Biol Invasions (2008) 10:977–984
DOI 10.1007/s10530-007-9175-0

ORIGINAL PAPER

Geographic expansion of the invasive red crayfish *Procambarus clarkii* (Girard, 1852) (Crustacea: Decapoda) in Mexico

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Received: 18 August 2007 / Accepted: 3 September 2007 / Published online: 28 September 2007

Abstract The red crayfish *Procambarus clarkii*, which is native to southcentral USA and northeastern Mexico, has been successfully introduced into several countries around the world. This study documents the geographic expansion of the exotic red crayfish in Mexico and discusses the consequence of a greater propagation of this species in Mexican inland waters. New state records of this crayfish in the Baja California peninsula and in the states of Durango and Sinaloa indicate its progressive dispersion. The propagation of *P. clarkii* in Mexico has been caused mainly by human introduction, but it is also facilitated because of the species' tolerance to an ample range of environmental conditions. Because of the invasive capability of *P. clarkii*, we suspect that this exotic species is competing for habitat and food with native freshwater shrimp of the genus *Macrobrachium* in many sites of northern Mexico.

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Keywords Baja California peninsula · Exotic fauna · Freshwater decapods · New records · Oasis

Introduction

In Mexico, the number of freshwater decapods is about 140 species (Álvarez et al. 1996, 2005). The Astacidea is one of the best studied groups because of the species richness that comprises at least 53 species of which 43 belong to the genus *Procambarus* (Hobbs 1989; Villalobos-Hiriart et al. 1993; Álvarez et al. 1996; López-Mejía et al. 2004).

The Astacidea *Procambarus clarkii* (Girard, 1852), *Orconectes virilis* (Hagen, 1870), and *Cherax quadricarinatus* (Von Martens, 1868) have been recorded as exotic species in Mexico (Hobbs 1989; Rodríguez-Almaraz and Campos 1994; Bortolini et al. 2007). The red crayfish *Procambarus clarkii* has its type locality between "San Antonio" and "El Paso" in Texas, USA (Hobbs 1989) on the eastern border of USA and Mexico. From its natural range, *P. clarkii* was successfully introduced into the western and eastern USA (Huner and Barr 1983; Hobbs et al. 1989). Also this species has been widely introduced in other countries of the American continent from Belize to Ecuador (Campos and Rodríguez-Almaraz 1992; Holdich et al. 1999; Rodríguez and Suárez 2001; Campos 2005), and in several countries in Asia (China and Japan), Africa (Kenya, Uganda, and Zambia) (Hobbs 1989), and Europe (Spain, France, Italy, Switzerland) (Barbaresi and Gherardi 2006; Harlioğlu and Harlioğlu 2006).

Thus, the current distribution of *P. clarkii* comprises all continents, except Australia and the Antarctic (Campos 2005). Its translocation has been mainly motivated for aquaculture purposes because this species is a popular dining delicacy in the USA (Huner 1980; Campos 2005; Barbaresi and Gherardi 2006) and is also used as an ornamental animal (Rodríguez and Suárez 2001). Additionally, attempts have been made to use *P. clarkii* as a biological control organism in Africa, especially by Hofkin et al. (1991) who showed experimentally that the red crayfish is an active predator of the schistosome-transmitting snails. In this respect, *P. clarkii* was shown to exert a significant impact on the avoidance of the transmission of human schistosomiasis under certain environmental circumstances (Mkoji et al. 1999). The success of its introduction is attributable to different factors such as its rapid somatic growth, its "r" reproductive strategy that comprises a short life-history and a high fecundity rate (Campos 2005; Barbaresi and Gherardi 2006), its ability to use a wide spectrum of feeds (ISSG 2007), and its ability to tolerate slightly saline and hot waters, dry periods, and low dissolved oxygen environments (Campos 2005). Because of the ecological characteristics already mentioned, *P. clarkii* is considered the most plastic species of the entire order Decapoda (Campos 2005; ISSG 2007). Likewise, it is also looked upon as a keystone species that might modify the nature of native plants and animal communities (ISSG 2007).

