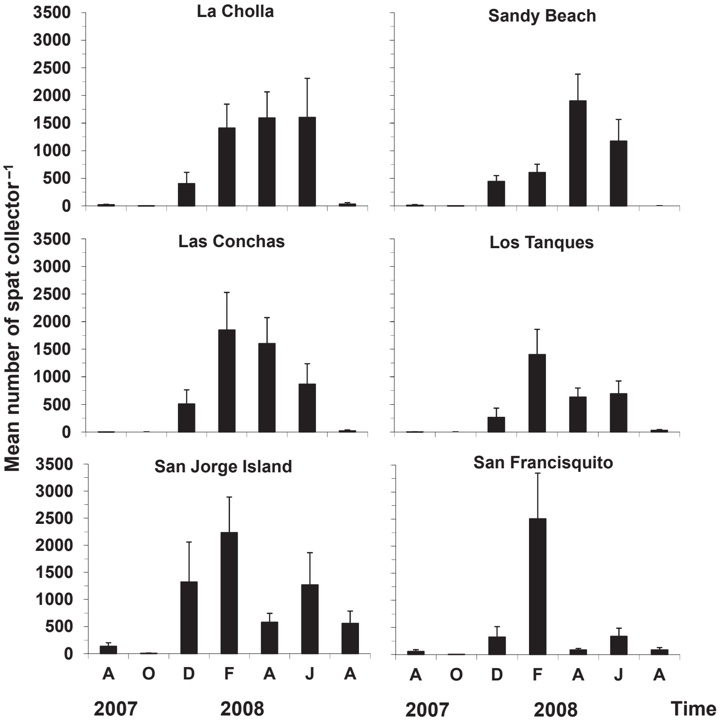

Figure 7 Bimonthly spat recruitment per collector (black bars) at each collection site. Vertical lines represent standard deviation.

surface, and San Jorge Island, with lower spat recruitment near the bottom than near the surface (Fig. 8c). In June, spat recruitment was lower near the bottom than near the surface at La Cholla, San Jorge and San Francisquito, whereas for Las Conchas and Los Tanques we observed the inverse pattern (Fig. 8d).

Spat shell size frequency distributions

We observed multimodal shell size frequency distributions at each site and bimonthly period (Figs 9–12; Table 2). In general, size distributions exhibited a multimodal pattern with one component ($\overline{\mu}_1$) characterized by small scallops (mean shell height range = 1.39–7.19 mm), followed by a second component ($\overline{\mu}_2$) of higher sized scallops (range = 4.07–18.94 mm). In most cases, a third component ($\overline{\mu}_3$) was also present (range = 7.21–19.08 mm) (Table 2). The mixing proportion of each of these components varied markedly between and within sites throughout seasons (Figs 9–12; Table 2).

At the northernmost site of La Cholla, the three components estimated for collectors retrieved in December and February (Figs 9 and 10; Table 2) explained similar proportions of spat recruitment. For example, in December, the smaller shell height distribution component showed a mean value of 1.58 mm (SD = 0.58), which represented 37% of the data, while the second component ($\overline{\mu}_2 = 5.96$mm, SD = 2.55) accounted for 40% of the data and the third distribution ($\overline{\mu}_3 = 11.9$mm, SD = 4.46) explained 23% of the data (Fig. 9; Table 2). On the other hand, in April and June, the majority of the data (>85%) were explained by the two larger size component distributions combined (Figs 11 and 12; Table 2). Similarly, Sandy Beach showed a distribution with three modes from December to June. For the spawning peak identified in April (Fig. 7), the smaller component distribution showed a mean shell height of 1.8 mm (SD = 0.7), and accounted for 14% of the data, while the second ($\overline{\mu}_2 = 7.95$mm, SD = 2.79) and third ($\overline{\mu}_3 = 18.90$mm, SD = 3.36) distributions accounted for 75% and 11% of the data respectively (Fig. 11; Table 2). For the central site of Las Conchas, we estimated a bimodal distribution in February. Fourteen per cent of the data were explained by the first component ($\overline{\mu}_1 = 2.55$mm, SD = 1.02) and 86% accounted for the second component distribution ($\overline{\mu}_2 = 7.91$mm, SD = 2.56). In a different pattern, in April, we estimated three modal distributions; however, we were unable to find the most appropriate mixed distribution fit (Figs 10 and 11; Table 2) (see Discussion section). For the spawning peak identified in Los

