Aquaculture Research

Aquaculture Research, 2014, 1–12 doi: 10.1111/are.12435

Spat availability of commercial bivalve species recruited on artificial collectors from the northern Gulf of California. Seasonal changes in species composition

Gaspar Soria[1,2], Miguel F Lavín[3] & Richard Cudney-Bueno[4]

[1]Centro Nacional Patagónico-CONICET, Puerto Madryn, Argentina
[2]School of Natural Resources and the Environment, University of Arizona, Tucson, AZ, USA
[3]Departamento de Oceanografía Física, Centro de Investigación Científica y de Educación Superior de Ensenada, Ensenada, Baja California, México
[4]Institute of Marine Sciences, University of California Santa Cruz, Santa Cruz, CA, USA

Correspondence: G Soria, Centro Nacional Patagónico-CONICET, Boulevard Brown 2915 Puerto Madryn, Chubut U9120ACD, Argentina. E-mail: soria@cenpat-conicet.gob.ar

Abstract

This study reports a year-round recruitment of spat of four commercial bivalve species; *Pteria sterna*, *Euvola vogdesi*, *Pinctada mazatlanica* and *Pinna rugosa* collected in the region of Puerto Peñasco, north-eastern coast of the Gulf of California. Bimonthly recruitment of commercial bivalve spat on netlon® collectors was evaluated for six sites from June 2007 to August 2008. To describe spat recruitment abundances with environmental parameters, sea surface temperature (°C) and surface chlorophyll *a* concentration (mg m^{-3}) were characterized by means of monthly Aqua/MODIS satellite data. For each species a repeated measures ANOVA was used to evaluate differences in the number of spat between months, sites and depths. Maximum sea surface temperature was recorded in August–September (~31.5°C) and the minimum in January–February (~15°C), while the minimum surface chlorophyll *a* was observed in June–September (mean range = 1.5–2 mg m^{-3}) and the maximum in January–March (mean range = 2–5 mg m^{-3}). Spat recruitment showed distinct patterns; *P. sterna* can be characterized as having a Winter–Spring pattern, *E. vogdesi* a winter pattern, while *P. mazatlanica* and *P. rugosa* a summer spat recruitment pattern. This information constitutes part of the fundamental data needed for the development of aquaculture and conservation initiatives in the region based on wild spat supply.

Keywords: *Pteria sterna*, *Euvola vogdesi*, *Pinctada mazatlanica*, *Pinna rugosa*, spat recruitment, Gulf of California

Introduction

In the Gulf of California, NW Mexico (Fig. 1a), there have been several attempts to cultivate bivalve species, which include pearl oysters, penshells and scallops among the most representative bivalve species. However, boom and bust cycles have characterized the aquaculture production of these bivalve species. Frequently, site selection, availability of spat and laboratory husbandry, among others, have been indicated as key factors undermining aquaculture initiatives (Reynoso-Granados, Maeda-Martínez, Cardoza-Velazco & Monsalvo-Spencer 1996; Félix-Pico 2006; Saucedo, Ormart-Castro & Osuna-García 2007). Aquaculture could increase the production of these species (Rangel-Dávalos 1990; Félix-Pico 2006), while helping to prevent social and economic shortcomings due to overfishing in the region as well.

In the case of pearl oysters, there are two commercial species of the Pteridae family: *Pteria sterna* and *Pinctada mazatlanica*. Although, both species have been fished and cultivated for over a century (Cáceres-Martínez, Ruíz-Verdugo & Ramírez-Fillipini 1992; INAPESCA 2011; Diario Oficial de la Federación 2013), the fisheries and aquaculture policy administration differ among species. While fishing

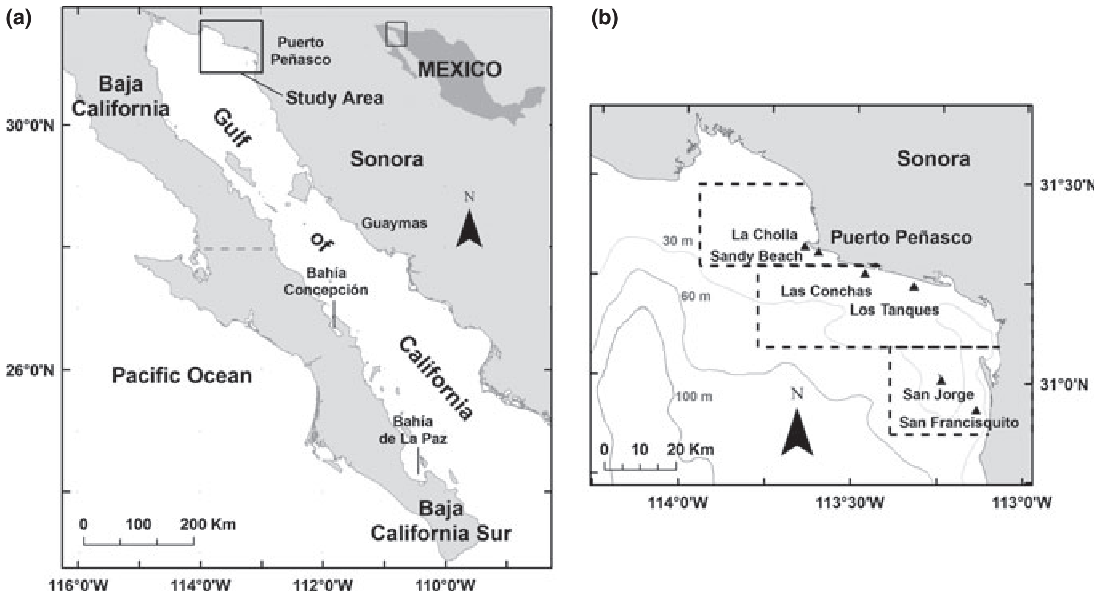

Figure 1 (a) The Gulf California, Mexico. (b) The study area showing spat recruitment sites (black triangles) and subregions (dotted lines) used in the text: The NW subregion contains La Cholla and Sandy Beach. The Central subregion includes Las Conchas and Los Tanques. The SE subregion includes San Jorge Island and San Francisquito.

P. mazatlanica requires a special permit issued by the Secretary of the Environment and Natural Resources, SEMARNAT, because it is listed as threaten species (Diario Oficial de la Federación 2010), requiring the setting of a quota and a management plan, *P. sterna* does not require a special permit. On the other hand, in 2013 a new regulation was approved for the aquaculture of both species, thus, the cultivation of each species requires a special permit (Diario Oficial de la Federación 2013). *P. sterna* is cultivated under natural conditions for the production of pearls and half-pearls (mabé) (Ruiz-Rubio, Acosta-Salmón, Olivera, Southgate & Rangel-Dávalos 2006). While significant progress has been made on hatchery and husbandry production of *P. sterna* (Cáceres-Puig, Cáceres-Martínez & Saucedo 2009), successful attempts to cultivate *P. mazatlanica* under both laboratory and natural conditions have been variable (Cáceres-Martínez *et al.* 1992; Saucedo, Bervera-León, Monteforte, Southgate & Monsalvo-Spencer 2005).

