DISTRIBUTION OF EXOTIC AUSTRALIAN CRAYFISH *Cherax quadricarinatus* (Von Martens, 1868) IN PUERTO RICO

By

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A thesis submitted in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCES

In

MARINE SCIENCES

UNIVERSITY OF PUERTO RICO
MAYAGÜEZ CAMPUS
2008

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Abstract

The crustacean *Cherax quadricarinatus* (redclaw), a crayfish from Australia that is widely cultured, was introduced illegally into Puerto Rico in the beginning of 1997. They escaped from a single culture facility at the headwaters of the Loíza River in 1998 during Hurricane Georges and subsequently were found in the Loíza River and later in the Lajas Valley, where they had been transferred for experimental purposes. The Bayamón River (Cidra reservoir), Espíritu Santo River, Lajas Drainage Canal and Loíza River systems were sampled quarterly for one year, to establish the range within Puerto Rico's streams to evaluate the crayfish population and determine its preferred habitat. The Arecibo, Blanco, La Plata, and Río Piedras rivers were sampled at least once to determine the presence of redclaw. Five 6-mm mesh cylindrical traps were used to catch redclaw and other organisms. Mean redclaw catch per unit of effort (CPUE) in 12 hours was 1.85, 1.60, and 1.45 in Loíza, Carite and Cidra reservoirs, respectively; and 1.0, 1.35, and 0.55 in the Lajas Drainage Canal, and Loíza reservoir headwaters (Gurabo and Loíza Rivers), respectively. No redclaw were captured below dams (tailwaters) of the Cidra and Loíza reservoirs, and no redclaw were captured in the Espíritu Santo River system. Positive correlations (species correlation with variable) were found for *Macrobrachium acanthurus*/pH (r= 0.651), *Macrobrachium faustinum*/pH (r= 0.857), *M. acanthurus*/DO (r= 0.831), *Macrobrachium carcinus*/turbidity (r= 0.744); negative correlations were found for redclaw/DO (r=-0.419), *Epilobocera sinuatifrons*/discharge (r=-0.447), *E. sinuatifrons*/temperature (r=-0.766), redclaw/*M. acanthurus* (r=-0.522), redclaw/*M. carcinus* (r=-484), redclaw/*Xiphocaris elongata* (r=-0.463). There were more than 24 aquatic exotic species trapped during the study. Thus,

redclaw is established in Puerto Rico. Slow-moving waters, including reservoirs and canals, and with muddy or silty bottoms were redclaw habitats. Assuming a constant rate of dispersion of redclaw of 0.5 river systems each year, 5 additional river systems would become theoretically inhabited by redclaw within the next ten years. Redclaw cause no evident environmental damage (though specific studies regarding their potential ecological impact are needed), and are being exploited as a food organism by an unknown number of local fishermen.

Resumen

El crustáceo *Cherax quadricarinatus* (quela-roja), una langosta de agua dulce de Australia que es altamente cultivada, fue introducida ilegalmente a Puerto Rico a comienzos del 1997. La especie escapó desde una sola facilidad de cultivo en la cabecera del Río Loíza en 1998, durante el Huracán Georges y subsecuentemente fue encontrada en el Río Loíza y luego en el valle de Lajas, donde estos fueron transferidos para propósitos experimentales. Los sistemas de Río Bayamón, Río Espíritu Santo, Canal de Drenaje de Lajas y Río Loíza fueron muestreados cuatro veces durante un año, para establecer el rango de dispersión dentro de los ríos de Puerto Rico y evaluar la población de langostas de agua dulce y determinar su hábitat preferido. Los ríos Arecibo, Blanco, La Plata y Río Piedras fueron muestreados por lo menos una vez para determinar la presencia del quela-roja. Cinco trampas cilíndricas de tela metálica de 5-mm fueron utilizadas para capturar los quela-roja y otros organismos. El promedio de captura por unidad de esfuerzo en 12 horas (CPUE) de los quela-rojas fue de 1.85, 1.60 y 1.45 para los embalses Loíza, Carite y Cidra, respectivamente; y de 1.0, 1.35 y 0.55 para el Canal de Drenaje de Lajas, Río Gurabo y Río Loíza, respectivamente. No se encontraron quelas-rojas en ninguno de los ríos bajo las compuertas de los embalses. Correlaciones positivas (correlación de especies con variable) fueron encontradas para *Macrobrachium acanthurus*/pH (r= 0.651), *Macrobrachium faustinum*/pH (r= 0.857), *M. acanthurus*/DO (r= 0.831), *Macrobrachium carcinus*/turbidez (r= 0.744); correlaciones negativas fueron encontradas para quela-roja/DO (r=-0.419), *Epilobocera sinuatifrons*/descarga (r=-0.447), *E.*

sinuatifrons/temperatura (r=-0.766), quela-roja/*M. acanthurus* (r=-0.522), quela-roja/*M. carcinus* (r=-484), quela-roja/*Xiphocaris elongata* (r=-0.463). Durante este estudio fueron capturadas 24 especies exóticas acuáticas. El quela-roja está establecido en Puerto Rico. El hábitat encontrado para esta especie es aguas lénticas, incluyendo embalses y canales, de fondo lodoso o arcilloso. Asumiendo un rango constante de dispersión del quela-roja de 0.5 sistemas de río por año, en los próximos 10 años, 5 sistemas de río adicionales deberían teóricamente estar habitados por este quela-roja. El quela-roja no ha causado ningún daño ambiental evidente (sin embargo se necesitan estudios específicos adicionales, considerando su potencial impacto ecológico) y está siendo explotado como alimento por un número no determinado de pescadores locales.

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Dedication

First at all, I thank God for giving me spiritual strength and hope to keep going on. I dedicate this thesis to my father, Gregorio García, who passed away on 2003. To my brother Luis Albert, who passed away on 2008. I also dedicate the thesis to my sisters Sara Enid and Sarined, my mother Sara Vázquez, my wife Vilmaree Rivera and my beloved children, Samuel Adrian and Yadiel.

Acknowledgements

During my graduate studies in the University of Puerto Rico several persons and institutions collaborated directly and indirectly with my research. I wish to dedicate this section to acknowledge their support. I would especially like to thank my thesis committee, Dr. Dallas E. Alston, Dr. Craig G. Lilyestrom and Dr. Ernest H. Williams for dedicating time, support, and supervision during this research. I want to thank everyone who participated in this project; without their support it would have been impossible to complete the research. They include Sara Vázquez, Sarined García, Sara Enid García, Hector D. Ríos, Sergio L. González, Antonio González, Viviana Martínez, Augusto Crespo, Luis G. Rivera, José Miguel Vázquez, Luis A. García, Fernando García, Ermer D. Torres, Yaritsa Lebrón, Ermer A. Torres, Samuel Andrés Rivera, Jorge L. Rivera, José L. Jiménez, Carián Rivera, Vilmaree Rivera and Nestor Moyet for their help on the field trips. I would also like to thank Milton Muñoz for his collaboration with a photo (Figure 5). To Hernán Torres and Dr. Carlos J. Santos for helped me on the procedure part of the research. To Carlos A. Rivera for his help in the traps construction. To Jorge Ferrer and Dr. Michael McGee who allowed access to their respective farms. Dr. Alexis Cabarcas and Arlene Megill for their help on the elaboration of the manuscript and Dr. Ernesto Otero who facilitate the equipment of water quality.

This research was supported by the Ford Motor Company, Sea Grant College Program and The University of Puerto Rico, Mayagüez Campus, Departments of Marine Sciences, Chemistry and Biology.

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Introduction

The crayfish *Cherax quadricarinatus* (von Martens), known as redclaw, is a decapod crustacean native from northeastern state of Queensland, Australia. The high reproductive capacity and ease of hatchery culture has resulted in widespread culture of this species (Cobb and Wang 1985; Medley et al. 1994). It is easy to acquire and can be purchased through various websites on the internet or from pet shops. However, the Department of Natural and Environmental Resources (DNER) does not grant permits to pet shops to import this species, or other crayfish species, to Puerto Rico.

Because of the relatively large size and distinguishing characteristics such as the red claws, the species has been cultured in many parts of the world, including Australia, Bahamas, Belize, China, Costa Rica, Ecuador, Fiji, Great Britain, Guatemala, India, Indonesia, Israel, Jamaica, Mexico, South Africa, Taiwan, Thailand, and the United States (Cobb and Wang 1985; Medley et al. 1994), both as an aquaculture species for food and as an aquarium species by hobbyists. Aquaculture is the rearing of aquatic organism under controlled or semicontrolled condition (Stickney, 1994). As a result of an unpermitted importation of the redclaw and an illegal attempt to culture this species for the first time in Puerto Rico, the organism escaped from an unknown aquaculture farm in San Lorenzo to the Loíza River (Figure 1)(In Puerto Rico, streams are named as rivers) during hurricane Georges flooding in 1998, eventually reaching the Lago Loíza reservoir (Williams et al. 2001).

Figure 1. Loíza River (Headwater)

The principal problem of an introduction is that when you detect a problem, it is already too late to resolve it. The causes of introduction can be accidents, escapes, natural causes, economic factors or food aspects (Bertonatti 1998). When an exotic species is introduced, the areas with high diversity of species become affected. Bernotani suggests some solutions to diminish the impact of species or to avoid future introductions. The legal figures should be fortified, for example increasing sanctions to the responsible persons for the illegal introductions. The potential environmental impact should be evaluated, before the introduction. If a species already was introduced, it is recommended to make an inventory map, conduct registration of the introduced species and create a mitigation or control plan. An important fact is that people often do not value the autochthonous species. In many cases, introduced species are preferred, by most people, than the ones that are indigenous. Not being satisfied with indigenous species, projects are developing every day to introduce new species.

The International Council for the Exploration of the Sea (ICES) was established in 1902. ICES is an organization concerned with the Atlantic Ocean and its adjacent seas. The principal functions of ICES (2005) are to promote and encourage marine research and to provide information for the protection of the marine environment and for fisheries conservation. ICES has publications to reduce risks of adverse effects from introduction by non-indigenous marine species. The ICES Code of Practice is divided in various steps. Strategy for implementation, the steps to take prior to introducing a new species, the steps to take after deciding to proceed with an introduction, policies for ongoing introductions, the steps to take prior to releasing genetically modified organisms, and the steps to take prior to releasing polyploidy organisms. Countries contemplating new introduction are requested to prepare a detailed prospectus on the proposed new introduction(s) for evaluation and comment. The prospectus should include: purpose and objectives of introduction, stage(s) in the life cycle proposed for introduction, area of origin and the target area(s) of release and, review of the biology and ecology of the species as these pertain to the introduction.

Most species introductions throughout the world have historically been made without analyses concerning possible environmental impacts. Exotic decapod crustacean species represent a threat to native crustacean species because they compete for habitat and food; they are potential predators for many native species, may harbor dangerous parasites or diseases and may change the ecosystem. For example, many crayfish have the capacity to make excavations (Gibling et al. 1998; Thorpe and Covich

2001) and to overpopulate an aquatic ecosystem (Edgerton 1999). Crayfish can tolerate salinity in excess of 12 ppt for extended periods with little adverse effects (Medley et al. 1994) and may transmit diseases to other crustaceans (Edgerton 1999).