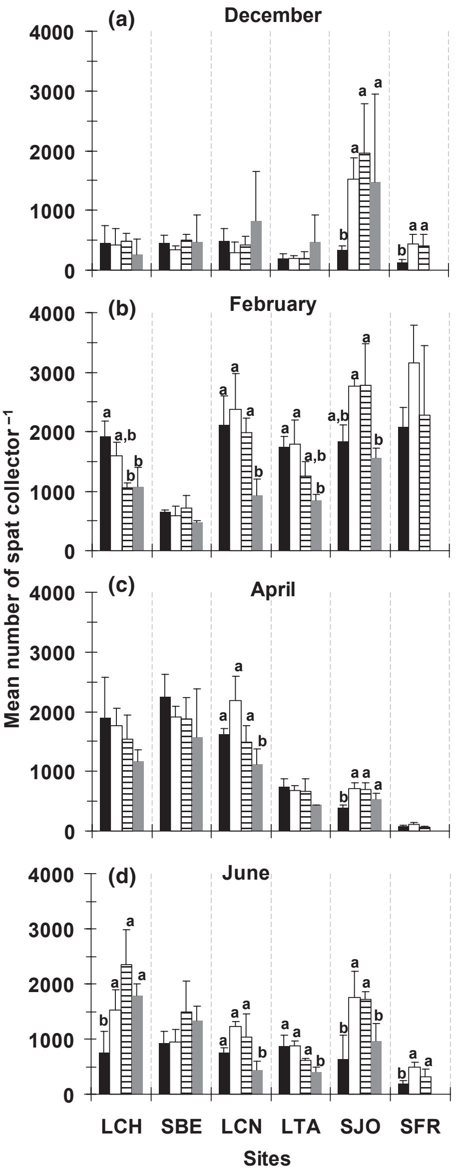

Figure 8 Mean number of spat recruited per collector at different depths 1 m (■), 3 m (□), 5 m (▤), and 7 m (▒) at each collection site at different bimonthly periods. Different letters indicate significantly different values (Tukeys's $P < 0.05$) between depths after one-way ANOVAS for each site and period of time. Vertical lines represent standard deviation. LCH: La Cholla, SBE: Sandy Beach, LCN: Las Conchas, LTA: Los Tanques, SJO: San Jorge Island, and SFR: San Francisquito.

Tanques in February (Fig. 7), shell size frequency distributions suggest a bimodal distribution with more than 97% of the data explained by the first mode (Fig. 10). Like for La Cholla and Sandy Beach, we estimated three modal distributions for the spat recruited at San Jorge Island from December to June. The proportion of the third component in San Jorge Island showed a tendency to increase from December (0.03%) to June when 65% of the data were explained by this distribution (Figs 9–12; Table 2). Finally, the outstanding recruitment observed in February at San Francisquito (Fig. 7) was mainly represented by small scallops ($\bar{\mu}_1 = 6.0$mm, SD = 2.94), which accounted for 76% of the data; however, we shall argue that this distribution might be overestimated (see Discussion section) (Fig. 10; Table 2).

Discussion

This is the first time that information concerning recruitment of *A. ventricosus* spat on commercial collectors is obtained for this region, which extends the geographical area where natural collection can be successful (Narvarte *et al.* 2001; Félix-Pico 2006). The Puerto Peñasco coastal area is characterized by a protracted period for the natural collection of spat: from November–December to May–June. On average, spat recruitment showed strong variations between seasons, and between and within sites (Figs 7 and 8). These highly fluctuating patterns in spat recruitment are similar to the patterns described for the species (Narvarte *et al.* 2001; Félix-Pico 2006) and other scallops species elsewhere (Narvarte *et al.* 2001; Orensanz *et al.* 2006). For *A. ventricosus*, Bahía Magdalena in the Pacific side of the Baja California Peninsula (Fig. 1) has been suggested as one of the best sites to collect spat naturally because of its low temperatures (range = 20–26.6°C) and high primary productivity (range 1.5–5.1 mg chlorophyll-*a* m^{-3}) throughout the year (Cruz *et al.* 2000; Félix-Pico 2006). Reports of spat recruitment for this bay ranged between 50 and 10 000 spat per collector depending on the season and on the site of collection (Félix-Pico 2006). Similarly, in Bahía Concepción in the west coast of the Gulf of California (Fig. 1), spat recruitment varied between 150 and 25 000 spat collector^{-1}, but was characterized by high fluctuations between years (Félix-Pico 2006). Although estimated spat abundances per collector for the Puerto Peñasco area are generally lower (e.g. highest mean value = 3152 spat collector^{-1}, SD = 640.08 at San Francisquito) than the maximum values observed in both Bahía Magdalena and Bahía Concepción, our estimates are higher than those from other regions within the Gulf of California including