Among scallops, the concave scallop *Euvola vogdesi* is also fished in the region along with the catarina scallop, *Argopecten ventricosus* and lion's paw, *Nodipecten subnodosus*. (Félix-Pico 2006). The concave scallop is fished along both margins of the Baja California Peninsula and mainland coast of Sonora, although it represents a smaller production than the other scallop species (Félix-Pico 2006). There have been several studies focused on spat collection (Ruíz-Verdugo & Cáceres-Martínez 1991; Tobias-Sanchez & Cáceres-Martínez 1994) and growth-out (Ruíz-Verdugo & Cáceres-Martínez 1994). In the case of penshells, *Pinna rugosa* has been the subject of several efforts addressing the culture of the species, covering the natural recruitment of spat and their culture in both suspended and bottom systems (Cendejas, Carvallo & Juárez 1985; Arizpe-Covarrubias & Felix 1986; Arizpe-Covarrubias 1987, 1995).

Despite their relevance, the aquaculture of pearl oysters, penshells and scallops in the Gulf of California has spat production constrains, mostly related to the availability of spat produced under laboratory condition or wild collected. Limitations of spat production hindered the development aquaculture efforts (Reynoso-Granados *et al.* 1996; Félix-Pico 2006; Saucedo *et al.* 2007).

We report, for the first time, the year-round availability of spat of four commercial bivalve species; *P. sterna*, *P. mazatlanica*, *E. vogdesi* and *P. rugosa* collected in the region of Puerto Peñasco, an important fishing town in the north-eastern coast of the Gulf of California (Fig. 1b). While most of the research on bivalve species has been conducted for the central and southern regions, case studies for the east coast of the Northern Gulf are less common. Moreover, given the contrasting biophysical characteristics of the Gulf of California (hereafter Gulf), results obtained for the central and southern regions, such as breeding cycles, spat recruitment season and growth rates, may not be applicable to northern populations, not even for the same species.

In this study, we provide information on optimum site locations, seasonal changes, depth variability and relative abundances of these four species of bivalves. This information can be useful for the development of aquaculture and conservation programmes in the region, considering the state of overfishing of several local mollusc populations (Cudney-Bueno & Rowell 2008; INAPESCA 2011) and the absence of aquaculture initiatives. The data reported in this article expand the results previously described by Soria, Lavín, Martínez-Tovar and Macías-Duarte (2013) for the scallop *A. ventricosus*, as they were obtained as part of the same research project.

Materials and methods

Spat recruitment

Detailed information about the materials and methodology is provided in Soria, Lavín, Martínez-Tovar *et al.* (2013). Briefly, bimonthly settlement of commercial bivalve spat on netlon® collectors (200 × 40 cm; mesh opening = 7 × 12 mm) was evaluated for six sites from June 2007 to August 2008 (Fig. 1b). These sites included La Cholla (31°20′N–113°38′W), Sandy Beach (31°19′N–113°36′W) in the NW, Las Conchas (31°16′N–113°26′W) and Los Tanques (31°14′N–113°19W), San Jorge Island (31°0′N–113°14′W) and San Francisquito (30°55′N–113°7′W). At each site, three vertical lines with collectors tied at 1, 3, 5 and 7 m starting from the bottom were deployed. The first set of collectors was deployed on 22 June 2007, and it was replaced with a new set every 2 months. Hereafter a month corresponds to the cumulative recruitment of spat produced over the 2 months before the replacement date. For each species a repeated measures ANOVA (longitudinal study) was used to evaluate differences in the number of spat between months, sites and depths. To meet normality and homogeneity of variance, a natural logarithmic transformation [i.e. ln $(x + 1)$] of the numbers of spat per collector was applied. Because the main factors (time, sites and depths) as well as their interactions were significant, one-way ANOVAs were performed to compare mean spat numbers at different depths for each site and month separately. A *post hoc* Tukey test was used to compare significant differences in mean values.

Seawater parameters

To describe spat recruitment abundances with environmental parameters, sea surface temperature (°C) and surface chlorophyll *a* concentration (mg m^{-3}) were characterized by means of monthly Aqua/MODIS satellite data (http://oceancolor.gsfc.nasa.gov) as described in Soria, Lavín, Martínez-Tovar *et al.* (2013). Briefly, the data resolution was 4 × 4 km. Monthly averages were made over the subregion marked in Fig. 1, as representative of (1) the north-west region, (2) the central region and (3) the south-east region. We take chlorophyll concentration as a rough proxy of primary productivity. Also, bottom temperature was recorded every 4 h at each site, as well as sea surface water salinity (g L^{-1}), dissolved oxygen (%) and temperature (Soria, Lavín, Martínez-Tovar *et al.* 2013).

Results

Seawater parameters

Overall, the maximum sea surface temperature was recorded in August–September (~31.5°C) and the minimum in January–February (~15°C), while the minimum surface chlorophyll *a* was observed in June–September (mean range = 1.5–2 mg m^{-3}) and the maximum in January–March (mean range = 2–5 mg m^{-3}) (Soria, Lavín, Martínez-Tovar *et al.* 2013). The summer chlorophyll minimum was higher in 2008 than in 2007, while the winter maximum was higher in 2008 than in 2007 as well (Soria, Lavín, Martínez-Tovar *et al.* 2013). In summer, the NW subregion is warmer and contains less SSChl than the Central and SE subregions, which is due to the sallowness of the former. For the same reason, the NW is cooler and contains more SSChl than the other two subregions in winter (Soria, Lavín, Martínez-Tovar *et al.* 2013).The sea bottom temperature also followed a marked seasonal signal (Soria, Lavín, Martínez-Tovar *et al.* 2013). Across all sites, sea bottom temperature reached the highest values in August (mean range = 30.0–31.3°C) and the lowest values in January (mean range = 14.4–15.3°C). However, during both August 2007 and 2008, the southernmost sites of San Jorge Island and San Francisquito showed lower bottom temperature values (mean range = 30.0–30.9°C respectively) than the Central and NW subregions (mean range = 31.1–31.3°C). Similarly, in January, NW and Central sites showed lower bottom temperature records (mean range = 14.4–14.6°C) in comparison to SE sites (mean range = 14.9–15.3°C). Overall, San Jorge Island showed warmer sea bottom temperature values during cold months, whereas during warm months it had colder temperature values (Soria, Lavín, Martínez-Tovar *et al.* 2013).