In many parts of the world, introductions of exotic species are the first or second most important threat for freshwater biodiversity and the ecosystem function (Álvarez et al. 1996; Wilcove et al. 1998; Sánchez and Angeler 2006). The aggressive behavior of the invasive red crayfish *P. clarkii* has caused the reduction or even disappearance of several native aquatic animals and plants and has damaged many water ponds because of its extensive burrowing activity (Holdich et al. 1999; Rodríguez-Almaraz and Campos 1994; Campos 2005). In Europe, *P. clarkii* have actively colonized new territory at the expense of the native crayfish (Astacidae) contributing to the decline of native populations of crustaceans (Gil-Sánchez and Alba-Tercedor 2002). In Kenya, *P. clarkii* was suspected of causing the complete disappearance of native floating-leaved and submerged plants (Smart et al. 2002). Laboratory and field experiments have also shown that *P. clarkii* prey on the eggs of native amphibians in Santa Monica mountain streams in California (Gamradt and Kats 1996). Moreover, this species acts as a vector for numerous crayfish diseases (Gil-Sánchez and Alba-Tercedor 2002) and is also an intermediate host for numerous helminth parasites of vertebrates (Sánchez and Angeler 2006).

Several papers on the geographical distribution of *P. clarkii* in Mexico reported the man-made introduction of this species in northern regions of the country in the states of Baja California, Sonora, and Tamaulipas (Huner 1980; Hobbs 1989; Campos and Rodríguez-Almaraz 1992). The objective of our work is to report the expansion of this invasive species into several new states and basins of Mexico and to discuss its probable effects on native species.

Materials and methods

The examined material of *Procambarus clarkii* comes from field collections made by L. Hernández, A.M. Maeda-Martínez, and G. Ruiz-Campos in the Baja California peninsula (in the states of Baja California and Baja California Sur), G. Rodríguez-Almaraz in the states of Coahuila, Nuevo León, and Tamaulipas, F. Alonzo-Rojo in the state of Durango, and J. C. Sainz in the state of Sinaloa. The specimens are deposited in the crustacean collections of Centro de Investigaciones Biológicas del Noroeste (CIB-NOR), Facultad de Ciencias, Universidad Autónoma de Baja California (UABC), and Facultad de Ciencias

Biológicas, Universidad Autónoma de Nuevo León (UANL FCB).

Total length (TL) measured from the tip of the rostrum to the distal end of telson and gender (gonopores on the base of the third pair of pereiopods for females and the same on the fifth for males) were determined in the specimens collected in the Baja California peninsula, Durango, Sinaloa, and Sonora. The specimens were taxonomically identified using the descriptions of Villalobos (1950) and Hobbs (1989).

Results

Diagnostic morphological features

All specimens examined were the species *Procambarus clarkii*. The morphological characteristics are carapace usually dark red and pigmented eyes; rostrum cuminate with presence of cervical spines; the palm of the first cheliped is elongated and comes with a row of tubercles along the mesial margin (Fig. 1A). There are hooks on the ischia of the males at the third and-or fourth pereiopods. Juvenile specimens are greenish-gray that became reddish with sexual maturity (Campos 2005).

Geographic distribution of *Procambarus clarkii* in Mexico

The distribution records of *Procambarus clarkii* in Mexico are listed in Table 1. The new state records are Baja California Sur, Durango, and Sinaloa (Fig. 2).