After a report of the original introduction (Williams et al. 2001), there have been no additional studies concerning the dispersion of this exotic species, redclaw, within Puerto Rico. This research will determine the range of dispersion of this species in Puerto Rico by sampling various streams and reservoirs.

Literature Review

Eight reservoirs supply about 45% of the public water supply of Puerto Rico (USGS 2007b) including the reservoirs Lago Guajataca, Lago Loíza, Lago La Plata, Lago de Cidra, Lago Toa Vaca, Lago Cerrillos, Lago Caonillas, and Lago Dos Bocas. Lago Loíza reservoir is located in the municipality of Trujillo Alto (USGS 2007b). Carraízo Dam (Figure 2), which impounds Lago Loíza reservoir, was constructed in 1953 by the Puerto Rico Aqueduct and Sewer Authority (PRASA). The reservoir is located 21.7 kilometers upstream from the mouth of the Loíza River on the Atlantic Ocean. Originally, it was constructed to generate hydroelectricity (3,000 kw), but now is used as a public water-supply source. Lago Loíza reservoir has a drainage area of 331 km^2 (Figure 3). Lago de Cidra reservoir, constructed in 1946 by PRASA, is located in the municipality of Cidra to supply municipalities of Aguas Buenas, Cidra, Comerío, and Guaynabo. The Cidra Reservoir has a drainage area of 13.8 km^2 (Figure 4).

Figure 2. Carraízo Dam (Loíza River Tailwater).

Crayfish are also known as crawfish or freshwater lobster. In Spanish, they are variously called “langosta” or “langostino de agua dulce”, “acocil”, “cangrejo de río” or “camarón” (Marx 1991); the term “ástaco” refers to the family *Astacidae*, another family of crayfish. Its meat is appreciated in different parts of the world and is compared with the meat of marine lobster.

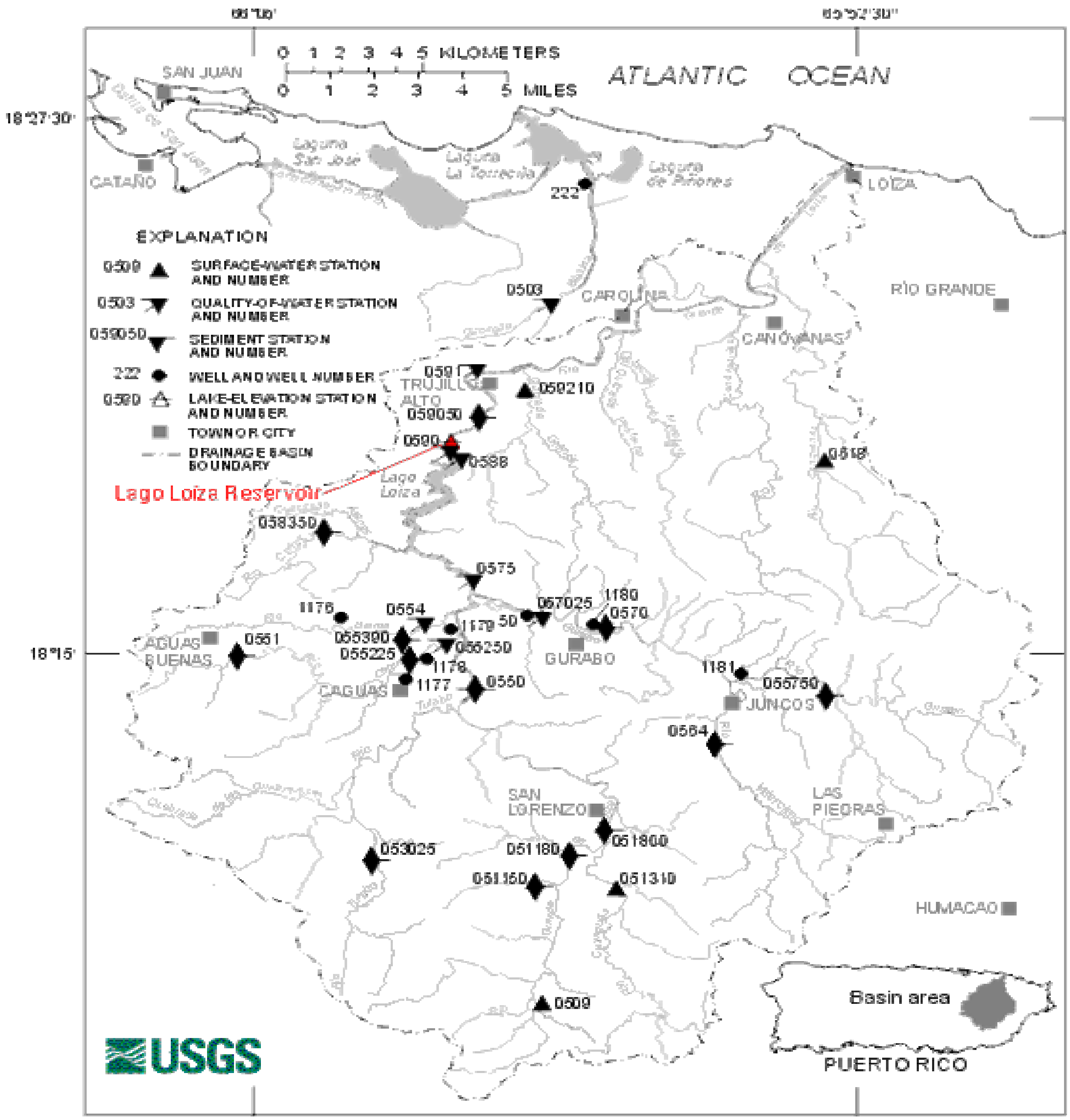

Figure 3. Lago Loíza reservoir basin of the Loíza River System. Courtesy USGS.

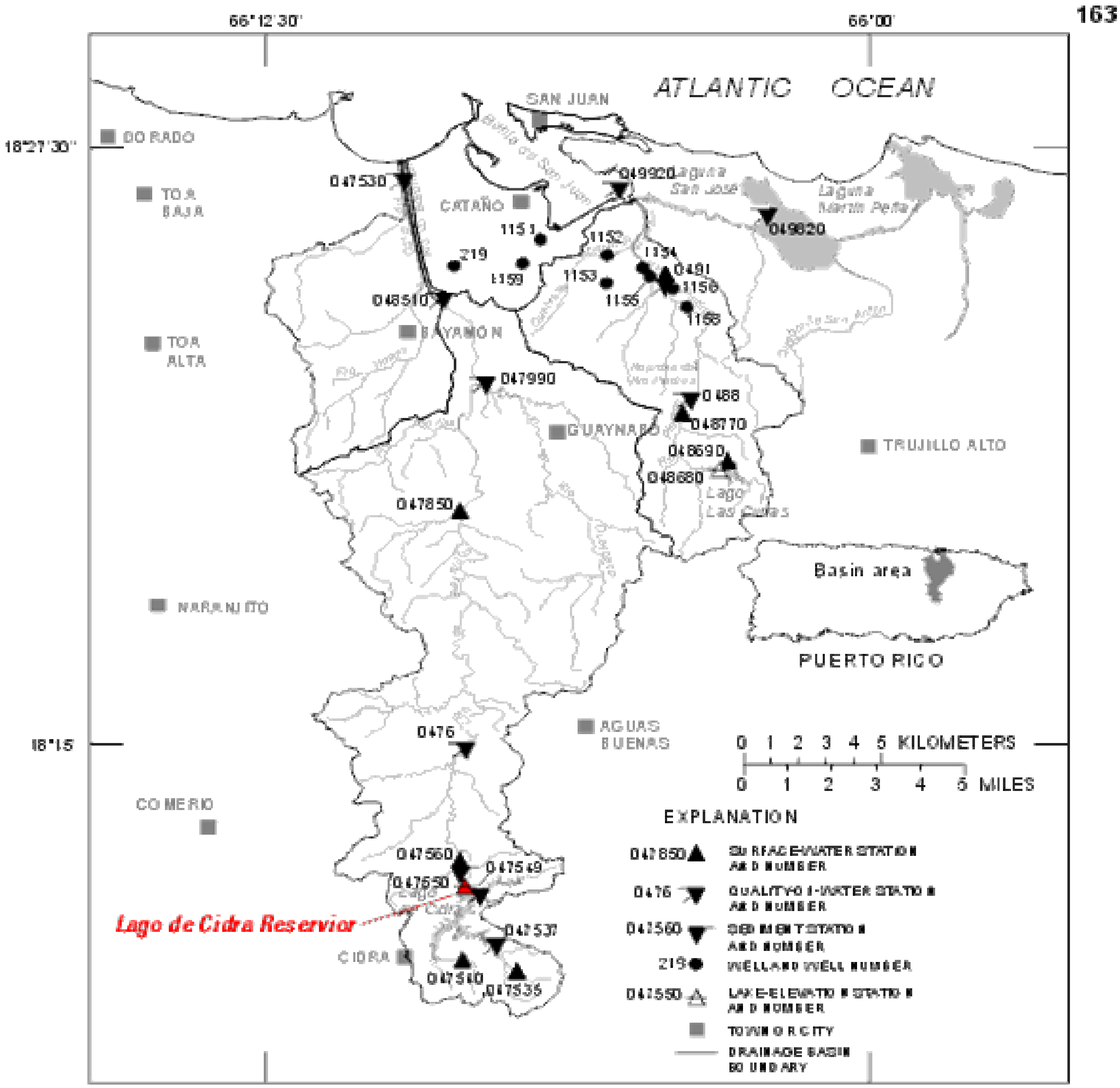

Figure 4. Lago de Cidra reservoir basin of the Bayamón River System. Courtesy USGS.

Figure 5. *Cherax quadricarinatus*, male (front) and female (rear).

The *Cherax* can be identified easily by some characters (identification key is courtesy of Noel & Mariah Coward, Texas Aquaponics, LLC). The first feature to observe is the red claw, which gives the species its common name. Each large claw (cheliped) of adult male redclaw has a soft red patch (Figure 6) on its outer margin (Jones 1990b); the function of this red membrane is not clearly understood, but may be associated with mating behavior..The second feature is the presence of four distinct carinae (ridges) on the dorsal surface of the cephalothorax (thus, the specific epithet: "*quadricarinatus*"). The inner parallel carinae extend onto the rostrum. Figure 7 shows secondary characters from the claws, the single mesial spine on the carpus, and dense ventral patch of setae (hairs) on the merus (inner segment of claw). Redclaw has a single prominent cervical groove between cephalon and thorax. On the ventrum, the sternal keel between the fifth pereiopods is developed into a distinct triangular spine (Figure 8). Pleopods are absent from segment number one (anterior) of the abdomen in females, and are vestigial in males (Figure 8).

Figure 6. Claw of *C. quadricarinatus*, male (left) and female (right).

The weight for this species ranges from 50-150 g during its first year with a maximum weight of about 600 g in 4-5 years (Table 1).