Spat recruitment

Spat recruitment showed distinct patterns; *P. sterna* can be characterized as having a winter–spring spat recruitment pattern (Fig. 2), whereas *E. vogdesi* showed a winter pattern (Fig. 3). Contrastingly, *P. mazatlanica* and *P. rugosa* exhibited summer spat recruitment patterns (Figs 4–5). Overall, after excluding the months with null or low spat recruitment, spat recruitment of each species differed significantly between sampling periods (bimonthly) considering all sites (repeated measures three-way ANOVA; $P < 0.001$). For each site, spat recruitment for each species was significantly different between sampling periods (repeated measures three-way ANOVA; $P < 0.001$). High standard deviation values observed for each species in Figs 2–5, which in some instances represent negative values, are related to significant depth differences on spat recruitment values and explain much of the variability in the observed spat recruitment values.

Pteria sterna

Spat recruitment of *P. sterna* in the study area began in December 2007 and extended until June 2008, totalling 138 934 spat (Fig. 2). Throughout the study period, 30% and 56% of the total spat recruited were collected in February and June respectively. Spat recruitment at the northernmost sites showed a single peak in June, although with similar values between sites (La Cholla mean = 1225 spat collector^{-1}, SD = 487, and Sandy Beach mean = 1330 spat collector^{-1}, SD = 623) (Fig. 2). Spat recruitment showed a different pattern for the central and south-east sites, with two marked peaks; one in February and another, more vigorous, in June. For instance, Las Conchas and Los Tanques, located in the central region, showed similar values in February (Las Conchas mean = 861spat collector^{-1}, SD = 183, and Sandy Beach mean = 638 spat collector^{-1},

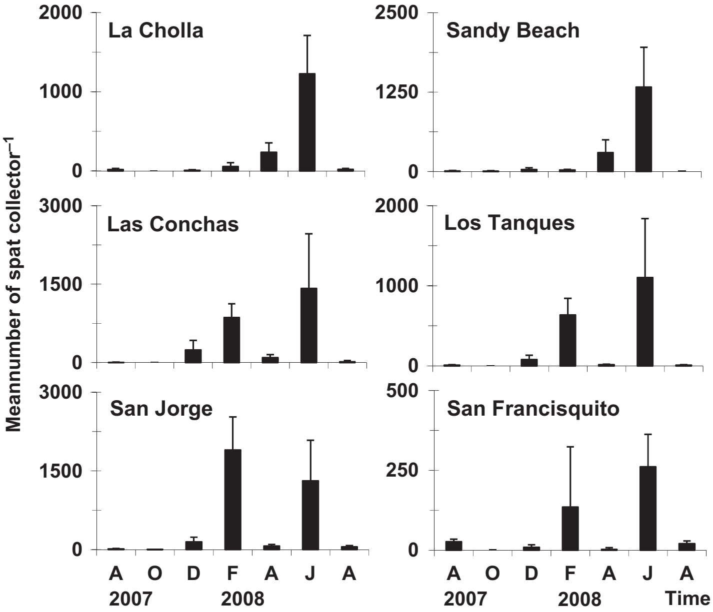

Figure 2 Bimonthly pearl oyster, *Pteria sterna*, spat recruitment per collector (black bars) at each recruitment site. Vertical lines represent standard deviation.

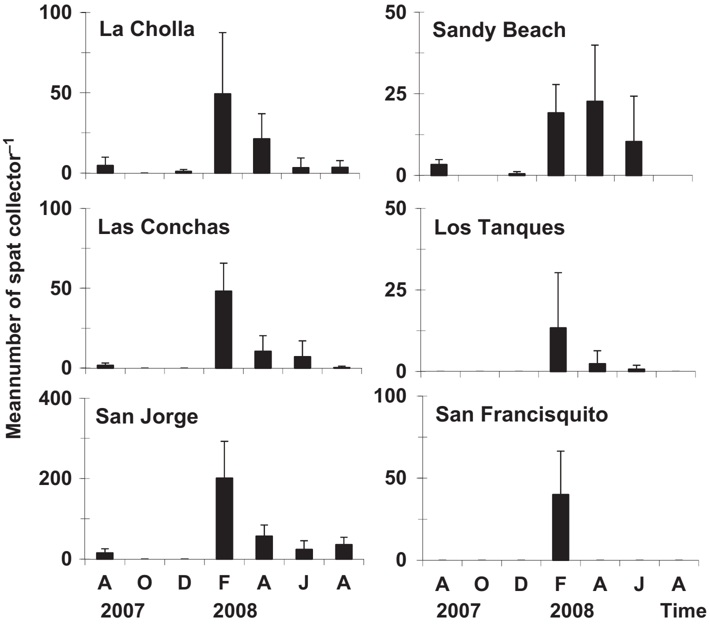

Figure 3 Bimonthly concave scallop, *Euvola vogdesi,* spat recruitment per collector (black bars) at each recruitment site. Vertical lines represent standard deviation.

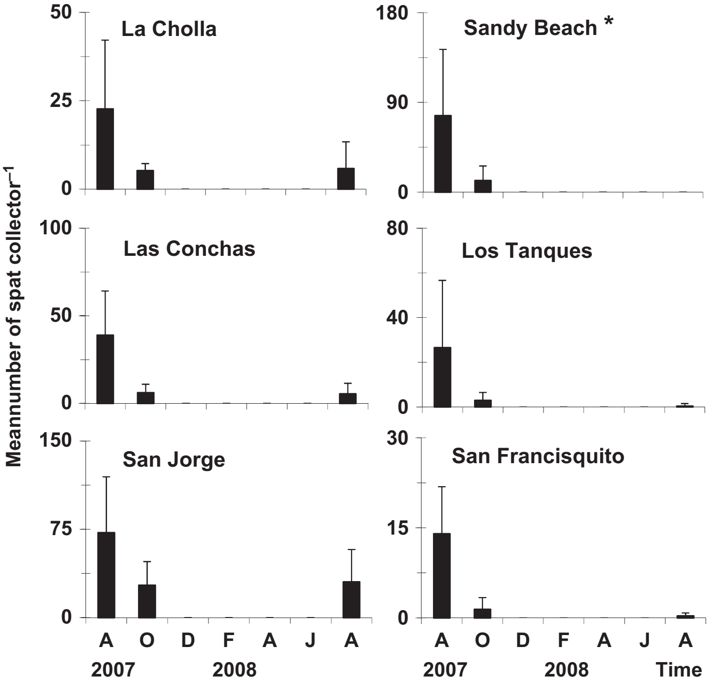

Figure 4 Bimonthly pearl oyster *Pinctada mazatlanica* spat recruitment per collector (black bars) at each recruitment site. Vertical lines represent standard deviation. * For Sandy Beach there is no record available because a full set of collectors were lost for July–August 2008.