Material examined

Baja California: *Arroyo el Descanso*, 7 females (30–48 mm TL), 4 males (43–63 mm TL) and 5 juveniles (<30 mm TL) (UABC-010); *Arroyo San Carlos*, 1 male (36 mm TL) (UABC-011); *Arroyo Las Ánimas*, 2 males (33–40 mm TL) and 2 females (66.2–73.5 mm TL) (UABC-012); *Arroyo Santo Tomás*, 9 females (22.2–76.5 mm TL) and 8 males (64.2–72.6 mm TL) (UABC-013). *Arroyo San Telmo*, 1 male (106.8 mm TL) (UABC-014); *Rancho Los Aguajes*, 1 female (69.8 mm TL) (UABC-015); *Arroyo San Juan de Dios*, 6 females (40–80.3 mm TL) and 2 males (63.8 and 72.2 mm TL) (UABC-016); *Arroyo Cataviña*, 3 males (38–81 mm TL) (UABC-017). Baja California Sur: *Oasis San Ignacio*, 10 males (48.2–78.2 mm TL) and 6 females (42–74.5 mm TL) (UABC-018); 4 males (36–79.3 mm TL) (CIBNOR-897); *Arroyo San Joaquín*, 6 specimens (UABC-019); *El Sauzal*, 1 male (78.2 mm TL) (UABC-020) and 2 males (72–76.8 mm TL) (CIBNOR-893) (Fig. 1B). Sonora: *San Luis Río Colorado*, 1 female (70.4 mm TL) (UABC-021). Sinaloa: Río Culiacán, 1 male (90 mm TL) and 1 female (98 mm TL) (CIBNOR-903) (Fig. 1C). Durango: *Río Nazas*, 2 males (107.3 and 128 mm TL) (CIBNOR-898) (Fig. 1D). Coahuila: *Ciudad Acuña*, 5 males (68–84 mm TL) and 2 females (71–75 mm TL) (UANL FCB-02586); *Nadadores*, 4 males (67–96 mm TL) and 6 females (34–92 mm TL) (UANL FCB-02594, 02573, 02476, 2598-2600); *San Buenaventura*, 1 male (73 mm TL) and 1 female (57 mm TL) (UANL FCB-02593); *Río Salado*, 2 males (38–57 mm TL) and 3 females (46–65 mm TL) (UANL FCB-02588, 02592). Nuevo León: *Santiago*, 2 males (74–86 mm TL) (UANL FCB-02533); *Parque Canoas*, 4 males (72–93 mm TL) and 2 females (72–85 mm TL) (UANL FCB-02465); *La Ciudadela*, 1 female (80 mm TL) (UANL FCB); *La Juventud* weir, 6 females (60–91 mm TL) (UANL FCB); *Cadereyta*, 2 males (73–82 mm TL) (UANL FCB-02522); *Rancho Pérez*, 3 females (52–71 mm TL) (UANL FCB); Tamaulipas: *El Carmen*, 1 male (94 mm TL) and 2 females (87–88 mm TL) (UANL FCB-02584-02586); *Nueva Cd. Guerrero*, 1 male (44 mm TL) (UANL FCB-02580); *Padilla*, 3 males (72–94 mm TL) and 3 female (39–87 mm TL) (UANL FCB); *La Pesca*, 1 female (72 mm TL) (UANL FCB-02596).

Discussion

Our study documents the geographic expansion of the invasive red crayfish *Procambarus clarkii* in water bodies of the two most important northern deserts of Mexico. In the Chihuahuan desert, in northcentral Mexico, the new record of *P. clarkii* from the Río Nazas basin (Fig. 1D) in Durango state is situated about 420-km south of the previously published record at the Río Conchos basin in Chihuahua state