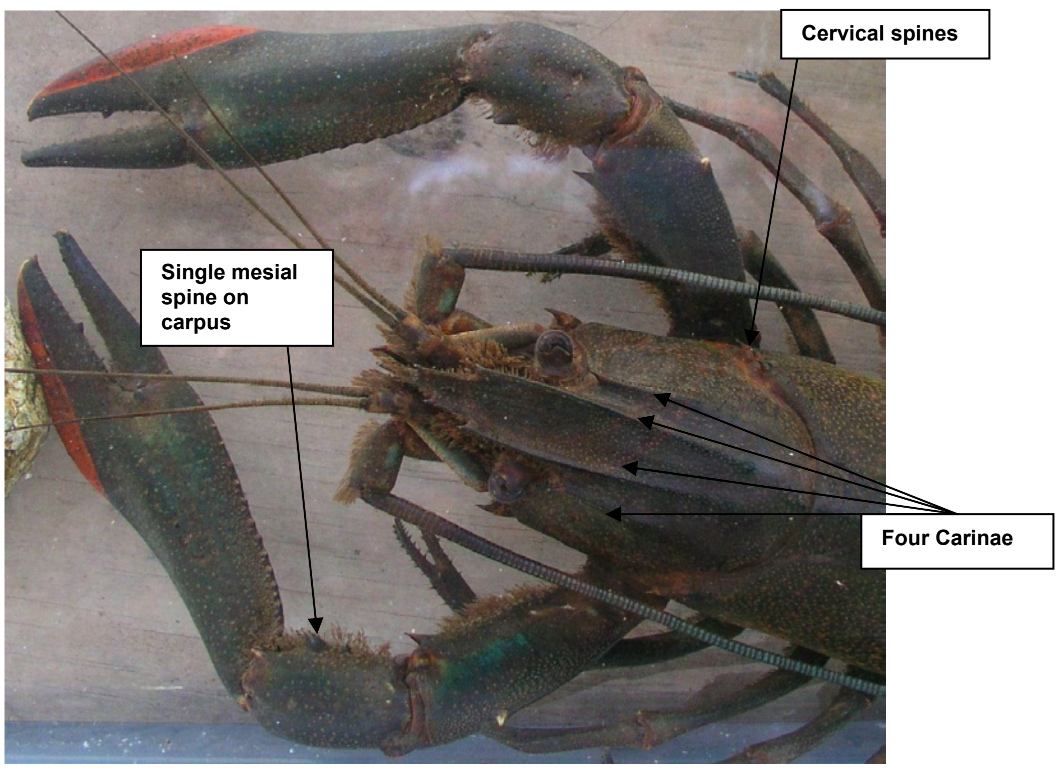

Figure 7. Presence of four long and distinct carinae (ridges) on the dorsal surface of the cephalon (*Cherax quadricarinatus*).

The diet of the adult redclaw primarily consists of vegetation and detritus (Medley et al. 1994, Verhoef et al. 1998). In contrast, the juveniles (0.5-1.0 g)(Jones 1990b) generally possess a different diet preference consisting of large portions of animal matter, including molluscs, worms, small fish, and aquatic insects (Verhoef et al. 1998).

This benthic species prefers water temperatures from 23-31ºC, but can tolerate a wide range of environments and can survive conditions with dissolved oxygen concentrations up to 1 mg/L (Cobb and Wang 1985; Medley et al. 1994; Verhoef et al. 1998). *Cherax quadricarinatus* can live more than 48 hours out of water in humid environments (Reartes 2003) that could facilitate movement between water bodies and range expansion. It has a simple life cycle without a free-living larval stage (Figure 9) and can reach sexual maturity 6-9 months after eclosion (Medley et al. 1994).

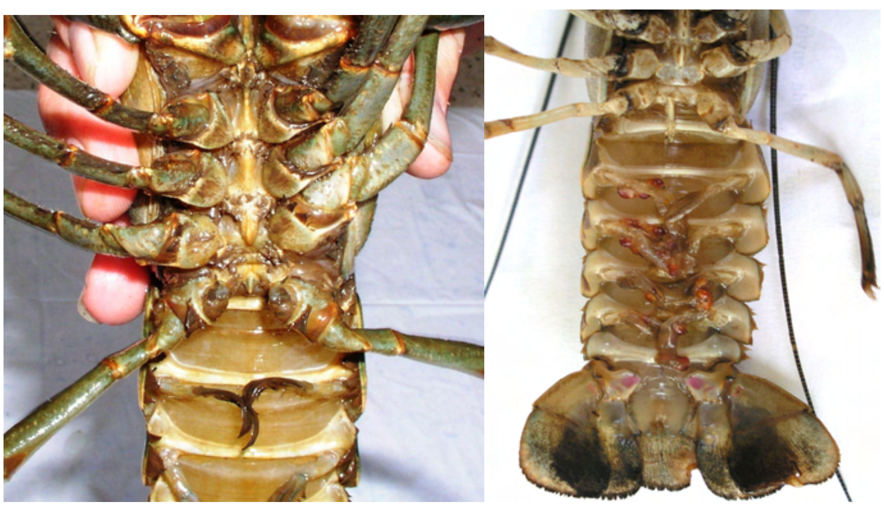

Figure 8. Partial ventral view of *C. quadricarinatus*. Male (left) and female after hatching (right).

Figure 9. Small *C. quadricarinatus*, seven days after hatching.

Preparation for mating is similar to that described for several other crayfish; however, a pre-mating molt described for other crayfish is not necessary (Jones 1990b). During mating, the male manipulates the female into a position where the female is ventral side up (Jones 1990b). With the ventral sides of the male and female together, a sticky white mass of sperm (spermatophore) is then deposited by the male on the female shell, between the walking legs. Depending on its size, the female deposits 100-1,000 eggs on the pleopods and continually aerates the eggs by moving the pleopods back and forth during an incubation period of 4-8 weeks (Jones 1990b, Medley et al. 1994). One or two weeks after the hatching period, the small crayfish remain attached to the pleopods of the female. They gradually become independent, foraging to greater distances and for longer periods, but return to the mother for refuge until they begin to forage on their own (Jones 1990b). Redclaw reach sexual maturity within one year at a size ranging from 50-100 g.

Cherax quadricarinatus is commonly found in areas with abundant shelter, including areas with rocky substrates or vegetation that provide food and protection (Cobb and Wang 1985). Rats, birds, and turtles are known predators of aquacultured *Cherax* (Hume et al. 1990). Crayfish sometimes leave the water. For example, if the crayfishes *Orconectes propinquus* are threatened by predators such as smallmouth bass (*Micropterus dolomieui*), they may migrate to other aquatic habitats with more shelter or fewer predators (Stein and Magnuson 1976).

Negative examples exist of impacts resulting from introduction of exotic freshwater crayfish into different countries. Some *Cherax* species can transmit viral, bacterial, and fungal agents or parasites that can cause infections in native crustaceans (Edgerton 1999). The red swamp crayfish *Procambarus clarkii*) was introduced into the Dominican Republic several years ago where it was considered a plague because it made excavations into berms of rice fields and ponds (Craig G. Lilyestrom, personal communication). Crayfish not only transmit parasites and diseases to other aquatic animals, but can cause food borne illness in humans. Paragonimiasis, caused by the parasitic fluke *Paragonimus*, is a worldwide pulmonary disease. It reproduces through a complex life cycle involving snails, crustaceans, and mammals. Humans acquire the disease by ingesting uncooked freshwater crab or crayfish (DeFrain and Hooker 2002).

In the past, introductions of *Procambarus clarkii* have been made in countries of Europe, that they have been harmful for the ecosystem and for other species of crayfish. For example in 1880, when *P. clarkii* was introduced to Europe; this brought with it the fungus *Aphanomyces astaci*. This illness diminished considerably the native populations of crayfish in Europe (Cobb and Wang, 1985).

Crayfish may also function as biological control agents. For example, the Louisiana crayfish, *P. clarkii,* feeds on the snail which hosts the parasite *Schistosoma haematobium* which causes bilharzia (schistosomiasis) in many countries such as in Kenya (Okello 1995). In addition, this crayfish feeds on the snail *Biomphalaria* (Hofkin et al. 1992), the same genus which causes bilharzia in Puerto Rico. However, it will also eat *Marisa cornuarietis*, which is a biological control agent for *B*. *glabrata* in Puerto Rico.

Most of the native freshwater species in Puerto Rico are amphidromous, beginning their lives in saline water and later enter freshwater systems. American eels (*Anguilla rostrata*) are catadromous, with juveniles entering streams; later adults return to reproduce in the Sargasso Sea of the Atlantic Ocean (Hickman et al. 1997). Some marine fish enter brackish or freshwater systems, including striped mojarra (*Eugerres plumieri*) and snook (*Centropomus undecimalis*). Fish species inhabiting reservoirs include mostly exotic fish introductions; several were imported for recreational fishing (DNER 2006) and others are aquarium or aquaculture releases or escapes.

Table 1. Maximum size and weight of cultured crayfish of the genus *Cherax*.

Species	Maximum weight (g)	Maximum length (cm)	References
Cherax quadricarinatus (redclaw)	600	na	a, c
Cherax destructor (yabbie)	320	28	a
Cherax tenuimanus (marron)	2700	40	a, b

a. Ackefors 1994
b. Alon et al. 1988
c. Jones 1990b
na = not available

Objectives

The general objective of this investigation is to contribute to the knowledge of the current distribution of the exotic redclaw crayfish, *Cherax quadricarinatus*, in Puerto Rico. The specific objectives are to:

- establish the distribution (range) of redclaw within Puerto Rico's freshwater drainages and reservoirs;
- explain differences in the presence or absence of native shrimp with the presence or absence of redclaw;
- document redclaw habitat conditions, including bottom type and water quality;
- make preliminary agonistic trial observations of interactions between individual *C. quadricarinatus* with individual native species of *Atya lanipes* (guábara, also sometimes called chágara), *Macrobrachium carcinus* (bigclaw river shrimp), *Agonostomus monticola* (mountain mullet), and *Anguilla rostrata* (American eel).

Methodology

Study Area

The study area focused on the Loíza River system where redclaw were originally encountered. This system includes the Lago Loíza reservoir; the Loíza and Gurabo Rivers are the main headwater streams entering Lago Loíza reservoir. Samples were also taken in the tailwaters below the Lago Loíza reservoir dam. The Loíza River and the adjacent Bayamón River and the Espíritu Santo River systems were sampled quarterly for one year to determine the extent of dispersion of redclaw in northeastern Puerto Rico. The Bayamón River system consisted of samples taken from the Cidra reservoir and from the tailwaters below the dam. Each of these systems has reservoirs; the height of each dam of the Espíritu Santo (Figure 10), Lago de Cidra, and Loíza reservoirs is 2.5, 24, and 42 m, respectively.