SD = 207) and June (La Cholla mean = 1420 spat collector^{-1}, SD = 1044, and Sandy Beach mean = 1104 spat collector^{-1}, SD = 736) (Fig. 2). In the southern region, San Jorge Island showed the highest spat recruitment peak in February (mean = 1900 spat collector^{-1}, SD = 627) and the lowest values in June (mean = 1310 spat collector^{-1}, SD = 772). The southernmost site of San Francisquito showed the lowest mean spat recruitment values of the study area in February (mean = 135 spat collector^{-1}, SD = 189) and June (mean = 261 spat collector^{-1}, SD = 102).

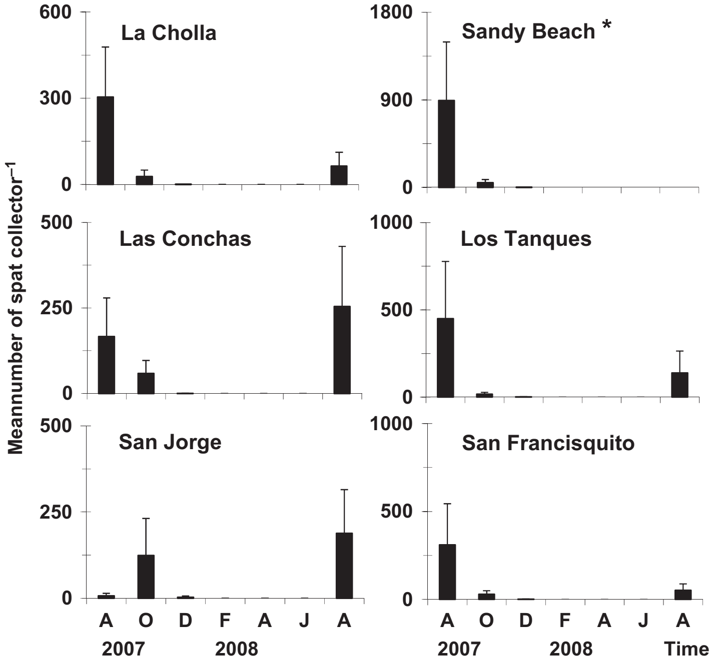

Figure 5 Bimonthly penshell, *Pinna rugosa*, spat recruitment per collector (black bars) at each recruitment site. Vertical lines represent standard deviation. *For Sandy Beach there is no record available because a full set of collectors were lost for July–August 2008.

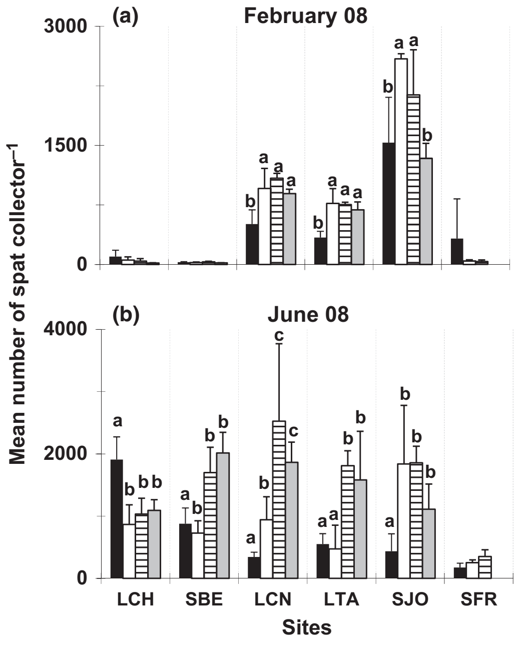

Figure 6 Mean number of wing oyster, *Pteria sterna*, spat per collector at different depths 1 m (■), 3 m (□), 5 m (▤) and 7 m (▒) at each recruitment site retrieved in (a) February and (b) June 2008. Vertical lines represent standard deviation. Different letters indicate significant differences between depths after one-way ANOVAS for each site and period of time (Tukeys's $P < 0.05$). LCH: La Cholla, SBE: Sandy Beach, LCN: Las Conchas, LTA: Los Tanques, SJO: San Jorge Island and SFR: San Francisquito.

Collectors retrieved in February and June showed a tendency of lower spat recruitment values near the bottom than in the middle and upper depths (Fig. 6).

Euvola vogdesi

Euvola vogdesi showed a strong spat recruitment in February, decreasing abruptly afterwards (between April and August), and being absent in most recruitment sites throughout autumn (Fig. 3). In total 7015 *E. vogdesi* spat were collected during the study period. In February, mean spat per collector was consistently higher in San Jorge Island (mean = 201 spat collector^{-1}, SD = 92) than any other site (mean range = 13–49 spat collector^{-1}, SD range = 9–38) (Fig. 3). With the exemption of San Jorge Island, spat recruitment registered for each site showed similar abundances across depths. In April 2008, spat recruitment in San Jorge Island was higher at 3 and 5 m than near the bottom and surface levels (Fig. 7).

Pinctada mazatlanica

Spat recruitment of *P. mazatlanica* showed a single peak during August throughout the study area. Lower values of collected spat were observed at the beginning of October. Mean values of collected spat were not proportional each year, showing a significant decrease, up to 10 times lower, in August 2008 compared to the 2007 season

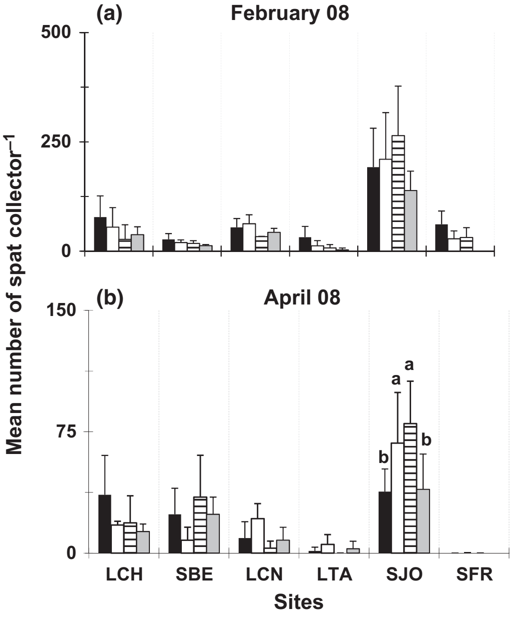

Figure 7 Mean number of concave scallop, *Euvola vogdesi*, spat per collector at different depths 1 m (■), 3 m (□), 5 m (▤) and 7 m (▩) at each recruitment site retrieved in (a) February and (b) April 2008. Vertical lines represent standard deviation. Different letters indicate significant differences between depths after one-way ANOVAS for each site and period of time (Tukeys's $P < 0.05$). LCH: La Cholla, SBE: Sandy Beach, LCN: Las Conchas, LTA: Los Tanques, SJO: San Jorge Island and SFR: San Francisquito.