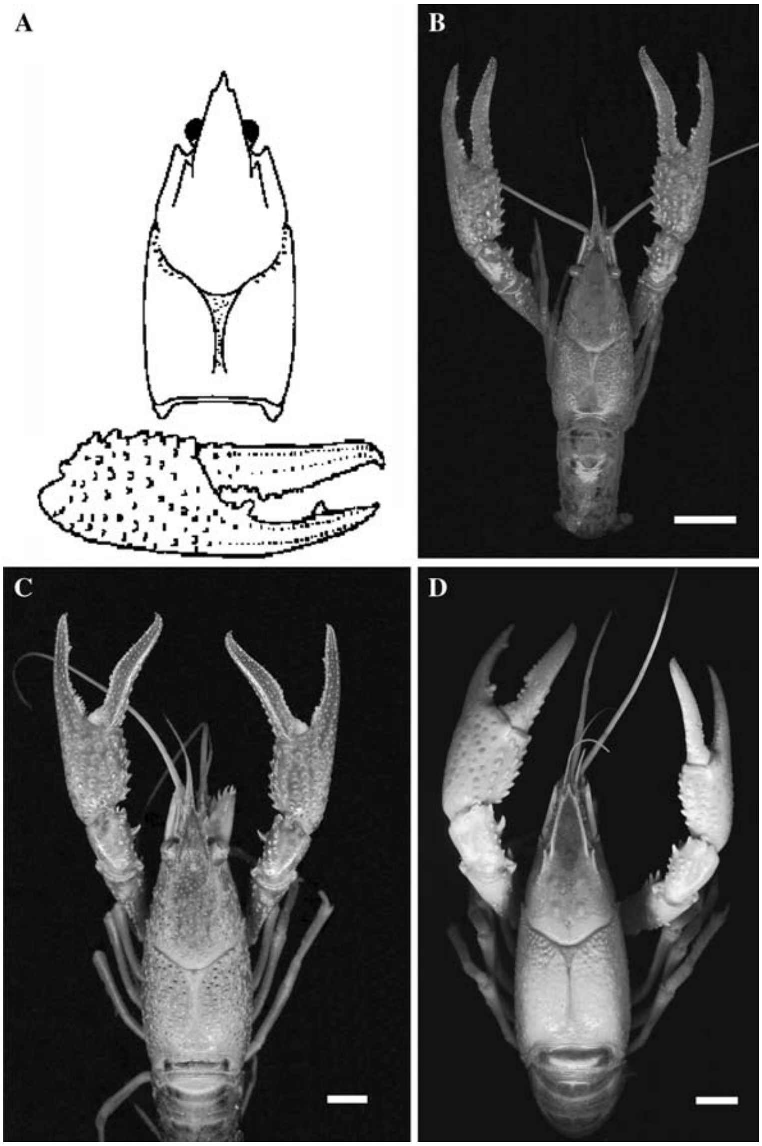

Fig. 1 *Procambarus clarkii*. (**A**) Carapace in dorsal view and chela of male (from Hobbs 1989). (**B**) Male from El Sauzal, Baja California Sur, Mexico. (**C**) Male from Río Culiacán, Sinaloa, Mexico. (**D**) Male from Río Nazas, Durango, Mexico. Scale bars = 10 mm

(Campos and Rodríguez-Almaraz 1992) (Fig. 2). In the Sonoran desert in northwestern Mexico, the new southernmost site inhabited by *P. clarkii* in the Baja California peninsula (Fig. 1B) is the oasis "El Sauzal" in the San Ignacio basin in Baja California Sur state (Fig. 2). This site is about 550-km south of the previously published record at Santo Tomás basin in the state of Baja California (Campos and Rodríguez-Almaraz 1992). Also, on the mainland of northwestern Mexico, the new record of the red crayfish in the tropical state of Sinaloa (Fig. 1C) is about 680-km south of the previously published record at Cananea, Sonora, on the Pacific slope in the Sonoran desert (Campos and Rodríguez-Almaraz 1992) (Fig. 2).

The dates and purposes of the introduction of *P. clarkii* into these new habitats are unknown. Because of the absence of a hydrological connection between the original habitat of the red crayfish in Mexico (Río Bravo basin) and the new basins recorded, the dispersion of this species has been likely caused by human introduction as previously concluded by Hobbs (1989), Campos and Rodríguez-Almaraz (1992), and Barbaresi and Gherardi (2006). Comparing the sites of previous records made by Campos and Rodríguez-Almaraz (1992)

Table 1 Records of *Procambarus clarkii* in Mexican states from different sources

State	Locality	Coordinates	Reference
Baja California	Abelardo L. Rodríguez weir	32°26′N; 116°54′W	Campos and Rodríguez-Almaraz (1992)
	El Porvenir	32°05′N; 116°38′W	Campos and Rodríguez-Almaraz (1992)
	Agua Caliente	31°54′N; 116°16′W	Campos and Rodríguez-Almaraz (1992)
	Arroyo Santo Tomás	31°32′N; 116°39′W	Campos and Rodríguez-Almaraz (1992), this study
Baja California Sur	Oasis San Ignacio	27°18′N; 112°53′W	This study
	San Joaquín	27°11′N; 112°51′W	This study
	El Sauzal	27°10′N; 112°52′W	This study
Chihuahua	Río Chihuahua	28°42′N; 106°00′W	Campos and Rodríguez-Almaraz (1992)
	Río San Pedro	28°20′N; 105°30′W	Campos and Rodríguez-Almaraz (1992)
	Río Conchos	28°15′N; 105°30′W	Campos and Rodríguez-Almaraz (1992)
Coahuila	La Amistad weir	29°27′N; 101°55′W	Campos and Rodríguez-Almaraz (1992)
	Río San Carlos	29°00′N; 101°53′W	Campos and Rodríguez-Almaraz (1992)
	Muzquiz	27°56′N; 101°26′W	Campos and Rodríguez-Almaraz (1992)
	Río Sabinas	27°54′N; 101°11′W	Campos and Rodríguez-Almaraz (1992)
	Río Salinas	27°50′N; 101°09′W	Campos and Rodríguez-Almaraz (1992)
	Allende	25°18′N; 100°01′W	Campos and Rodríguez-Almaraz (1992)
Durango	Río Nazas	25°43′N; 103°36′W	This study
Nuevo León	Río Salado	27°11′N; 99°56′W	Campos and Rodríguez-Almaraz (1992)
	Santiago	26°59′N; 100°09′W	Campos and Rodríguez-Almaraz (1992)
	La Boca weir	26°52′N; 100°08′W	Campos and Rodríguez-Almaraz (1992)
	Río La Silla	25°37′N; 100°05′W	This study
	Cadereyta	25°37′N; 100°07′W	Campos and Rodríguez-Almaraz (1992)
	Planta Tratadora de Aguas	25°25′N; 100°08′W	This study
	Palo Alto, Vallecillo	26°29′N; 99°45′W	This study
Sonora	San Luis Río Colorado	32°26′N; 116°56′W	Campos and Rodríguez-Almaraz (1992), Hobbs (1989), this study
	El Sauz	31° 09′N; 110°03′W	Campos and Rodríguez-Almaraz (1992)
	Cananea	30°56′N; 110°10′W	Campos and Rodríguez-Almaraz (1992)
	Bacoachi	30°38′N; 109°57′W	Campos and Rodríguez-Almaraz (1992)
Tamaulipas	Ciudad Guerrero	26°37′N; 99°15′W	Rodríguez-Almaraz et al. (1993)
	Reynosa	26°04′N; 98°17′W	Rodríguez-Almaraz et al. (1993)
	Río Purificación	22°44′N; 98°59′W	Campos and Rodríguez-Almaraz (1992)
	Coronado	–	Campos and Rodríguez-Almaraz (1992)
	Río Salado	26°37′N; 99°14′W	Campos and Rodríguez-Almaraz (1992)