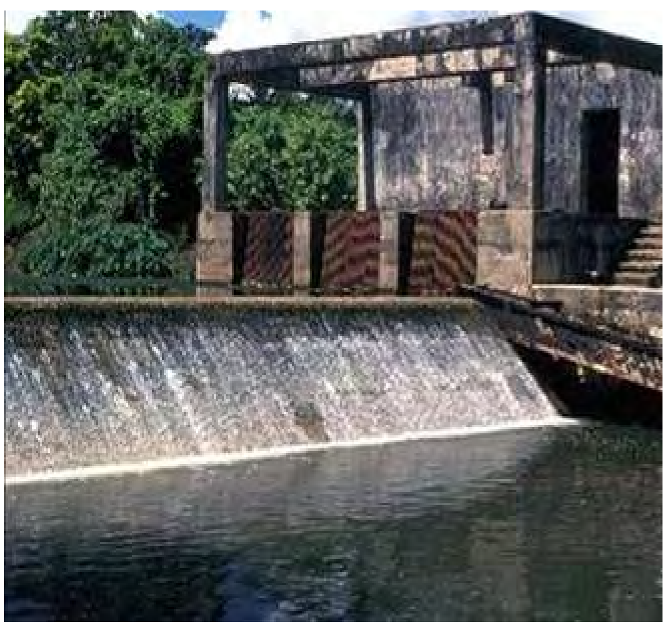

Figure 10. Espíritu Santo River Dam

An escape of redclaw from the University of Puerto Rico was documented by sampling the drainage canal at the Department of Marine Sciences Lajas Field Station and in a pond of a local farmer, and thus this area was also included in the quarterly sampling schedule. The Lajas drainage canal does not have a reservoir, but is a tributary of the Loco River system. Loco River system has a reservoir; however, it was not sampled because the Loco River was not part of the initial investigation. It was included late in the research, to determine that *Cherax quadricarinatus* through Lajas drainage canal, had gained access to Mondongo stream, which is tributary of Loco River. Other stream systems were sampled at least once to determine the presence or absence of redclaw; these included the Arecibo, Blanco (Naguabo), La Plata (Vega Alta), Loco (Guánica), and Piedras (Río Piedras) Rivers.

Sampling Procedure

Five cylindrical traps (Figure 11) were constructed with 6-mm galvanized mesh to trap redclaw and other crustaceans; not unexpectedly, fish were also trapped. Each trap measured 76-cm (length) by 23-cm (diameter), with a 38-cm-long inverted cone with a 23-cm outer diameter and 8-cm inner diameter inserted at one end of each trap. A compartment was constructed within the trap to house the bait (fresh tilapia flesh). To determine the best bait in this research some preliminary samples were made with different types of bait (coconut, mango, squid, fresh and frozen tilapia, codfish, chicken guts and chicken skin). Fresh tilapia attracted the most adult redclaw and continued to attract redclaw with decomposition. Juvenile crayfish prefer an animal matter diet (Jones 1990b). Native filter feeding shrimp were not attracted to tilapia flesh.

Figure 11. Sampling trap.

A sampling regime was developed to determine the distribution of redclaw at quarterly intervals in the three river systems and in the Lajas drainage canal. For tailwaters below dams, a “1000-m sampling procedure” was established which entailed the placement of each of five traps haphazardly placed within consecutive 200-m sections along a 1000-m transect downstream from the dam. Once redclaw were trapped below the dam, the 1000-m sampling procedure was performed progressively downstream from the previous sampling site at quarterly intervals until no redclaw were trapped. There was no “in-situ” replication.

For sampling immediately above the dam within the reservoir, the 1000-m sampling procedure described above was performed at similar quarterly intervals; once one or more redclaw were captured immediately above the dam, the next 1000-m sampling procedure began at the headwaters of the reservoir where streams flowed into the reservoir. Thus, it was assumed that redclaw trapped near the dam within the reservoir would be distributed throughout the respective reservoir; redclaw trapped in headwater streams would indicate that they live in stream conditions. Once redclaw were trapped in the headwaters entering the reservoir, the 1000-m sampling procedure was performed progressively upstream from the reservoir headwaters. Because there were two headwater streams entering Lago Loíza Reservoir, each was sampled using the 1000-m sampling procedure. Thus, the Cidra reservoir (which had no headwaters) was sampled on the Bayamón River system; the Espíritu Santo Reservoir (and its headwaters) was sampled on the Espíritu Santo River.

The sampling procedure for other stream systems which were sampled once, entailed placement of each of five traps haphazardly placed within 200-m sections near the center of the stream (<200 cm). The traps must be touching the ground. A total of five traps (see above) were immersed starting at 1800 hr during a 12 hr period; two traps were placed in the respective headwaters of reservoirs, one in the reservoir, and two in the tailwaters. Thus, this sampling regime was qualitative to determine the presence of redclaw in the respective system. A Global Positioning System (GPS) receiver (12 CX GARMIN®) was used to determine the location and elevation of each sampling point.

The purpose of sampling the Bayamón and Espíritu Santo River systems was to determine if the redclaw had gained access to other streams near the geographic area where they had been initially encountered in the Loíza River system. If no redclaw were found in adjacent streams during the sampling period, the shrimp populations of these streams were compared to shrimp populations of streams where redclaw were present.

Habitat description included bottom type and depths for each replicate trap for each station. Fresh tilapia flesh was used for bait. Because crayfish and shrimp are nocturnal animals, traps were immersed at about 1800 hours during each sampling period at each station for about 12 hours. The discharge (m^3/s) was obtained from the US Geological Survey web page (USGS 2007a) for each sample period for each station.

Water Quality

Water quality variables were measured in each stream system at 1700 hr at each sampling site before biological sampling. Conductivity (mS/m), dissolved oxygen concentration (mg/L), water temperature (°C), pH, turbidity (mg/L), and salinity were taken with a Horiba® Water Quality Monitoring System (Model U-22-30).

Identification and Population Characteristics

Collected organisms were identified taxonomically using bibliographic references (Chace, 1969; Dawes, 2005; Schliewen, 2005; Coward, 2007). The weight and total length of each decapod crustacean were measured and, in addition, the sex of each collected redclaw was determined by observing gonopores located between the base of the third pair of pereiopods of females where eggs are released or of the fifth pair of males (Jones 1990b). One specimen of redclaw captured at the Lajas Aquaculture Field Station had characteristics of both sexes, although it was not determined if they were functional. Berried females (with external eggs deposited on the pleopods of the abdomen) were noted and females without eggs were dissected to determine the presence of internal developing ova. Mass (g), standard length (mm), and total length (mm) of each incidentally trapped fish was recorded. Each fish was returned to the respective water body; redclaw were not returned to the water body. To determine the reproductive period (percentage of berried females), 50 female and 50 male mature redclaw were stocked into earthen ponds with vertical concrete walls and fed with raw fresh tilapia flesh at the Lajas Aquaculture Field Station. Random samples of trapped redclaw were transported to the laboratory alive and analyzed for the presence of parasites.

Preliminary Agonistic Trials

Preliminary agonistic trials determined the interactions of redclaw with other species under controlled conditions. Four aerated 38-liter aquaria were filled with 26 L of tap water with a 12-hr light and 12-hr dark regime. Seven drops of an anti-chlorine conditioner (Tap Water Conditioner®) were added. No food or additional substrates were offered before or during the trial. One specimen of each species (*Anguilla rostrata, Agonostomus monticula, Macrobrachium carcinus*, or *Atya lanipes*) of similar mass was placed in an aquarium with a 100-g male redclaw during each trial. For instance, one *A. rostrata* (approximately 150 g) was placed in each of the four aquaria with one 150-g male redclaw. For each pair of organisms in each trial, six 15-min sessions of observations totaling 4 hr of observations were performed. The first 24-hr observation period was performed once every 4 hours (modeled after Karplus et al. 1992). The next observation period was perform once every 8 hours for an additional trial period of 72 hours. Minimum and maximum temperature (ºC), pH values, and dissolved oxygen (mg/L) concentrations were monitored.

Analyses

Standard procedures were followed by microscopically examining redclaw specimens externally and internally for parasites and symbionts. Correlation analyses were performed to compare the "Catch per unit of effort" (CPUE for12hours) of crustaceans with water quality variables. Also, correlation analyses were performed between crustacean species. CPUE was calculated as the mean number of individuals of each species per trap in a period of 12 hours. Diversity indices were based on the Shannon-Weiner Diversity Index (Odum 1971) using the following formula:

$$H=-\Sigma p_i \ln p_i$$

H= diversity index
S=total number of species in the community
P_i=proportion of *S* made up of the *i*th species

Results

Distribution of *Cherax quadricarinatus* in Puerto Rico

This study was conducted since November 2005 until December 2006. A total of 130 *C. quadricarinatus* were captured during this study (72 females and 58 males). Mean weight was 71.48 grams and mean size was 122.05 millimeters (eye to tail). A maximum size of 208 mm (318g) was recorded in Lajas drainage canal. Mean redclaw CPUE was 1.85, 1.60, and 1.45 in Loíza, Carite and Cidra reservoirs, respectively; and 1.0, 1.35, and 0.55 in the Lajas Drainage Canal, Loíza reservoir headwaters (Gurabo and Loíza Rivers), respectively (Figure 12). No redclaw were captured below dams (tailwaters) of the reservoirs and no redclaw were captured in the Espíritu Santo River system.

Native shrimp were captured in Lago Loíza reservoir and in the Espíritu Santo Reservoir which has only a 2.5-m high dam with a non-functional fish ladder which, if repaired, would allow for native aquatic organisms to ascend into the reservoir. Whether or not there were redclaw in the reservoirs, the prevalent native shrimp were (Figure 13) *Macrobrachium faustinum* (coyuntero), X*iphocaris elongata* (chirpe or salpiche), *Macrobrachium acanthurus* (flautino), and *Macrobrachium carcinus* (bigclaw river shrimp). Fish captured inadvertently in traps are included in Appendix B. CPUE and standard deviations are included for each species for each stream system.