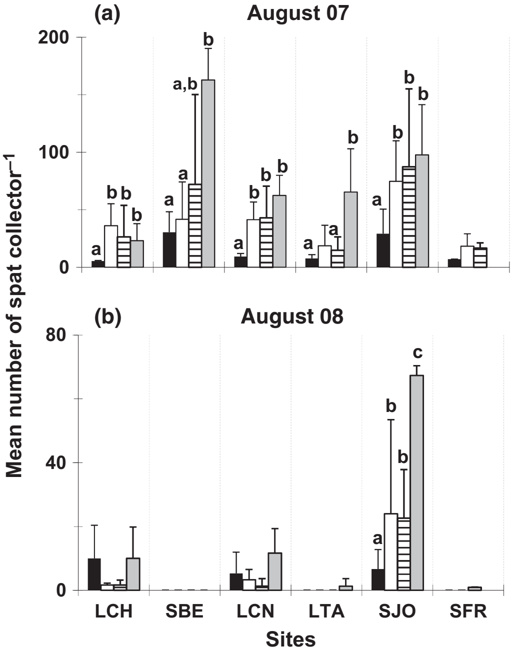

Figure 8 Mean number of pearl oyster, *Pinctada mazatlanica*, spat per collector at different depths 1 m (■), 3 m (□), 5 m (▤) and 7 m (▩) at each recruitment site retrieved in (a) August 2007 and (b) August 2008. Vertical lines represent standard deviation. Different letters indicate significant differences between depths after one-way ANOVAS for each site and period of time (Tukeys's $P < 0.05$). LCH: La Cholla, SBE: Sandy Beach, LCN: Las Conchas, LTA: Los Tanques, SJO: San Jorge Island and SFR: San Francisquito.

(Fig. 4). Although a complete set of collectors were lost to severe weather conditions for Sandy Beach in August 2008, a total 4130 spat were collected during the study period. In 2007, 72% of the total of spat collected along the study area was collected in August, mostly at Sandy Beach. In August 2007, Sandy Beach showed the highest mean value of collected spat (mean = 77 spat collector^{-1}, SD = 67). An inverse relationship between depth and mean spat abundance was observed in most sites, with higher spat recruitment values near de surface (Fig. 8).

Pinna rugosa

Spat recruitment of *P. rugosa* occurred mainly during August in all sites with the exception of San Jorge Island where it was higher in October 2007 (Fig. 5). In total, 36 450 penshell spat were collected. For those collectors retrieved in August, the highest mean values were observed in Sandy Beach (mean = 893 spat collector^{-1}, SD = 604), whereas nearby sites of La Cholla and Las Conchas showed lower values (less than 300 spat collector^{-1}) (Fig. 5). Los Tanques also showed considerable recruitment of spat (mean = 450 spat collector^{-1}, SD = 328). For Las Conchas and San Jorge Island, mean spat recruitment values increased between 2007 and 2008; however, an inverse relationship was observed for all the other sites (Fig. 5). In August 2007, mean spat recruitment values were similar at each depth in La Cholla and Las Conchas, whereas in the other sites higher spat recruitment values were observed near the surface in 2007 and 2008 (Fig. 9).

Discussion

This work presents new data on spat recruitment of *P. sterna*, *E. vogdesi*, *P. mazatlanica* and *P. rugosa* for the Gulf of California, which extends the area where spat recruitment of these commercial species

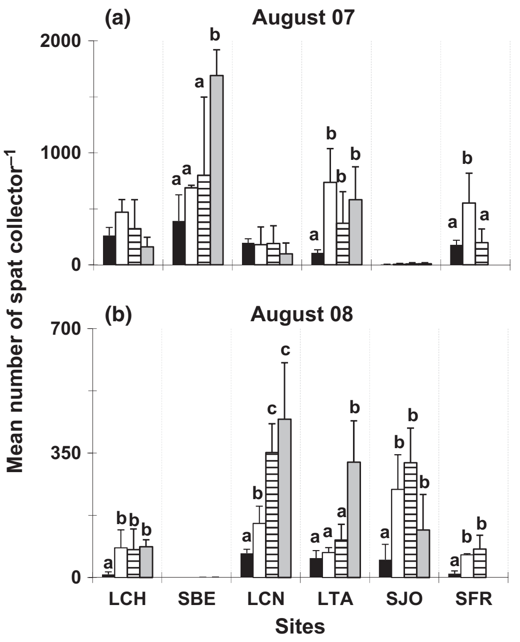

Figure 9 Mean number of penshell, *Pinna rugosa*, spat per collector at different depths 1 m (■), 3 m (□), 5 m (▤) and 7 m (▨) at each recruitment site retrieved in (a) August 2007 and (b) August 2008. Vertical lines represent standard deviation. Different letters indicate significant differences between depths after one-way ANOVAS for each site and period of time (Tukeys's $P < 0.05$). LCH: La Cholla, SBE: Sandy Beach, LCN: Las Conchas, LTA: Los Tanques, SJO: San Jorge Island and SFR: San Francisquito.

can be obtained in the gulf. Previous studies documenting spat recruitment of these bivalve species on artificial collectors have been conducted in the central and southern regions of the Gulf of California and the Pacific Coast of the Baja California Peninsula (Cendejas *et al.* 1985; Cáceres-Martínez *et al.* 1992; Tobias-Sanchez & Cáceres-Martínez 1994; Félix-Pico 2006; Cáceres-Puig 2012). These regions are characterized by distinct oceanographic and environmental conditions (Alvarez Borrego 2010), different to those of the Northern Gulf of California, which significantly affect spat recruitment of the above species.