with the new ones provided by our study, the geographic expansion of *P. clarkii* has been an average of 28 km/year in the Mexican mainland (Chihuahuan desert), of 36 km/year in the Baja California peninsula (Sonoran desert), and of 45 km/year in the Sonoran desert. If the "rhythm" of this propagation continues, *P. clarkii* will likely invade fragile habitats as the Baja California oases with native species of decapods. In the contiguous oases of the San Ignacio basin several species of the native freshwater shrimp *Macrobrachium* occur (Hernández et al. 2007). *Macrobrachium* are considered ancient forms that colonized freshwater streams since the Pleistocene (Bouvier 1895; Hedgpeth 1949). Species of this genus have certain fragility and some populations in the oases of the Baja California peninsula have disappeared gradually from their natural sites.

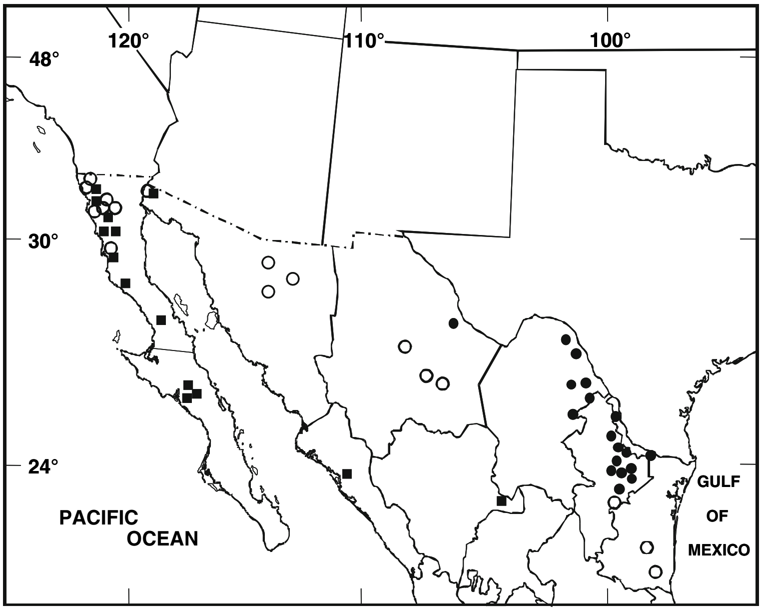

Fig. 2 Geographical distribution of *Procambarus clarkii* in México. Black dots = natural distribution. White circles = previous records of the exotic *Procambarus clarkii* (Huner 1980; Hobbs 1989; Campos and Rodríguez-Almaraz 1992; Rodríguez-Almaraz and Campos 1994). Black squares = new records of the exotic *Procambarus clarkii*