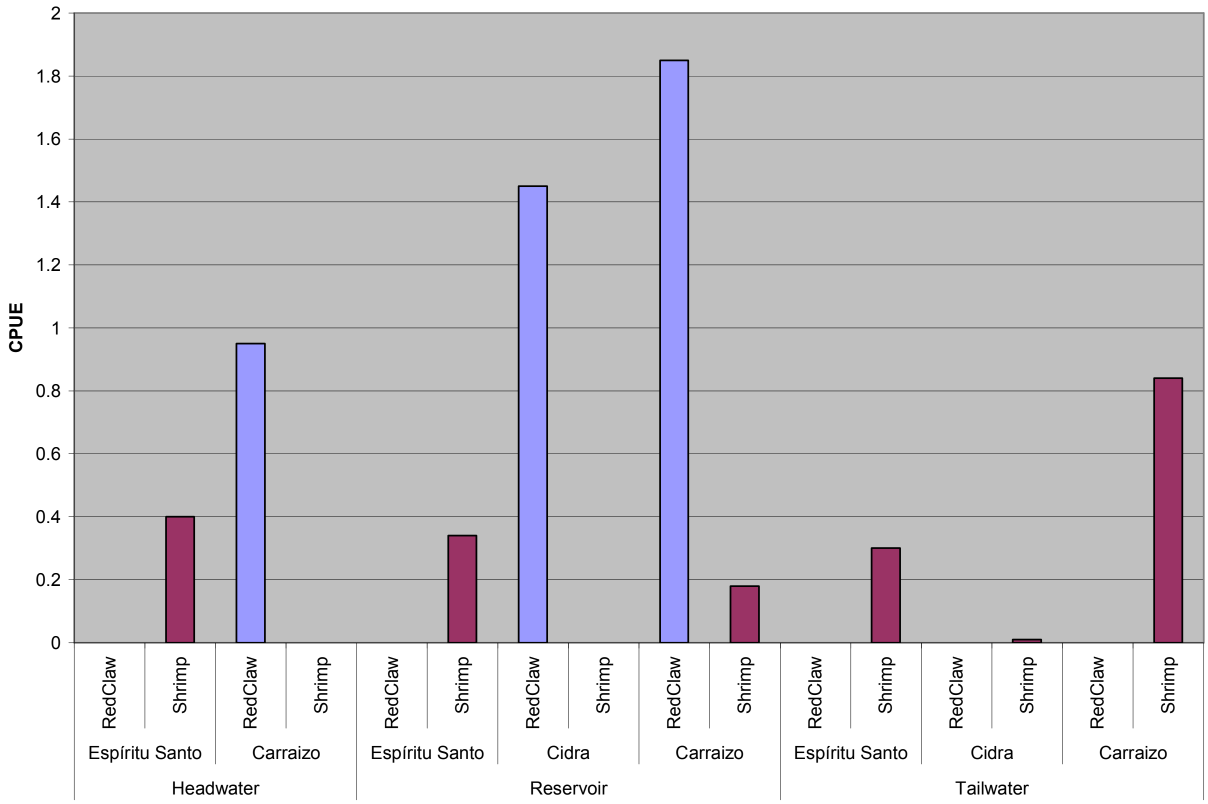

Figure 12. Red Claw CPUE (12 hours) compared to total shrimp CPUE (mean shrimp/trap) in Espíritu Santo, Lago de Cidra, and Loíza reservoir systems and their headwaters and tailwaters. Note that Lago de Cidra reservoir does not have headwaters.

Figure 14 compares the diversity of decapod crustaceans in headwaters, reservoirs, and tailwaters below the reservoir. Note that Lago de Cidra reservoir has no significant headwaters, so it was not included in the sampling under this category. During the regular sampling, redclaw were only captured in two of the reservoirs (Loíza and Cidra) and not in the tailwaters; however redclaw were captured in the headwaters of Lago Loíza in the Loíza River, but not in the Gurabo River. No redclaw were captured within the Espíritu Santo River system, indicating probably that redclaw have not reached this system or that the habitat was not favorable for them, although the redclaw inhabit the canóvanas river, which is the closest point where *Cherax* are know to occur, relative to the Espíritu Santo River. The CPUE and diversity of the native shrimp population was higher in the Espíritu Santo River system (headwaters, reservoir, and tailwaters). The highest CPUE of redclaw was found in the Lago Loíza reservoir. Redclaw were not captured in the tailwaters of Lago de Cidra or Lago Loíza reservoir; however, native shrimp CPUE and diversity were high.

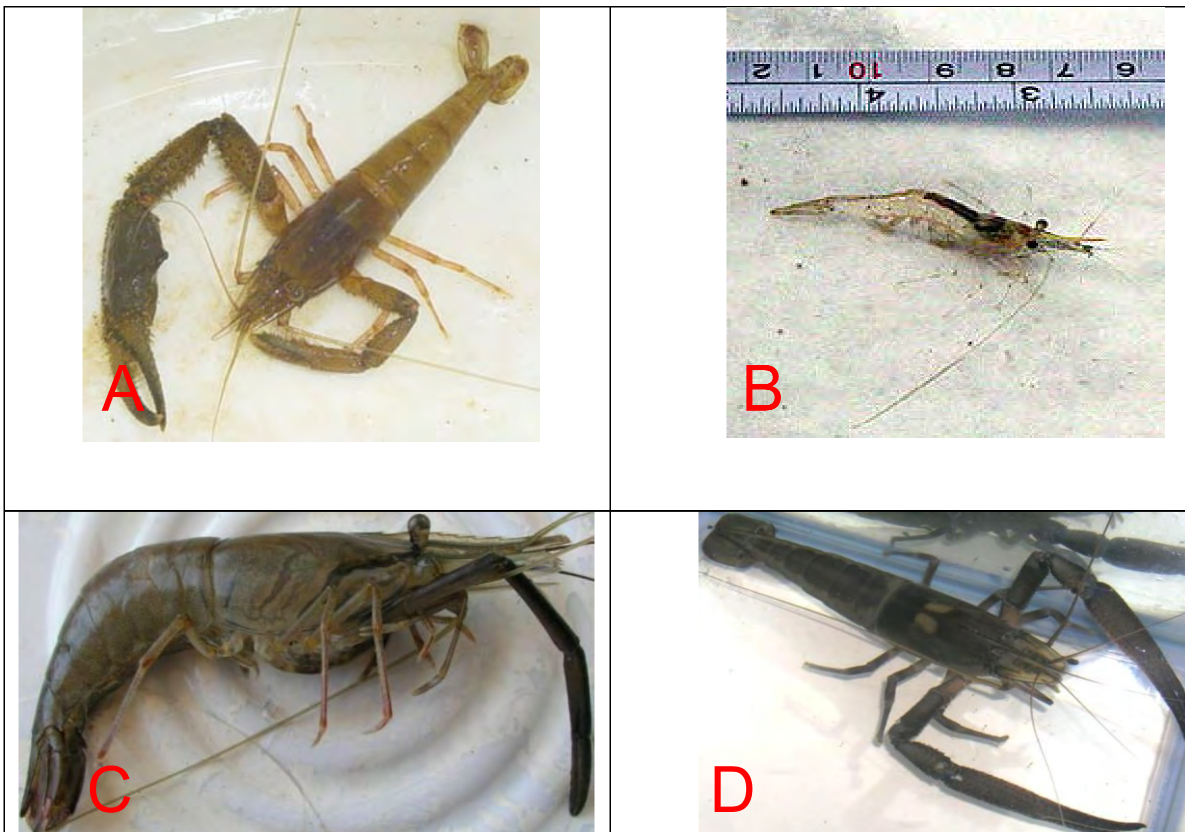

Figure 13. A. *Macrobrachium faustinum*, B. *Xiphocaris elongata*, C. *Macrobrachium acanthurus*, and D. *Macrobrachium carcinus*.

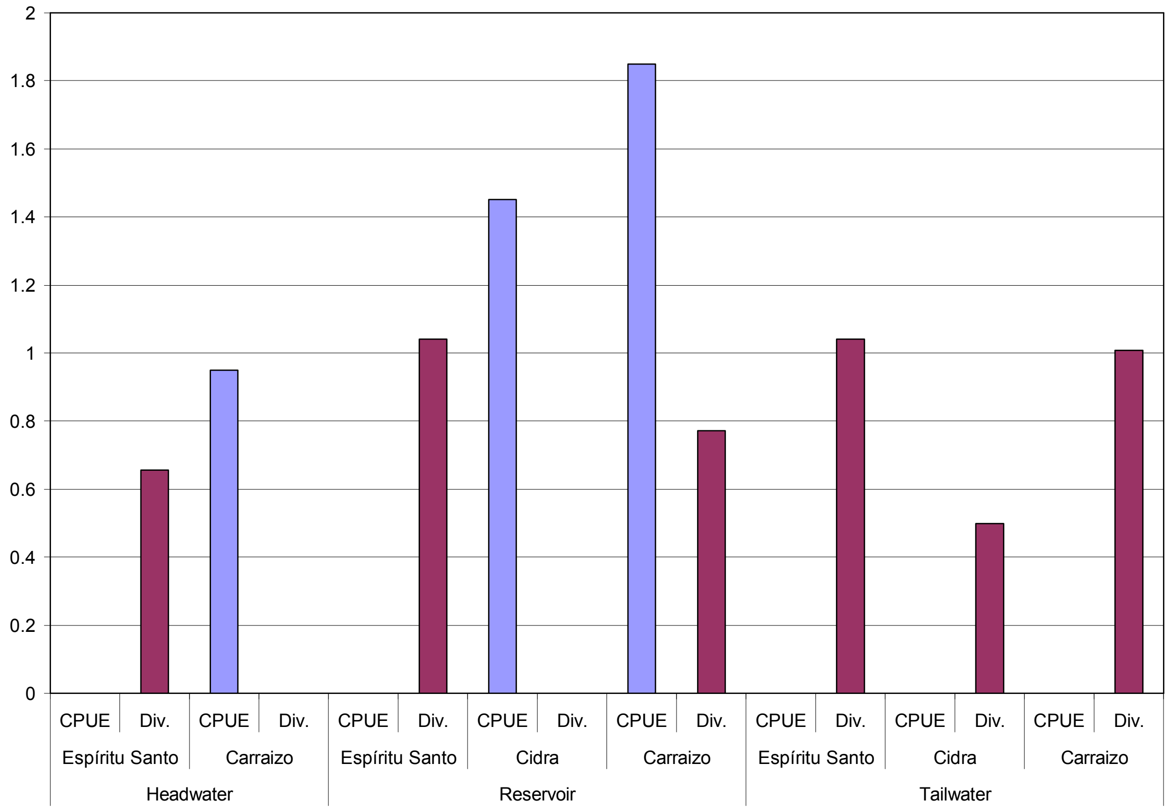

Figure 14. Diversity (Shannon-weiner)of total decapod crustaceans (redclaw, native shrimp, crab) vs CPUE (12 hr) of *Cherax* for Espíritu Santo, Cidra, and Loíza reservoir systems and their headwaters and tailwaters.

Latitude and longitude coordinates for each sampling site are listed in Appendix C. For the headwater tributaries of the Lago Loíza reservoir, the Gurabo and Loíza Rivers, the coordinates represent the upper point at which redclaw were encountered; in other words, they had dispersed from the Lago Loíza reservoir into the stream tributaries. Coordinates for the Lago Loíza and Lago de Cidra reservoirs represent the sampling area near their respective dams where the redclaw were encountered; in each case, the species was actually dispersed throughout each reservoir. Lago de Cidra reservoir is located at the headwaters of the Bayamón River, so headwater tributaries are small compared to headwaters of Lago Loíza reservoir with its two tributaries (Gurabo and Loíza Rivers).

Even though redclaw were captured in Lago de Cidra reservoir, redclaw were not collected from the tailwaters (the Bayamón River) during quarterly sampling during the study period (see coordinates, Appendix C). Thus, redclaw, although inhabiting the Bayamón River system in Lago de Cidra reservoir, it was not captured in the tailwaters of the reservoir. There are various coordinates (Appendix C) for the Lajas Valley; the origin of the redclaw escape in Western Area of Puerto Rico, is suspected to be the drainage canal at the UPRM Aquaculture Field Station. The drainage canal connects with the Mondongo stream which is a tributary of the Loco River; redclaw were captured in the Mondongo stream.

The other streams which were sampled produced only one site with redclaw specimens, in Carite Reservoir, part of the La Plata River system. Coordinates for the stream sites sampled are found in Appendix C and the organisms trapped in each stream are included in Appendix D. The coordinates for these other stream systems correspond to the respective dam on each reservoir on each stream, except for the Turabo River which is a tributary of the Loíza River system. The coordinates for the sampling site on the Turabo River are downstream from Highway 183 because this river has no dams (or reservoirs).