In the area of Puerto Peñasco, spat recruitment patterns varied among species, each of them having different patterns according to site location and depth. In the case of *P. sterna,* the species showed two spat recruitment peaks taking place in late spring, when primary productivity was reaching the lowest values of the year (~2.5 mg m^{-3}) and temperatures were ~25°C, and winter when primary productivity is relatively high (mean range = 2–5 mg m^{-3}) and temperature is low (~15°C). Local site differences were also observed. For instance, the northernmost site showed one peak in winter, whereas the central and southern sites showed two peaks: one in winter and another at late spring. The general pattern resembles the winter–spring recruitment season described for the species in La Paz, Baja California Sur (Cáceres-Martínez *et al.* 1992; Monteforte, Kappelman-Piña & Lopez-Espinosa 1995; Cáceres-Puig 2012). In the southern portion of the Gulf of California, *P. sterna* is characterized by continuous gametogenesis throughout the year, with winter and spring spawning peaks (Díaz & Buckle-Ramírez 1996; Saucedo & Monteforte 1997; Vite-García & Saucedo 2008). The natural availability of spat along the study area indicates a breeding cycle that resembles southern populations. On the contrary, *P. sterna* populations from Guaymas (located ~200 km south of the study area) in the central region of the Gulf may spawn in spring (March and May) (Arizmendi-Castillo 1996), whereas in the Pacific coast the species may spawn from October to April (autumn and winter) (Hernández-Olalde, García -Domíngez, Arellano-Martínez & Ceballos-Vázquez 2007) according to environmental conditions. In La Paz, Baja California Sur, *P. sterna* showed higher spat recruitment values at higher depths (Cáceres-Puig 2012), contrary to the recruitment pattern observed in this study.

Spat recruitment of *E. vogdesi* occurred over a short period in winter (January-February), coinciding in part with that of *P. sterna*. Low recruitment abundances (less than 50 scallops per collector) were observed in autumn (March–April). In contrast, the recruitment season described for the species in La Paz, Baja California Sur, takes place between January and July, with a peak in spring (Ruiz-Verdugo & Cáceres-Martínez 1990; Tobias-Sanchez & Cáceres-Martínez 1994). Mean *E. vogdesi* spat recruitment value reported for the study area is in accordance with those documented for Bahia de La Paz (Félix-Pico 2006). In contrast, the overall abundance of collected spat in the study area is one or two orders of magnitude lower than the values described for the scallop *A. ventricosus* (mean = 2555 spat collector^{-1}) for the same sites (Soria, Lavín, Martínez-Tovar *et al.* 2013). In spite of lower numbers of recruited *E. vogdesi* spat, both scallop species showed a predominant winter recruitment season and maximum mean values at the southernmost sites.

In the study area, *P. mazatlanica* was collected mostly in summer, when water temperature was high (~31°C), coupled with reduced levels of chlorophyll *a* (mean range chlorophyll $a = 1.5$–$2\ \mathrm{mg\ m^{-3}}$), while lower values were obtained at the beginning of autumn, when sea temperature was decreasing and primary productivity was increasing. This recruitment pattern suggests an annual reproductive cycle with spawning peaks throughout summer along the mainland coast, similarly to the spat recruitment season in Baja California Sur, which takes place mostly in summer (at 29–30°C) (Cáceres-Martínez *et al.* 1992; Bervera-León 2002). However, a late spring (Saucedo & Monteforte 1997; Saucedo, Racotta, Villareal & Monteforte 2002; Saucedo *et al.* 2007) or early autumn (Garcia-Domínguez, Ceballos-Vázquez & Tripp-Quezada 1996) spat recruitment may be expected depending on environmental conditions. The species also showed predominance of higher spat abundances near the surface along the study area, which is consistent with patterns registered for Baja California Sur (Cáceres-Martínez *et al.* 1992; Bervera-León 2002).

Like *P. mazatlanica,* the spat recruitment of *P. rugosa* was limited to summer and early autumn. Contrary to this pattern, the spat recruitment season in the southern region of the Gulf of California takes place from July to December with a recruitment peak in autumn (Arizpe-Covarrubias 1987). This southern pattern is correlated with histological analysis of the gonads of *P. rugosa* for southern populations of Bahía de La Paz and Bahía Concepción where ripe and spawning stages are found predominantly at the end of the summer (Noguera de Gómez & Gómez-Aguirre 1972; Ceballos-Vázquez, Arellano-Martínez, García -Domíngez & Villalejo-Fuerte 2000).

The circulation of the Northern Gulf of California is seasonally reversing (Lavín & Marinone 2003; Alvarez Borrego 2010). There is a summer cyclonic phase which lasts from June to September and includes a poleward coastal current over the mainland continental shelf that has its origin in the southern region (Carrillo, Lavín & Palacios-Hernández 2002; Palacios-Hernández, Beier, Lavín & Ripa 2002; Marinone 2008; Peguero-Icaza, Sánchez-Velasco, Lavín, Marinone & Beier 2011), whereas the anticyclonic phase lasts from November to April (Marinone 2008). The presence of such large-scale (hundreds of km) process could explain the occurrence of diverse spat recruitment patterns, and also point out to the likely origin of larvae arriving to the study area. For instance, in the case of *P. sterna,* recruited spat could include southern or northern sources in summer and winter respectively, as well as local sources. In the case of *P. mazatlanica* and *P. rugosa,* spat recruitment could be linked to both local and southern sources (<200 km south of the study area). Based on biophysical modelling, such connectivity pattern was suggested for the rock scallop, *Spondylus* (*calcifer*) *limbatus*, inhabiting the study area and having a similar spat recruitment season to that of *P. mazatlanica* and *P. rugosa* (Soria, Munguía-Vega, Marinone, Moreno-Báez, Martínez-Tovar & Cudney-Bueno 2012). Similarly to *P. sterna,* the clockwise current circulation throughout winter suggests that *E. vogdesi* larvae may be originating NW of the study area as well. Potential winter sources, derived from biophysical modelling, can include locations from the Baja California Peninsula (Soria, Lavín & Marinone 2013). Local site conditions (e.g. sea water parameters and primary productivity) can drive observed settlement patterns for each species at each recruitment site as well. Further research is needed to address the sources of larvae that recruit within the study area, which is biophysically complex system characterized by seasonally reversing currents. Knowledge about the potential sources will benefit the development of proper management plans of each commercial species.

With regards to production of pearl oysters, penshells and scallops, the success obtained in spat recruitment in this study is promising as a source of spat to supply potential aquaculture demands, and stock enhancement and repopulation programmes (Reynoso-Granados *et al.* 1996; Félix-Pico 2006; Saucedo *et al.* 2007). However, for each species, site selection must vary by month given the highly variable seasonality in spat recruitment values along the study area. Overall, the lack of recruitment observed in collectors retrieved in late autumn (collectors deployed in October and retrieved in December) might suggest a brief resting period which is common for all the species reported in this study. Further studies are needed to understand the reproductive cycle of these bivalve species for the Northern Gulf of California and the role of environmental parameters moulding the timing of spawning events in the region.