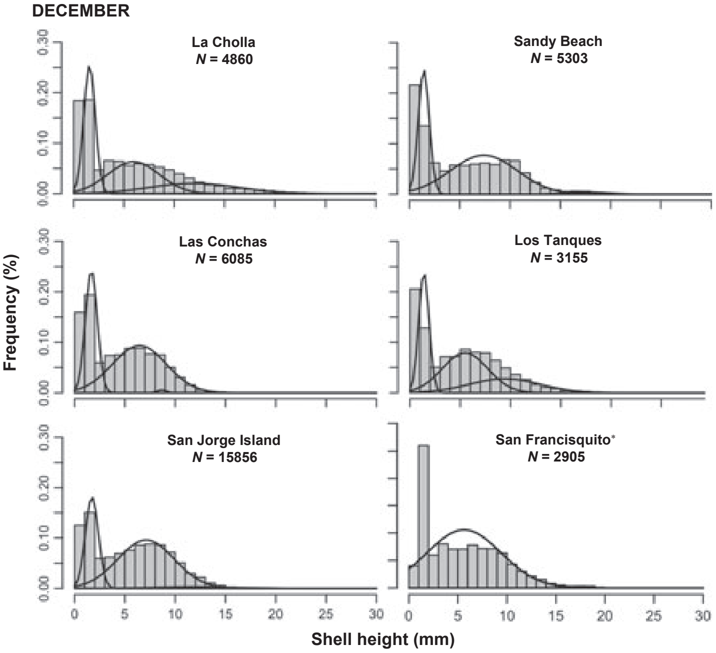

Figure 9 Modal analysis of size frequency distributions of *Argopecten ventricosus* spat recruited over a period of 2 months on artificial collectors and retrieved in December 2007 at different sites in Puerto Peñasco. Cohorts were fitting mixture distributions to the size dataset. LCH: La Cholla, SBE: Sandy Beach, LCN: Las Conchas, LTA: Los Tanques, SJO: San Jorge Island, and SFR: San Francisquito. *In these cases, the analysis did not differentiate the smaller spat (<3 mm in shell height size) as an independent cohort, which may represent a recently recruited cohort.