According to Wilcove et al. (1998), the greatest threats to biodiversity are habitat destruction (degradation or loss) and introduction of nonnative (alien, exotic) species. In retrorespect, the disappearance of *Macrobrachium digueti* from its type locality, the oasis of Mulegé, is a good example of habitat degradation. This oasis is one of the most disturbed by anthropogenic modification and is putting the survival of native flora (León de la Luz and Domínguez 2006) and fauna (Ruiz-Campos et al. 2003, 2004) at risk. To date, there is no record of *M. digueti* in this location after the work of Holthius (1952). Currently, the invasive *P. clarkii* in the Río Culiacán in Sinaloa state co-occurs with *Macrobrachium americanum*, however no data on the effect of that exotic species on native decapod species exist. Although the endorheic Río Nazas basin is rich in species of fish, no decapod shrimp had been recorded in this system. An extensive monitoring in this basin is required to establish the geographic extension of the red crayfish into this basin. Huner (1980) advised that introductions of any nonnative crayfish could result in an ecological nightmare unless they occupied a wholly unused niche, which does not occur very often. Gil-Sánchez and Alba-Tercedor (2002) noted that the presence of *P. clarkii* in the Spanish province of Granada appears to have caused the regression of the native astacid *Austropotamobius palipes*. Josh and Martin (2004) indicated that any action against exotic species is justified because the negative effects that they cause on the ecosystems and their biodiversity. Studies about the conservation status and dynamics of the native populations of decapod species are imperative to establish a sustainable management proposal.

Until today, there is no evidence of the co-occurrence and competition between the native fauna of decapods (*Macrobrachium* spp.) and the exotic *P. clarkii* in the Baja California peninsula. Based on the known impacts of the exotic crayfish in other countries, the possible scenario if *P. clarkii* continues its propagation in the Baja California peninsula could be that they will compete with and eventually displace the native freshwater shrimp. An extensive spreading of this species could also change profiles of the aquatic vegetation leading to drastic changes in associated invertebrates and vertebrates, acting as an intermediate host for numerous helminth parasites (ISSG 2007). Additionally, the diseases generally transported by *P. clarkii* could damage the actual aquatic communities, e.g. the transmission of the fungus-like *Aphanomyces astaci* responsible for the crayfish plague in Europe (Barbaresi and Gherardi 2006). An example in Mexico of an introduced exotic species is the red claw *Cherax quadricarinatus*, which was introduced by the aquaculture sector in 1995 (Bortolini et al. 2007). Today, this species has escaped from its culture ponds and is out of control in several rivers in mainland Mexico, with high densities and reproductive populations (Bortolini et al. 2007). Some countries and states of the USA have taken legal measures to avoid the introduction and culture of this alien animal in their territories (Lodge et al. 2000). That *Procambarus clarkii* in Baja California was collected without other decapods can mean either that this crayfish is occupying a free habitat or that the scenario we mentioned above has started. According to our data and a recent paper, freshwater systems (oasis, ponds, and creeks) of the Baja California peninsula are actually dominated by the exotic astacids in the north (from Tijuana to the San Ignacio oasis) and by the native palemonids (*Macrobrachium* spp.) in the south (from Mulegé to San José del Cabo) (Hernández et al. 2007). In several streams of northern Mexico, the situation is more delicate than in the Baja California peninsula because *P. clarkii* was found along with palemonids and cambarids (Rodríguez-Almaraz and Campos 1994). Thus these groups are at risk to disappear and the loss of biodiversity in these streams is plausible. Because both the control and the elimination of exotic species represent a difficult task, Mexican authorities should be vigilant in the propagation of the invasive red crayfish populations. They should also inform residents in the geographic areas where *P. clarkii* is currently distributed about the risk that can be perpetuated if this species is transported from one place to another.

Acknowledgements This work was supported by the projects "Decápodos de los oasis de Baja California Sur" and "Biodiversidad de los peces y crustáceos de los oasis de Baja California Sur" of CIBNOR, SEMARNAT-CONACyT-2002-C01-73, SEMARNAT-CONACyT 173/A-1, and SEMARNAT-2002-COI-0583. L. Hernández is a recipient of a Ph.D. scholarship from CONACyT (number 144309). We also thank Oscar Armendaris for editing the figures. Thanks to Dr. Ellis Glazier for editing this English-language text.

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