Aquaculture of bivalve species relies on an efficient supply of spat, as well as other biological, technical and commercial issues. In this sense, the spat recruitment results for each species provided in this study (e.g. site locations, season, depth variances) constitute part of the fundamental data needed for the development of aquaculture and conservation initiatives (e.g. repopulation programmes through collection and sowing of spat) in the region.

Acknowledgments

The work was funded by The Nature Conservancy through its RJ KOSE Grant Program. Logistic support was provided by Intercultural Center for the Study of Deserts and Oceans (CEDO) and Comunidad y Biodiversidad, A. C. (COBI). Thanks to D. Manjon, W. Ludt, J. Hall, J. Salazar, I Martínez-Tovar and R. Loaiza-Villanueva for assistance in the field. Spat recruitment was conducted under the fishing permit #DGOPA 11216.0611109. 3883 issued by the Secretaría de Agricultura, Ganadería, Desarrollo Rural, Pesca y Alimentación (SAGARPA), México. This is a scientific contribution of the PANGAS Project (www.pangas.arizona.edu), supported by the David and Lucile Packard Foundation. Dr. A. Cinti reviewed and provided insightful comments. Additional comments from anonymous referees greatly improved the manuscript.

References

Alvarez Borrego S. (2010) Physical, chemical, and biological oceanography of the Gulf of California. In: *The Gulf of California: Biodiversity and Conservation* (ed. by R.C. Brusca), pp. 22–48. University of Arizona Press, Tucson.

Arizmendi-Castillo E. (1996) *Ciclo reproductivo de las ostras perleras, Pinctada mazatlanica (Hanley, 1856) y Pteria sterna (Gould, 1851), (Pteriidae), en el a rea de Guaymas, Sonora, Mexico*. Instituto Tecnológico de Estudios Superiores de Monterrey, Guaymas.

Arizpe-Covarrubias O. (1987) Reclutamiento y mortalidad de *Pinna rugosa* (Sowerby, 1835) en condiciones semicontroladas en Bahía de la Paz, México. *Anales del Instituto de Ciencias del Mar y Limnológicas* **14**, 249–254.

Arizpe-Covarrubias O. (1995) Mortality, growth and somatic secondary production of the bivalve, *Pinna rugosa* (Sowerby), in suspended and bottom culture in Bahia de la Paz, Mexico. *Aquaculture Research* **26**, 843–853.

Arizpe-Covarrubias O. & Felix R. (1986) Crecimiento de *Pinna rugosa* (Sowerby, 1835) en la Bahía de La Paz. *Anales del Instituto de Ciencias del Mar y Limnológicas* **13**, 167–172.

Bervera-León H. (2002) *Distribucion y abundancia espacio-temporal de semilla de Pinctada mazatlanica (Bivalvia: pteriidae) en la Bahia de La Paz, Baja California Sur, Mexico*. CICIMAR, Instituto Politecnico Nacional, La Paz, 134pp.

Cáceres-Martínez C., Ruíz-Verdugo C.A. & Ramírez-Fillipini D.H. (1992) Experimental collection of pearl oyster, *Pinctada mazatlanica* and *Pteria sterna*, spat on a filament substrate. *Journal of World Aquaculture Society* **23**, 234–240.

Cáceres-Puig J.I. (2012) *Dinámica del reclutamiento de juveniles de concha nacar Pteria sterna en la Bahía de la Paz*, Centro de Investigaciones Biológicas del Noroeste, La Paz, Baja California Sur, México, 177pp.

Cáceres-Puig J.I., Cáceres-Martínez C. & Saucedo P.E. (2009) Annual reproductive effort of pacific winged pearl oyster *Pteria sterna* and its relation with the timing for planning pearl seeding operations. *Journal of Shellfish Research* **28**, 471–476.

Carrillo L., Lavín M.F. & Palacios-Hernández E. (2002) Seasonal evolution of the geostrophic circulation in the Northern Gulf of California. *Estuarine, Coastal and Shelf Science* **54**, 157–173.

Ceballos-Vázquez B.P., Arellano-Martínez M., García - Domíngez F. & Villalejo-Fuerte M. (2000) Reproductive cycle of the rugose pen shell, *Pinna rugosa* Sowerby, 1835 (Mollusca: bivalvia) from Bahía Concepción, Gulf of California and its relation to temperature and photoperiod. *Journal of Shellfish Research* **19**, 95–99.

Cendejas J.M., Carvallo M.G. & Juárez L.M. (1985) Experimental spat collection and early growth of the pen shell, *Pinna rugosa* (Pelecypoda: Pinnidae), from the Gulf of California. *Aquaculture* **48**, 331–336.

Cudney-Bueno R. & Rowell K. (2008) Establishing a baseline for management of the rock scallop *Spondylus calcifer* (Carpenter 1857): Growth and reproduction in the Upper Gulf of California, Mexico. *Journal of Shellfish Research* **27**, 625–632.

Diario Oficial de la Federación (2010) *NORMA Oficial Mexicana NOM-059-SEMARNAT-2010*. Diario Oficial de la Federación, Secretaría de Medio Ambiente y Recursos Naturales (SEMARNAT), Mexico City, 78pp.

Diario Oficial de la Federación (2013) *NORMA Oficial Mexicana NOM-058-SAG/PESC/SEMARNAT-2013*. Diario Oficial de la Federación, Secretaría de Medio Ambiente y Recursos Naturales (SEMARNAT), SAGARPA: Secretaría de Agricultura, Ganadería, Desarrollo Rural, Pesca y Alimentación, Mexico City, 8pp.

Díaz A.H. & Buckle-Ramírez L.F. (1996) Ciclo gonádico de *Pteria sterna* (Gould, 1851) (Mollusca, Bivalvia) en Baja California, México. *Ciencias Marinas* **22**, 495–509.

Félix-Pico E.F. (2006) Mexico. In: *Scallops: biology, Ecology and Aquaculture* (ed. by S.E. Shumway & G.J. Parsons), pp. 1337–1390. Elsevier, Amsterdam.

Garcia-Domínguez F., Ceballos-Vázquez B.P. & Tripp-Quezada A. (1996) Spawning cycle of the pearl oyster, *Pinctada mazatlanica* (Hanley, 1856), (Pteriidae) at Isla Espiritu Santo, Baja California Sur, Mexico. *Journal of Shellfish Research* **15**, 297–303.

Hernández-Olalde L., García -Domíngez F., Arellano-Martínez M. & Ceballos-Vázquez B.P. (2007) Reproductive cycle of the pearl oyster *Pteria sterna* (Pteriidae) in the Ojo de Libre Lagoon, B.C.S, Mexico. *Journal of Shellfish Research* **26**, 543–548.