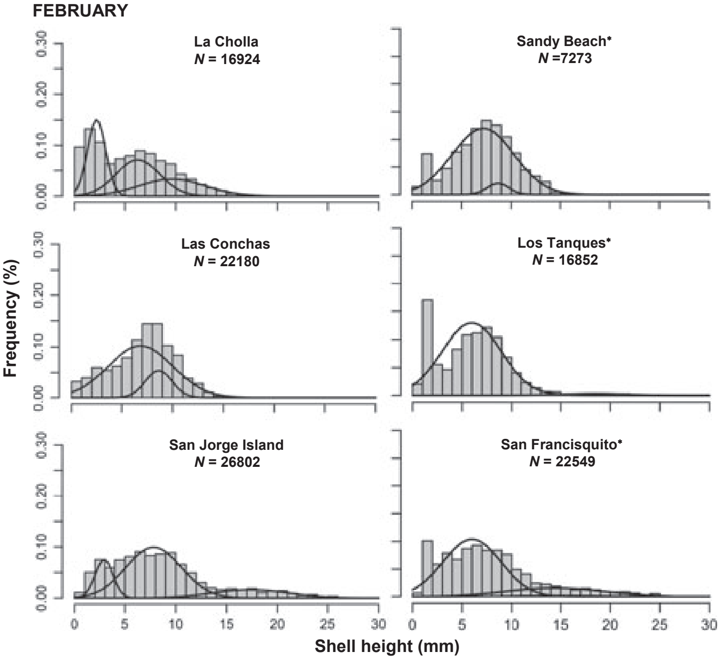

Figure 10 Modal analysis of size frequency distributions of *Argopecten ventricosus* spat recruited over a period of 2 months on artificial collectors and retrieved in February 2007 at different sites in Puerto Peñasco. Cohorts were fitting mixture distributions to the size dataset. LCH: La Cholla, SBE: Sandy Beach, LCN: Las Conchas, LTA: Los Tanques, SJO: San Jorge Island, and SFR: San Francisquito. *In these cases, the analysis did not differentiate the smaller spat (<3 mm in shell height size) as an independent cohort, which may represent a recently recruited cohort.

Bahía de Bacochibampo (1700 spat collector^{-1}) and Bahía de la Paz (10–650 spat collector^{-1}) (Félix-Pico 2006).

Spat recruitment in the study area also showed different patterns according to site and deployment depth (Figs 7 and 8). The presence of diverse recruitment patterns suggests that large scale processes (seasonal currents, proximity to parental stock, etc.) and local site conditions (e.g. sea water parameters and primary production) may be playing a significant role as drivers of the observed patterns, as has been observed in most commercial scallops worldwide (Thouzeau 1991; Narvarte 2001; Orensanz *et al.* 2006; Cyr, Myrand, Cliche

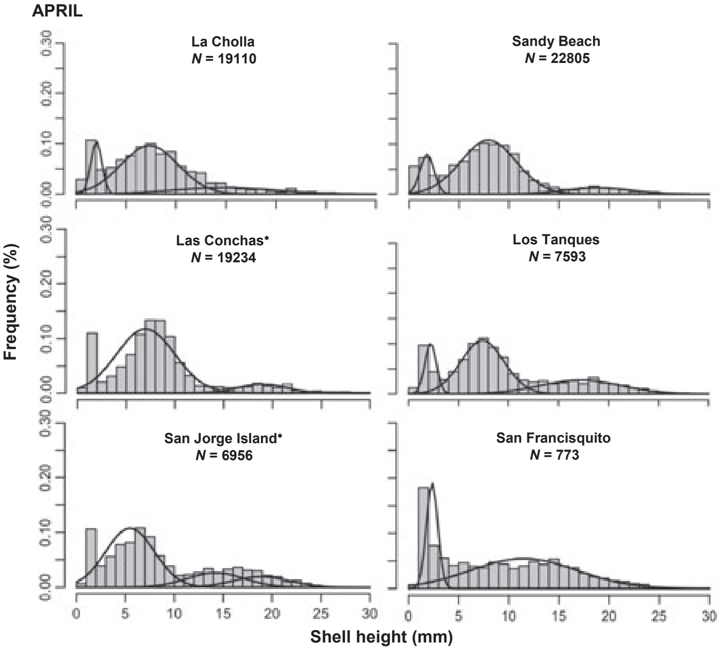

Figure 11 Modal analysis of size frequency distributions of *Argopecten ventricosus* spat recruited over a period of 2 months on artificial collectors and retrieved in April 2007 at different sites in Puerto Peñasco. Cohorts were fitting mixture distributions to the size dataset. LCH: La Cholla, SBE: Sandy Beach, LCN: Las Conchas, LTA: Los Tanques, SJO: San Jorge Island, and SFR: San Francisquito. *In these cases, the analysis did not differentiate the smaller spat (<3 mm in shell height size) as an independent cohort, which may represent a recently recruited cohort.