Caribbean Fisheries, Inc., is located within the Lajas Valley. Occasionally redclaw reach this facility (Dr. Michael McGee, personal communication) which is approximately 7 km from the Lajas Aquaculture Field Station drainage canal. However, sampling at the Caribbean Fisheries for redclaw with traps yielded no redclaw specimens. Nevertheless, the reported appearance of redclaw indicates that it is dispersing throughout the Lajas valley. The Lajas valley has little change in elevation, which facilitates redclaw dispersion throughout the slow-moving stream systems.

The average depth of each trap placed for sampling (Figure 15) was 114 ± 1.0 cm, ranging from 10 cm in the Piedras River to 488 cm in the Lago de Cidra reservoir. The greatest sample depth occurred within the reservoirs which have steep sides in mountainous areas.

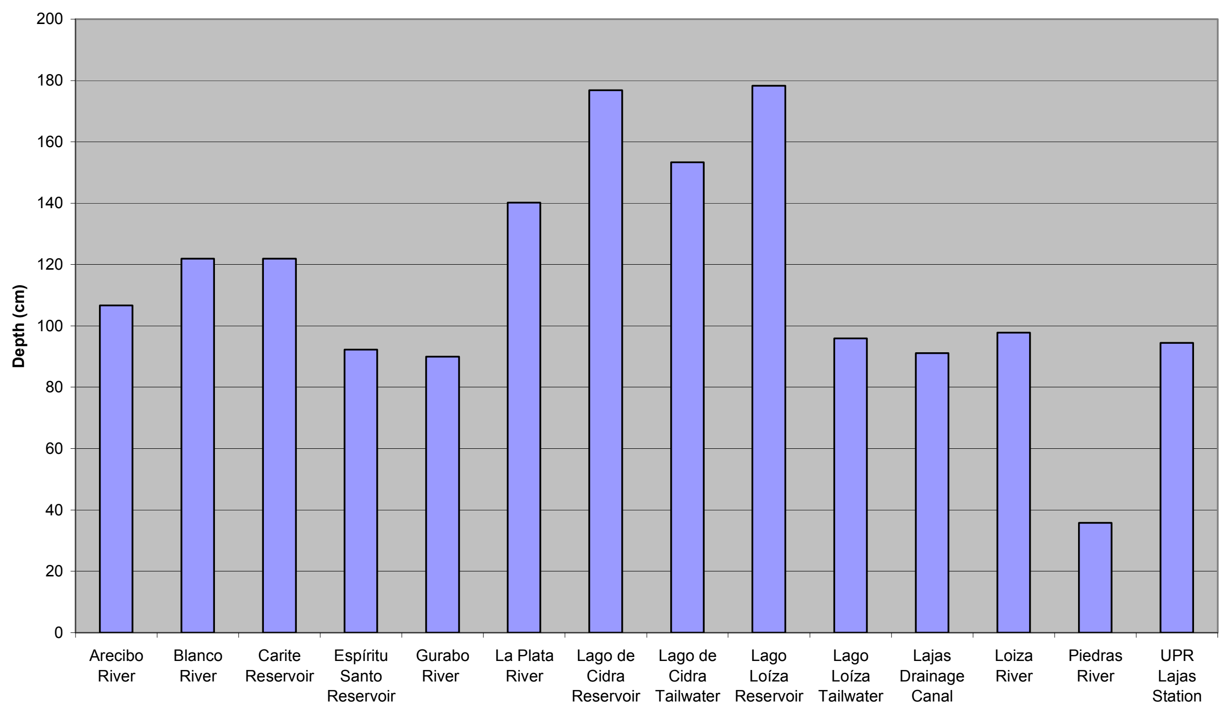

Figure 15. Mean trap placement depth (cm) in each water body.

There were no correlations of the CPUE of *Cherax* with pH values; however, there was a positive correlation (>0.4) for CPUE of *M. acanthurus* (r= 0.651), *M. faustinum* (r= 0.857), *M. carcinus* (r=0.832), and for *X. elongata* (r=0.723), with pH. Thus, as pH values increased, CPUE of these two native shrimp species increased. There was a positive correlation for CPUE of *M. acanthurus* (r= 0.831) with dissolved oxygen concentration; however, there was a negative correlation (-0.419) between CPUE of redclaw and dissolved oxygen.

There were no correlations between CPUE and discharge and between CPUE and temperature for *M. acanthurus* (r= 0.099). However, there was a negative correlation (<0.4) between CPUE of a crustacean freshwater crab species, *Epilobocera sinuatifrons* (Bruquena or Buruquena), and discharge (r=-0.447); thus, with increasing discharge, there were fewer crabs. Temperature taken during sample periods ranged from 18.0ºC (March) to 31.9ºC (May). A negative correlation also existed between this crab species and temperature (r=-0.766); thus where temperature is lower, we find more crabs.

There was no correlation between the blue crab species *Callinectes bocourtis* (cocolía azul) and redclaw. There was a positive correlation of the CPUE of *M.carcinus* (r= 0.744) and *M. faustinum* (r= 0.663), with turbidity.

Results of Agonistic Trials

The first four interactions (Table 2) reflect agonistic acts of the redclaw against other species; the last row reflects agonistic acts of *M. carcinus* against redclaw. Agonistic acts include: nip - crustacean closes down the tips of its chelae onto a body part of other; push –crustacean pushes one of its chelae onto a body part of other; embrace – one crustacean surrounds another with its chelae; cheliped extend – extending one or both chelae againsts other; meral spread –elevated body position while both chelae are raised horizontally with the ischium and merus spread perpendicularly to the body.

Results of the agonistic trials indicate that redclaw are more aggressive than the selected native aquatic animals (Table 2). The only animal which made agonistic acts against redclaw was *M. carcinus* (2.25 acts ± 0.73 SD); however, agonistic acts were higher for redclaw (8.00 acts ± 1.63) against *M. carcinus* (see appendix I and J). However, there were no instances where redclaw killed other organisms. Agonistic acts of redclaw (9.75 ± 1.86) were significantly higher against guábara than against other species.

Table 2. Agonistic trials of redclaw during 4.0 hours of observations in a period of 96-hr trial with various native species, modeled after Karplus et al. (1992).

Treatment	No. of acts	Acts without physical contact		Acts with physical contact		
		Meral spread	Extend	Nip	Push	Embrace
Cherax vs *Anguilla*	8.50± 1.93	0.25± 0.25	1.25± 0.60	0.25± 0.25	2.00± 0.73	4.75± 1.33
Cherax vs *Agonostomus*	3.25± 0.91	0.75± 0.54	1.25± 0.79	0	0.75± 0.54	0.25± 0.25
Cherax vs *Atya*	9.75± 1.86	0.75± 0.40	3.50± 0.81	2.50± 0.96	0.25± 0.25	2.75± 1.08
Cherax vs *M. carcinus*	8.00± 1.63	0.75± 0.40	0.75± 0.40	1.75± 0.4	2.75± 0.79	2.00± 0.97
M.carcinus vs *Cherax*	2.25± 0.73	0.25± 0.25	0.75± 0.40	0.25± 0.25	1.00± 0.58	0

Redclaw tried to catch guábara, but in each case, they scooted away from redclaw. Redclaw were successful in damaging guábara by removing a mean of 1.0 pereiopod/guábara during the total trial. Guábara made grooming movements on redclaw, with a mean of 1.0 grooming acts during each 15-minute observation. Redclaw were agonistic (3.25 acts ± 0.91) towards mountain mullet even though they swam above redclaw within the water column. Redclaw made 8.50 ± 1.93 agonistic acts towards American eel; however, redclaw were not able to grip the slippery mucous coating of the eel. Native eels are the main predator of redclaw in their native range.

Parasites and Diseases carried by Redclaw

No parasites or diseases were found in redclaw (Ernest Williams, personal communication), but a symbiont *Craspedella pedum,* Cannon and Sewell, 1995 (Platyhelminthes: Temnocephalida) occurred on the gills. However, *Chironomidae* (Insecta; Diptera) larvae were found beneath the cephalothorax and abdomen of one redclaw in Lago de Cidra reservoir and two redclaw in Lago Loíza reservoir. *Plumatella repens* (Phylum Bryozoa) were found stuck to the carapace of redclaw in Lago de Cidra reservoir (identification was made by Dr. Carlos J. Santos-Flores).

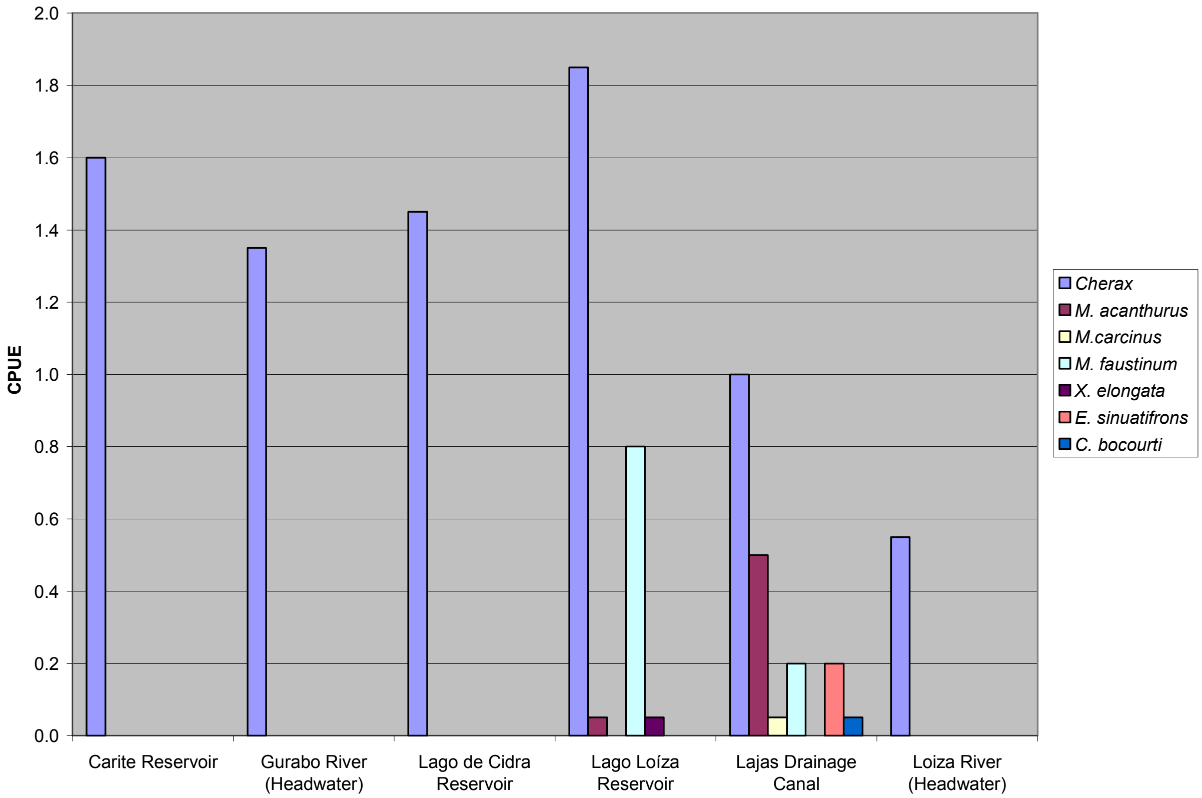

Figure 16. CPUE of decapod crustacean species in each water body in which redclaw was captured.