INAPESCA (2011) *Evaluación de un banco de callo de árbol en el Desemboque, Sonora en marzo/abril de 2011*. Instituto Nacional de la Pesca, Dirección General de Investigación Pesquera en el Pacífico Norte, Guyamas, pp. 1–16.

Lavín M.F. & Marinone S.G. (2003) An overview of the physical oceanography of the Gulf of California. In: *Nonlinear Processes in Geophysical Fluid Dynamics* (ed. by O.U. Velasco-Fuentes, J. Sheinbaum & J. Ochoa), pp. 173–204. Kluwer Academic Publishers, Netherlands.

Marinone S.G. (2008) On the three-dimensional numerical modeling of the deep circulation around Ángel de la Guarda Island in the Gulf of California. *Estuarine, Coastal and Shelf Science* **80**, 430–434.

Monteforte M., Kappelman-Piña E. & Lopez-Espinosa B. (1995) Spatfall of pearl oyster, *Pteria sterna* (Gould), on experimental collectors at Bahía de La Paz, South Baja California, Mexico. *Aquaculture Research* **26**, 497–511.

Noguera de Gómez O.M. & Gómez-Aguirre S. (1972) Ciclo sexual de *Pinna rugosa* Sowerby, 1835 (Lamellibranchia, Pinnidae) de La Paz, B. C., México. In: *IV Congreso Nacional de Oceanografía* (ed. by J. Carranza), pp. 273–283. Universidad Nacional Autónoma de México, México, D. F.

Palacios-Hernández E., Beier E., Lavín M.F. & Ripa P. (2002) The effect of winter mixing on the circulation of the Northern Gulf of California. *Journal of Physical Oceanography* **32**, 705–728.

Peguero-Icaza M., Sánchez-Velasco L., Lavín M.F., Marinone S.G. & Beier E. (2011) Seasonal changes in connectivity routes among larval fish assemblages in a semi-enclosed sea (Gulf of California). *Journal of Plankton Research*, **33**, 517–533.

Rangel-Dávalos C. (1990) El cultivo de moluscos marinos en México. In: *La acuicultura en México de los conceptos a la producción* (ed. by G. de la Lanza-Ezpino & J.L. Arredondo-Ezpino), pp. 107–138. Instituto de la Biología, Universidad Nacional Autónoma de México, México.

Reynoso-Granados T., Maeda-Martínez A., Cardoza-Velazco F. & Monsalvo-Spencer P. (1996) Cultivo de Hacha. In: *Estudio del Potencial Pesquero y Acuícola de Baja California Sur, Mexico* (ed. by M. Casas-Valdez & G. Ponce-Díaz), pp. 88–92. Centro de Investigaciones Biológicas del Noroeste, La Paz, Mexico.

Ruiz-Rubio H., Acosta-Salmón H., Olivera A., Southgate P.C. & Rangel-Dávalos C. (2006) The influence of culture method and culture period on quality of half-pearl (mabé) from the winged pearl oyster *Pteria sterna*, Gould, 1985. *Aquaculture*, **254**, 269–274.

Ruiz-Verdugo C.A. & Cáceres-Martínez C. (1990) Estudio preliminar de captación de juveniles de moluscos bivalvos en la Bahía de La Paz, B.C.S, México. *Investigaciones Marinas* **5**, 29–38.

Ruíz-Verdugo C.A. & Cáceres-Martínez C. (1991) Experimental spat collection of scallops *Argopecten circularis* (Sowerby, 1835), and *Pecten vogdesi* (Arnold, 1906) on a filament substrates in Falsa Bay, B.C.S., Mexico. In: *An International Compendium of Scallop Biology and Culture. World Aquaculture Workshops*, Baton Rouge, LA, USA, pp. 21–27.

Ruíz-Verdugo C.A. & Cáceres-Martínez C. (1994) Cultivo sobre el fondo de almeja voladora *Pecten vogdesi* en la Bahía de La Paz, Baja California Sur, Mexico. *Revista de Investigación Científica* **1**, 60–66.

Saucedo P. & Monteforte M. (1997) Breeding cycle of pearl oysters *Pinctada mazatlanica* and *Pteria sterna* (Bivalvia: Pteriidae) at Bahia de La Paz, Baja California Sur, Mexico. *Journal of Shellfish Research* **16**, 103–110.

Saucedo P., Racotta I., Villareal H. & Monteforte M. (2002) Seasonal changes in the histological and biochemical profile of the gonad, digestive gland, and muscle of the calafia mother-of-pearl, *Pinctada mazatlanica* (Hanley, 1856) associated with gametogenesis. *Journal of Shellfish Research* **21**, 127–135.

Saucedo P.E., Bervera-León H., Monteforte M., Southgate P.C. & Monsalvo-Spencer P. (2005) Factors influencing recruitment of hatchery reared pearl oyster (*Pinctada mazatlanica*; Hanley 1856) spat. *Journal of Shellfish Research* **24**, 215–219.

Saucedo P.E., Ormart-Castro P. & Osuna-García M. (2007) Towards development of large-scale hatchery cultivation of larvae and spat of the pearl oyster *Pinctada mazatlanica* in Mexico. *Aquaculture* **273**, 478–486.

Soria G., Munguía-Vega A., Marinone G., Moreno-Báez M., Martínez-Tovar I. & Cudney-Bueno R. (2012) Linking bio-oceanography and population genetics to assess larval connectivity. *Marine Ecology Progress Series* **463**, 159–175.

Soria G., Lavín M.F. & Marinone S.G. (2013) Settlement of concave scallop *Euvola vogdesi* on artificial collectors in the NE coast of the Gulf of California: seasonal changes and potential origin of larvae. In: *International Pectinid Workshop*, Florianopolis, pp. 37–38.

Soria G., Lavín M.F., Martínez-Tovar I. & Macías-Duarte A. (2013) Recruitment of catarina scallop (*Argopecten* *ventricosus*) larvae on artificial collectors off the NE coast of the Gulf of California. *Aquaculture Research* **44**, 1383–1398.

Tobias-Sanchez M. & Cáceres-Martínez C. (1994) Colecta experimental de juveniles de *Pecten vogdesi* sobre diferentes sustratos artificiales en la Bahía de La Paz, B.C.S, México. *Revista de Investigación Científica* **5**, 45–53.

Vite-García N. & Saucedo P.E. (2008) Energy storage and allocation during reproduction of pacific winged pearl oyster *Pteria sterna* at Bahía de la Paz, Baja California Sur, Mexico. *Journal of Shellfish Research* **27**, 375–383.