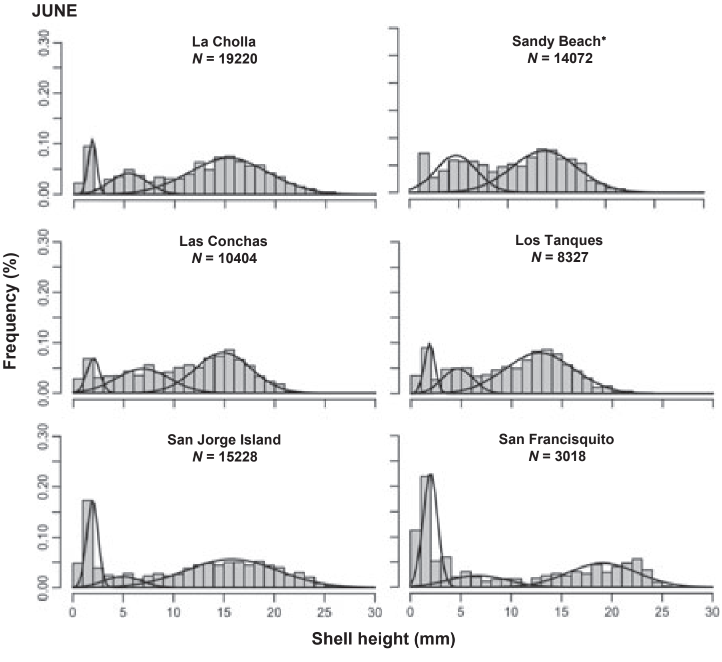

Figure 12 Modal analysis of size frequency distributions of *Argopecten ventricosus* spat recruited over a period of 2 months on artificial collectors and retrieved in June 2007 at different sites in Puerto Peñasco. Cohorts were fitting mixture distributions to the size dataset. LCH: La Cholla, SBE: Sandy Beach, LCN: Las Conchas, LTA: Los Tanques, SJO: San Jorge Island, and SFR: San Francisquito. *In these cases, the analysis did not differentiate the smaller spat (<3 mm in shell height size) as an independent cohort, which may represent a recently recruited cohort.

& Desrosiers 2007). A large-scale process probably affecting spat recruitment in the region may be the seasonal-reversing currents that dominate the circulation in the Northern Gulf of California. Throughout summer (from June to September), marine currents on the mainland shelf flow from Southeast to Northwest, whereas in winter, they move in the reverse direction (Lavín & Marinone 2003; Sánchez-Velasco, Lavín, Peguero-Icaza, León-Chávez, Contreras-Catala, Marinone, Gutiérrez-Palacios & Godínez 2009). Even though the location of *A. ventricosus* beds outside the study area are unknown, the seasonal current pattern suggests that spat recruiting throughout

Table 2 *Argopecten ventricosus*. Spat shell size frequency distributions at each site and period from December 2007 to June 2008. Cohorts were identified fitting mixture distributions to the size dataset. Mean ($\overline{\mu}$), standard deviation (SD) and proportion (%) of data explained by each component of the modelled mixture distributions