CPUE of redclaw (Figure 16) was negatively correlated with the presence of native shrimp species (r=-0.522 *M. acanthurus*, r=-0.484 *M. carcinus*, r=-0.397 *M. faustinum* and r=-0.463 *Xiphocaris elongata*). Redclaw co-inhabited only the Lago Loíza reservoir and the Lajas drainage canal with native freshwater crustaceans (Figure 16).

Discussion

There were more berried female redclaw found during sampling and in man-made ponds during warmer months. Barlow and Jones (1990) found that reproduction increased during the warmer months in Australia. However, due to the few redclaw collected in this experiment (Appendix E), it is difficult to ascertain if they reproduced during other months.

A total of 13 (18%) female redclaw captured in the wild had eggs attached externally to the pleopods; the mean length of these females was 12.0 cm ranging from 8.8 to 15.5 cm. The berried females were captured in the following water bodies: Gurabo River (3), Lago Loíza reservoir (6) and Lajas Drainage Canal (6). Berried females were captured during late February, when the temperature began to increase, March, May, August, and September. The presence of berried females concurred with the same months from the concrete ponds at Lajas.

Dams in Puerto Rico represent barriers for native fish and shrimp in Puerto Rico (Holmquist 1998). The CPUE of native fish and shrimp is higher in the tailwaters downstream from the reservoir dams. Shrimp which do manage to enter the reservoir often have sparse populations, although *X. elongata* is occasionally found in abundance in reservoirs. *Macrobrachium acanthurus*, *M. faustinum*, and *X. elongata* were captured within the reservoirs, but because the latter species are small, few were collected within the traps which selected only larger organisms.

The CPUE of native shrimp species in tailwaters or in rivers with no dams was lower than redclaw CPUE within reservoirs. However, there were no redclaw within the Espíritu Santo reservoir which has a 2.5 m high dam. Redclaw have probably not dispersed to this reservoir. Native fish were not collected within reservoirs with dams higher than 2.5 m, even though there are isolated reports of the presence of *Anguilla rostrata* (Holmquist et al. 1998) and *Gobiomorus dormitor* (bigmouth sleeper) (Neal et al. 2001). However, these latter two species were captured in the Espíritu Santo reservoir which had a low head dam of 2.5 m height.

Even though it is illegal to import non-native aquatic species into Puerto Rico to culture or to release them into natural waters, pet shops continuously import and sell a variety of non-native aquatic species. For example, *P. clarkii*, which has caused environmental problems in other countries, can be purchased in local pet shops. Exotic fish such as goldfish are sometimes purchased from pet shops to be used as live bait; these fish escape or are deliberately released by fishermen into reservoirs. Sometimes, when people move off the island, they will release aquarium pets into native waters. As a result of these and similar activities, over 24 different exotic species inhabit freshwater water bodies in Puerto Rico; thus, the 24 exotic species represent 56% of the total species captured. Ten species captured during 2006, including *Hemichromis bimaculatus* (Jewelfish),*Gyrinocheilus aymonieri* (Chinese algae eater)(Figure 17, left), *Cichlasoma managuense* (Jaguar cichlid)(Figure 17 right), *Amphilophus labiatus* (Red devil)*, Archocentrus nigrofasciatus* (Convict cichlid), *Astronotus ocellatus* (Oscar), *Pterygoplichthys pardalis* (Amazon sailfin), *Puntius conchonius* (Rosy barb), *Puntius tetrazona* (Sumatra barb) *and Xiphophorus hellerii* (Green swordtail), are commonly sold in pet shops. One previously unreported exotic fish species was captured during this study, *Hemichromis bimaculatus*. DNER (2006) reported two species, the

Archocentrus nigrofasciatus and *Cichlasoma managuense* (Craig Lilyestrom, personal communication) and Dr. Kwak et al. (2007) reported *Gyrinocheilus aymonieri,* which have not been previously found in Puerto Rico.

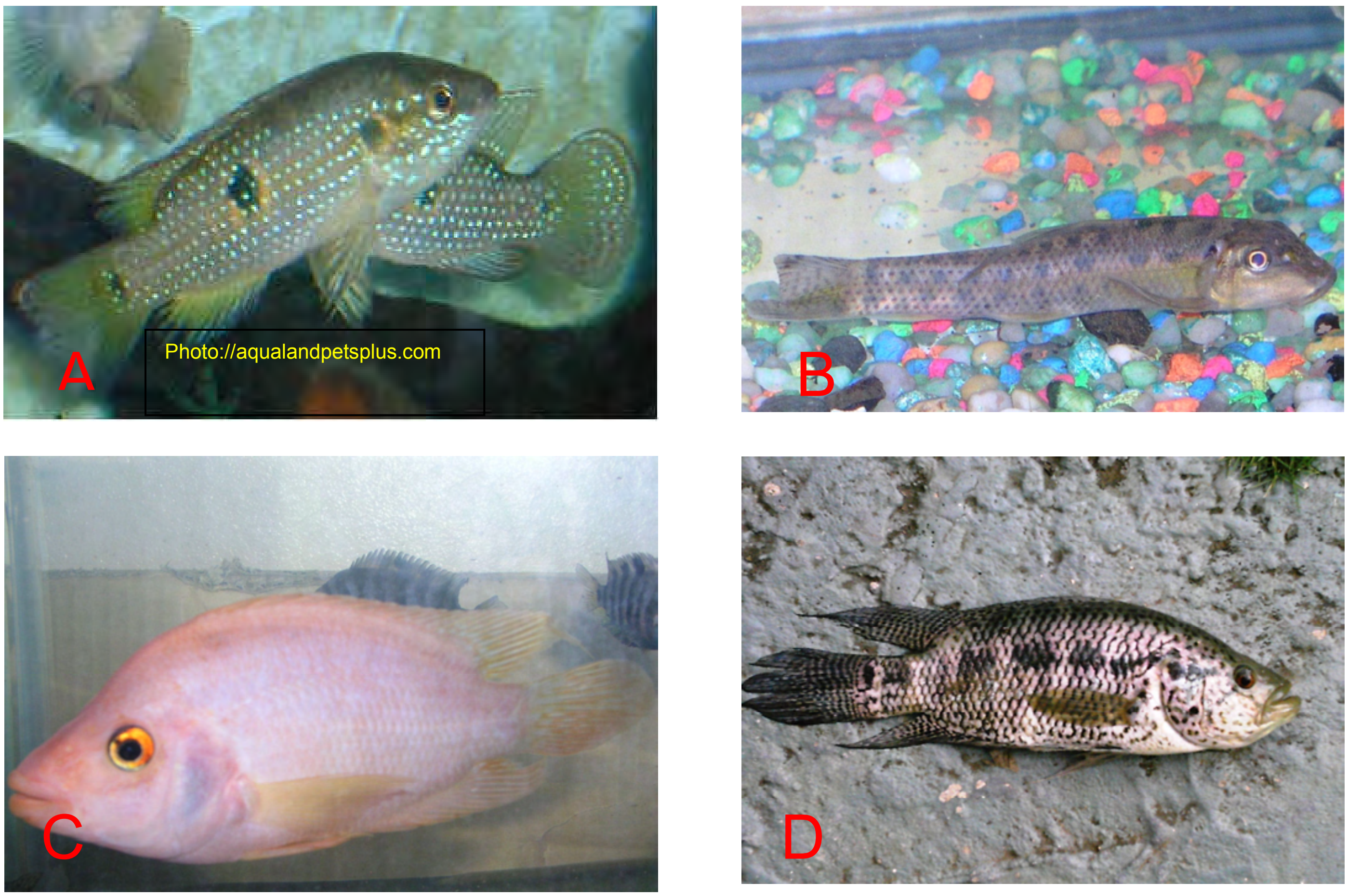

Figure 17. A. Hemichromis bimaculatus (Jewelfish), B. Gyrinocheilus aymonieri (Chinese algae eater), C. Amphilophus labiatus (Red devil), and D. Cichlasoma managuense (jaguar cichlid).

Cherax quadricarinatus has dispersed throughout several regions in the northeast and southeast sections of Puerto Rico, now inhabiting five river systems (Bayamón, Loíza, Loco, La Plata, and Patillas), thus providing evidence that the species can reproduce in Puerto Rico watersheds, especially in slow-moving water systems such as reservoirs and canals (Lajas). There are several factors contributing to the success of the dispersion of redclaw.

Factors affecting distribution

Holmquist et al. (1998) reported no *C. quadricarinatus* during their study which was made before Hurricane Georges; the first report of this species was made by Williams et al. (2001) within the Loíza River system in 1998 in the Lago Loíza Reservoir. This study demonstrates that the distribution of the species has increased since its first release and discovery. During August 2003, the author discovered this species in the Gurabo River, a tributary of Loíza River (Figure 18). In February 2004, this species was discovered in the Lajas Aquaculture Field Station drainage canal. During August 2005, it was captured and reported by the author in the Cidra reservoir in the Bayamón River. During 2006, individual specimens were captured in the Carite Reservoir of the La Plata River. By 2007, the species had been reported in Patillas Reservoir of the Patillas River (unpublished information from the Department of Natural and Environmental Resources), in the Guaynabo River, tributary of the Bayamón River system (USGS 2007c) and in the Canóvanas River, tributary of the Loíza River system (Kwak et al. 2007).

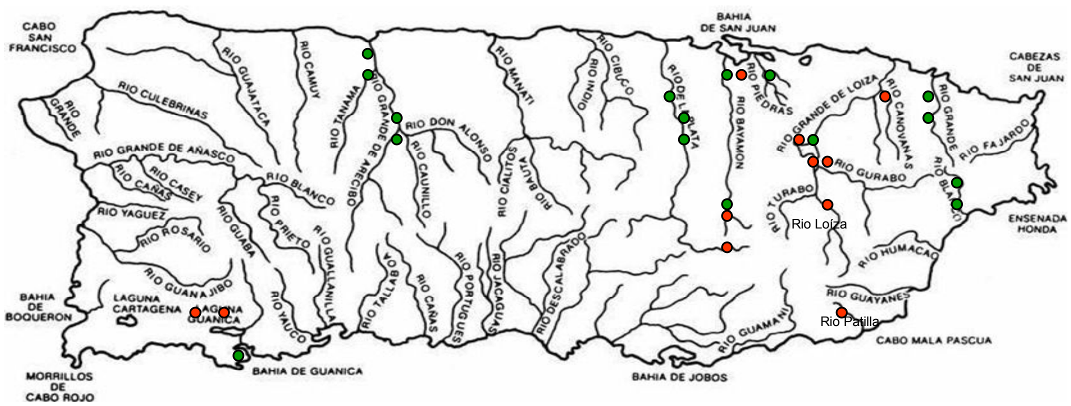

Figure 18. Distribution of *Cherax quadricarinatus* in Puerto Rico river systems.