Period	Site	$\overline{\mu}_1$ (SD)	% $\overline{\mu}_1$	$\overline{\mu}_2$ (SD)	% $\overline{\mu}_2$	$\overline{\mu}_3$ (SD)	% $\overline{\mu}_3$	*n*
December	La Cholla	1.58 (0.58)	0.37	5.96 (2.55)	0.40	11.99 (4.46)	0.23	4860
	Sandy Beach	1.43 (0.55)	0.34	7.40 (3.32)	0.64	17.68 (2.05)	0.02	5304
	Las Conchas	1.63 (0.58)	0.37	4.07 (1.31)	0.14	7.21 (2.51)	0.49	6085
	Los Tanques	1.39 (0.51)	0.31	5.47 (2.26)	0.45	9.43 (3.51)	0.24	3155
	San Jorge Island	1.72 (0.65)	0.29	7.11 (2.81)	0.67	12.08 (4.12)	0.03	15856
	San Francisquito*	5.62 (3.76)	0.99	9.19 (0.01)	0.01	–	–	2905
February	La Cholla	2.16 (0.89)	0.34	6.25 (2.16)	0.39	9.65 (3.26)	0.27	16924
	Sandy Beach*	7.19 (3.14)	0.94	8.67 (1.11)	0.06	–	–	7273
	Las Conchas	2.55 (1.02)	0.14	7.91 (2.56)	0.86	–	–	22180
	Los Tanques*	5.97 (3.01)	0.97	18.41 (3.17)	0.03	–	–	16852
	San Jorge Island	2.92 (0.89)	0.17	7.82 (2.72)	0.68	17.39 (3.75)	0.15	26802
	San Francisquito*	6 (2.94)	0.76	14.42 (5.13)	0.24	–	–	22549
April	La Cholla	2.04 (0.55)	0.14	7.37 (2.88)	0.69	14.84 (5.11)	0.16	19110
	Sandy Beach	1.8 (0.7)	0.14	7.95 (2.79)	0.75	18.90 (3.36)	0.11	22805
	Las Conchas*	7 (3.03)	0.89	18.94 (3.03)	0.11	–	–	19234
	Los Tanques	2.21 (0.57)	0.15	7.40 (2.17)	0.58	17.22 (3.98)	0.27	7593
	San Jorge Island*	5.48 (2.48)	0.67	14.24 (2.88)	0.19	18.92 (2.84)	0.14	6956
	San Francisquito	2.35 (0.57)	0.27	11.49 (5.32)	0.72	–	–	773
June	La Cholla	1.83 (0.4)	0.11	5.44 (1.81)	0.19	15.38 (3.93)	0.70	19220
	Sandy Beach*	4.75 (2.09)	0.36	13.76 (3.35)	0.65	–	–	14072
	Las Conchas	1.98 (0.65)	0.11	6.90 (2.65)	0.32	14.90 (2.79)	0.56	10404
	Los Tanques	1.83 (0.52)	0.13	4.63 (1.5)	0.19	12.75 (3.41)	0.69	8327
	San Jorge Island	1.94 (0.56)	0.25	4.93 (1.88)	0.11	15.79 (4.62)	0.65	15228
	San Francisquito	1.96 (0.72)	0.41	6.69 (2.95)	0.17	19.08 (3.46)	0.42	3018

*In these cases, the analysis did not differentiate the smaller spat (<3 mm in shell height size) as an independent cohort, which may represent a recently recruited cohort.

November–December to May–April might be originated from scallop beds located north of the study area. On the other hand, during summer, it is likely that the spat might be originated from southern sources. Furthermore, during the last fishing pulses in 2009–2010, fishermen targeted a bed located between Los Tanques and San Jorge Island within the study area (Martinez-Tovar, pers. obs.). Given the seasonal-reversing currents, this scallop bed might contribute with larvae either to northern and central sites in summer (though with a relative lower quantity), or to San Jorge Island and San Francisquito, or even further locations, in winter. More research is needed to confirm or reject these hypotheses.

Overall, spat recruitment along the Puerto Peñasco area was negatively correlated with seawater temperature values and positively with chlorophyll-*a* concentration. For most sites, higher spat recruitment abundances were observed in collectors retrieved in February (Figs 7 and 8) when SST was ~15°C and SSChl was high (~3.5 mg m^{-3}) (Figs 4 and 5); this suggests that these spat recruitment peaks take place when primary productivity is relatively higher in comparison with summer. For the study area, chlorophyll-*a* concentration ranged between 2 and 5 mg m^{-3} from December to June, with maximum values in February (4–5.2 mg chlorophyll-*a* m^{-3}). On the other hand, reduced levels of chlorophyll-*a* throughout July–August (1.5–2 mg chlorophyll-*a* m^{-3}) are coupled with high sea surface temperature, which might explain the low recruitment levels observed in August and October at all sites (Fig. 7).

Site selection for the deployment of collectors should vary by season because of the strong seasonality in spat recruitment of *A. ventricosus* observed in the study area (Figs 7 and 8). For instance, in December, spat recruitment at San Jorge Island (mean = 1321 spat collector^{-1} SD = 739) could be 3–5 times higher than in other sites. In February, all sites but Sandy Beach showed significantly higher spat recruitment compared with other months. In April, the northern sites and Las Conchas showed spat abundances 3–15 times higher than in other sites. In June, with the exception of San Francisquito, spat recruitment was very similar among all collecting sites (mean = 690–1600 spat collector^{-1}). Despite the low recruitment observed in August of both years, spat recruited at San Jorge Island accounted for >85% of the total spat recruiting in the study area during this period. As the upper thermal tolerance for juvenile scallops of the same shell size has been suggested to be around 29°C (Sicard, Maeda-Martínez, Ormart, Reynoso-Granados & Carvalho 1999; Maeda-Martínez *et al.* 2000; Sicard, Maeda-Martínez, Lluch-Cota, Lodeiros, Roldán-Carrillo & Mendoza-Alfaro 2006), observed high survival rates might be related to lower temperatures recorded around the island (i.e. 1–1.5°C less in comparison with the other sites; see Table 1 and Figs 5 and 6), which is due to is offshore location.

Multimodal shell size frequencies and strong peaks of small-sized scallops (mean shell height range = 1.43–2.92 mm) characterized spat recruitment patterns in most cases (Figs 9–12). However, in some cases, the software provided inappropriate mixture distributions. These cases were: San Francisquito in December (Fig. 9), Sandy Beach, Los Tanques and San Francisquito in February (Fig. 10), Las Conchas and San Jorge Island in April (Fig. 11) and Sandy Beach in June (Fig. 12). In these cases, the analysis did not differentiate the smaller spat (<3 mm in shell height size) as an independent cohort, which may represent a recently recruited cohort. In this regard, *A. ventricosus* spat can attain a shell height range of 5–8 mm in <1 month under hatchery conditions (Maeda-Martínez, Reynoso-Granados, Monsalvo-Spencer, Sicard, Mazón-Suástegui, Hernandez, Segovia & Morales 1997), which suggest that the smaller component may correspond to a recently recruited cohort <2 weeks. Nevertheless, we successfully fitted a distribution to each peak in the size data in most cases. Such multicohort distributions imply that spat collectors could be retrieved and replaced in less than 2 months, particularly during warmer months (April–June) when larger size scallops (>10 mm in shell height size) are present. Usually, spats are transferred to juvenile intermediate culture devices (e.g. pearl-nets, nestier trays) when shell sizes are ~10 mm (Secretaria de Pesca 1994; Avendaño *et al.* 2001). Fewer cases in April and most cases in June showed a third component distribution that corresponded with higher values (mean range = 14.84–19.08 mm) than the reference value used as a proxy to transfer spat to the next rearing condition (Figs 11–12). Also, the third modal distributions (range = 12.75–19.08) observed in June explained between 42% and 70% of the data, which is an indicator of the relative abundance of spat that could be ready be transferred to further grow-out devices. On the other hand, the lack of a clear correlation between spat recruitment and collector depth suggests that local site conditions (e.g. primary productivity, dissolved oxygen, temperature, competitors, predators, etc.) might be responsible for such trends. Further research on this topic is needed to address more conclusively the role of local effects.

Histological analyses of the gonads have shown that mature and spawning *A. ventricosus* scallops can be found year-round in most regions in Northwest Mexico. In spite of this, reproductive patterns of *A. ventricosus* in Northwest Mexico vary markedly according to local conditions (Villalejo-Fuerte & Ochoa-Baez 1993; Baqueiro-Cárdenas & Aranda 2000; Cruz *et al.* 2000; Luna-González *et al.* 2000). According to Barber and Blake (2006), the reproductive cycle of scallops is a genetically controlled response to environmental factors, with temperature and food availability as the most important drivers. Thus, the reproductive pattern in a particular location will depend on the interactions between endogenous and exogenous factors (Cruz *et al.* 2000; Barber & Blake 2006). Like many other scallops species, *A. ventricosus* has the capacity to mature and spawn through the use of available food from the environment or, if primary productivity is scarce, through the use of energy stored in the adductor muscle (Villalejo-Fuerte & Ceballos-Vásquez 1996; Luna-González *et al.* 2000; Barber & Blake 2006). The interplay of such characteristics might be responsible for the observed differences on the reproductive patterns of *A. ventricosus* in Northwest Mexico. For example, scallops from La Paz, Baja California Sur (Fig. 1) show a protracted spawning period from July to December (summer and fall months) with minor peaks at the end of winter and early spring, and a clear resting period in June (end of spring) (Luna-González *et al.* 2000). On the other hand, in Bahía Concepción, the main spawning season is from September to April with peak activity in January and February, which coincided with the lowest temperature (16°C) recorded in the area, and another minor peak in June (Villalejo-Fuerte & Ochoa-Baez 1993). In a different pattern, scallops from Bahía Magdalena in the Pacific coast, spawn from March to May when water temperatures are close to 20°C (Cruz & Ibarra 1997), whereas northern populations located at Ojo de Liebre Lagoon spawn all year round with three moderate peaks (March, August and December), without resting period (Baqueiro-Cárdenas & Aranda 2000).

Histological studies addressing the reproductive cycle of *A. ventricosus* from the Northern Gulf of California have not been conducted yet. However, the observed patterns of spat recruitment on artificial collectors in the Puerto Peñasco area suggest that the species has a protracted spawning activity, with an intense activity throughout cold and temperate months (Fig. 7). A reproductive pattern that resembles the reproductive strategy of scallops from Bahía Concepción (Villalejo-Fuerte & Ochoa-Baez 1993). The existence of multicohort distributions (Figs 9–12) in the majority of the sites suggests an intense spawning activity, which might be related to the capacity of spawned scallops to mature and spawn again in less than 4 weeks when environmental conditions are appropriate (Monsalvo-Spencer *et al.* 1997). Lack of recruitment in October (collectors were deployed in August) suggests a brief resting period from the end of summer to the beginning of spring. High temperature (>30°C) and low chlorophyll concentration (<1.5 mg m^{-3}), similar to those observed for the study area in summer, have been suggested as plausible factors triggering oocyte reabsorption and gonads atresia followed by a resting stage in *A. ventricosus* scallops from Bahía Concepción (Cruz *et al.* 2000). Therefore, scallops in our study area may experience unfavourable conditions throughout the summer, which may trigger a period of low gametogenic activity and lead to low spat recruitment levels. Further studies are needed to address the likely role of environmental parameters as drivers of the reproductive cycle of the species in this region.

In this work, we demonstrated that the natural collection of *A. ventricosus* spat in the study area can be successfully performed over a protracted period. Also, spat recruitment varied markedly between seasons and highly significant differences per site were observed. This information can be used to promote further activities such as aquaculture initiatives, stock enhancement and repopulation programmes. Site selection has been shown to be a key factor in any successful bivalve aquaculture initiative (Uribe & Blanco 2001; Sicard *et al.* 2006). In this regard, there are several studies that can be used to help guide the selection of appropriate locations for further grow-out. For instance, under laboratory conditions, oxygen consumption and algae ingestion rates measured on juvenile scallops (shell height size = 10 mm) reared at different temperatures (range = 16–28°C) showed optimum values between 19 and 22°C. These values were also correlated with higher growth and survival rates. On the other hand, detrimental effects on these physiological rates were observed at temperatures higher than 26°C with an upper lethal thermal tolerance of 29°C (Sicard *et al.* 1999, 2006; Maeda-Martínez *et al.* 2000). Furthermore, according to Singnoret-Brailowski, Maeda-Martínez, Reynoso-Granados, Soto-Galera, Monsalvo-Spencer and Valle-Meza (1996), the species is osmoconformist with an ample salinity tolerance (27–47 g L^{-1}), and thus salinity concentration observed in the region might have no detrimental effects on scallops held on grow-out setting. As for adult scallops, massive mortalities (>95%) of cultured scallops have been associated with intense spawning events coupled with higher temperatures (>30°C). These massive mortalities were likely attributable to the thermal tolerance observed for the species (reviewed in Maeda-Martínez *et al.* (2000, 1997)). Therefore, given the strong seasonality of environmental parameters that characterize the study region, these physiological references could be used as a proxy to select the most suitable sites for further grow-out or conservation programmes in the area.

Finally, grow-out methods include bottom cultures, such as direct sowing (Maeda-Martínez *et al.* 2001), and the culture of scallops in plastic sleeves (Maeda-Martínez *et al.* 2000), suspended cultures in plastic cages (Nestier trays) (Maeda-Martínez *et al.* 1997) and lanterns units (Félix-Pico 2006). Each method has been shown to have specific advantages over the others depending on local environmental and ecological conditions. Determining whether the *A. ventricosus* in the region of study should be reared following a particular methodology requires further study.

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