The Puerto Rico Department of Agriculture received a permit effective from February 25, 1998 until February 28, 1999 to import specimens of *C. quadricarinatus* for scientific purposes (Department of Natural and Environmental Resources permit number 98-I-10). Specimens were authorized to be housed at the University of Puerto Rico Lajas Aquaculture Field Station or at the Magueyes Island Marine Laboratory. Stipulations of the permit included: a) illegality to liberate, sell, transfer, or give the imported specimens to others without informing DNER; b) prevention against escape or liberation of the specimens into Puerto Rico waters; c) specimens were to be inspected by Doctor Ernest Williams and Dr. Lucy Bunkley-Williams (UPRM) for parasites and diseases; and d) notification to DNER of each imported delivery of live organisms. Later, Williams et al. (2001) examined various *C. quadricarinatus* for parasites and diseases after several specimens were captured from the Loíza River and the Lago Loíza Reservoir (after the mass escape during Hurricane Georges). They found harmless commensals. Some of the animals were maintained live for experimental purposes at the UPRM Aquaculture

Field Station. Some samples of redclaw were also deposited in the Invertebrate Collection of the Department of Marine Sciences, UPRM.

The station maintained the species in indoor tanks within a facility which was locked after work hours. However, they were later transferred to outdoor ponds with vertical concrete borders (to prevent escape). The ponds were covered with protective netting to prevent bird predation. In spite of the measures taken to prevent escape, specimens of the redclaw were reported from the Lajas Aquaculture Field Station drainage canal after a flooding incident. A report to DNER of the escape of redclaw was confirmed by the author who captured several specimens downstream from the station's drainage canal in February 2004.

Thus, the introduction of this species was initially attributed to an illegal human activity by introducing it into Puerto Rico, and its accidental release by an act of nature (Hurricane Georges) that flooded the culture system near the Loíza River. However, multiple mechanisms are probably involved in its distribution throughout the Loíza and Bayamón River systems. The human factor involved in the dispersal cannot be discarded because some local fishermen probably transferred live specimens to other reservoirs. Those in Cidra and Carite reservoirs may be examples. Holmquist et al. (1998) noted as a personal observation that fishermen transport juvenile American eel (*Anguilla rostrata*) into reservoirs.

Because native shrimp are blocked from entering many reservoirs (Holmquist et al. 1998) by dams, there are few native shrimp in the man-made reservoirs. Native shrimp larvae need saline water to reproduce; when postlarvae swim upstream, they are frequently blocked by dams with no spillway discharge (Holmquist et al.1998). Prior to this study the only freshwater shrimp species found in Puerto Rico reservoirs was *M. faustinum* (Holmquist et al.1998). In addition, two other native shrimp species, *Macrobrachium acanthurus* and *Xiphocaris elongata* were captured during this study.

Once native shrimp species successfully make their way into a reservoir, they face another obstacle, i.e., surviving depredation while searching headwater streams entering the reservoir. Fish trapped in the Cidra and Lago Loíza reservoirs included the predators *Cichla ocellaris* (peacock cichlid)*, Ictalurus punctatus* (channel catfish)*,* and *Micropterus salmoides* (largemouth bass). Other fish species (*Amphilophus labiatus, Anguilla rostrata*, and *Astronotus ocellatus*) will opportunistically prey on shrimp in other reservoirs in Puerto Rico. *Gobiomorus dormitor*, a native predator species, has been found in Carite and Patillas reservoirs (Neal et al. 2001). In July 2008, the author observed one *Gobiomorus dormitor* vomiting a *Cherax*, later of stress produced by a electrofishing procedure in Carite reservoir. Reservoirs which block native shrimp also eliminate native fish fauna (Holmquist et al. 1998). In summary, the paucity of shrimp species in headwaters of reservoirs is attributed to the difficulty of shrimp to make their way into reservoirs and survive to reach headwater streams.

Other distribution mechanisms include the possibility of redclaw leaving their habitat and traversing land barriers. Because of predation by fish predators, this could be one stimulus which induces causes the crayfish to migrate (Stein and Magnuson 1976). Birds transfer fish from one water body to another; for instance, a common occurrence at the Lajas Field Station, which is located about 7 to 10 km from the Boquerón State Forest and Natural Reserve, which includes a Bird Sanctuary. Predatory birds such as osprey (*Pandion haliaetus*) capture fish, only to drop them into another pond (personal observation).

Flooding may be another mechanism for distribution, although distribution usually occurs within a stream system. There are no studies of the distribution of freshwater crayfish during floods which lower the coastal salinity. However, this is a probable mechanism for freshwater shrimp which have larval stages in saline water. Because redclaw can survive in salinities in excess of 12 ppt for extended periods (Medley et al. 1994), this dispersal mechanism is theoretically viable during flooding. However, there is no evidence to support this theory. Dispersal during flooding is also unlikely to occur in the headwaters of reservoirs during flooding because redclaw primarily inhabit lentic waters such as lakes or slow moving streams. Although inundations may be relatively frequent in headwater streams, especially during the rainy season, the events usually last only a matter of hours because of steep slopes (USGS 2007a).

Aquaculture is responsible for the legal and illegal introduction of these species in many countries. According to the Department of Agriculture of Puerto Rico (Agricultural Statistics Office), there are more than 70 aquaculturist in Puerto Rico. However, these species cannot be legally cultured in Puerto Rico without a permit. The crustacean *Macrobrachium rosenbergii* from the Indo-Pacific region (Bardach et al. 1972) has been legally cultured in Puerto Rico since its legal introduction during the 1970s. Because it is a favorite culture species in freshwater ponds, many mass releases of *M. rosenbergii* have occurred in Puerto Rico and throughout the Caribbean without apparent ill effects (Williams et al. 2001). *Macrobrachium rosenbergii* is less aggressive than the native freshwater shrimp *M. carcinus*; however redclaw is more aggressive than *M. rosenbergii*

(Williams et al. 2001). The larval stage of *M. rosenbergii*, similar to native Puerto Rico shrimp species, occurs in saline water. However, it has not dominated Puerto Rican streams and has not been found in native streams.

Because the culture of *M. rosenbergii* involves a complex hatchery cycle, and because its yield is significantly less than that of marine shrimp per unit of area, there has been a search for a freshwater crustacean species reaching commercial size. The yield of redclaw is about the same as that of *M. rosenbergii* with yields typically ranging from 3,000-4,000 kg/ha (Bardach et al. 1972). The culture of redclaw has been popular in America, because it is promoted as a freshwater lobster.

Rate of Dispersion

Based on the factors discussed in the previous section, it is difficult to estimate the rate of dispersion. However, this species dispersed into five river systems within a period of less than a decade from 1997 until 2007, or about 0.5 systems per year. In spite of the various dispersal mechanisms, dispersion by fishermen is probably the most significant cause of dispersion, especially because fishermen encounter a sparse population of shrimp species in reservoirs. Using this theoretical rate of dispersion, it is especially important for DNER to note any exotic decapod crustacean introductions within a few months at most, to attempt to eliminate the species. The measures required to eliminate the species would necessarily be drastic, however, to the native fish and crustacean population.

Perhaps, more viable means of avoiding introductions are through education and enforcement of rules for introductions. Because pet shops have been indirectly responsible for the majority of exotic fish populations, exotic species introductions should be monitored closely, especially to avoid species which are prohibited for importation. Species such as *P. clarkii* have caused problems in other islands such as the neighboring Dominican Republic, so inspectors should be vigilant concerning this species and other species introductions.

Agonistic Trials

Adult redclaw prefer decomposing organic matter; more specifically it feeds as a detritivore (Jones 1990b). Jones suggested that redclaw need aquatic fungi as a nutritional requirement. However, there is no evidence that redclaw attacked other animals to kill them. Redclaw would probably eat a moribund animal, however. Because the agonistic trials only lasted 96 hr, prediction cannot be made to determine which pair of animals would survive long-term starvation.

Because crustacea are often territorial, the agonistic acts may have been defensive instead of hostile. However, Medley et al. (1994) report that redclaw are cannibalistic on other recently molted redclaw. *Macrobrachium rosenbergii* is also cannibalistic on recently molted individuals (Karplus et al. 1992). Male *M. rosenbergii* defend against the approach of other males while it protects a harem of several females. When one of the females molts, it guards the defenseless female until the carapace hardens (at which time the male mates with the newly molted female).

Figure 19. *Atya lanipes* on top of a redclaw.

Damage Caused by Redclaw

Since redclaw have become established within Puerto Rico water systems, it has caused no evident environmental damage (Figure 19), though this was not the main focus of the present study. Moreover, determining such impacts is difficult. Probably the long-term impact of dams during the last 60 years has had more impact than the redclaw on native shrimp populations (see discussion below), especially because many of the native shrimp species inhabit flowing stream environments. However, as mentioned previously, the local shrimp fishermen have apparently been content with the introduction of redclaw, especially since they grow to a maximum of 600 g (1.3 lb) in Australia (Ackefors 1994; Jones 1990b). Because it does not compete directly with native shrimp for food or habitat, there is no evidence that this species has caused a significant environmental impact. More research is needed in this area however because of the difficulty in determining ecological impacts.

Impacts of Reservoirs on Stream Systems

Native shrimp populations are being impacted much more by dams without spillways (Holmquist et al. 1998) than by redclaw introductions. Native shrimp populations have been totally eliminated from reservoir and headwater streams on reservoirs with dams with no spillways. These barriers are effective obstructions for native shrimp (and fish) which spend part of their life cycle in saline water. If Puerto Rico continues to care for its freshwater streams and reservoirs, structures such as fish ladders need to be developed for native shimp and fish to pass.

The states of the Pacific Northwest invested in fish ladders to provide passage for various species of salmon. The same concept applies to Puerto Rico. For instance, an interesting scenic attraction for local and visiting nature lovers is the San Cristobal Canyon between Aibonito and Barranquitas. Because La Plata reservoir dam obstructs shrimp, there are few native shrimp species within the river system which winds about 9 km throughout this rugged canyon. Native shrimp are important for the ecology of Puerto Rico streams, so the streams within the canyon will never return to normal without human intervention which caused the problem in the first place by constructing dams without spillways. Nevertheless, it must be recognized that the economic importance of Pacific Northwest salmon populations is far greater than that of native Puerto Rico fish and shrimp species.

With a current population of 3.9 million inhabitants, Puerto Rico will continue to need reliable water supplies. Water shortages near San Juan have resulted in the construction of an aqueduct system which draws off much of the water from the Arecibo River. Each reservoir is important in Puerto Rico, especially to supply water and to a lesser extent, to supply electrical power. Yet, a balance is needed to protect native streams for future generations.

Cherax quadricarinatus can survive within water bodies with most of the water quality parameters encountered within this study, including areas with low dissolved oxygen concentrations of 4.4 mg/L (Lago Loíza). DNER (2006) reported a mean dissolved oxygen concentration of 3.23 mg/L in Lago Loíza reservoir and encountered redclaw during sampling with electro-fishing devices. Physical factors were important in the distribution of redclaw, including slow-moving or lentic water bodies such as lakes and canals, and muddy or silty bottoms. However, turbidity was not correlated with its presence. For instance, even though tailwaters adjacent to reservoirs were available as habitat for redclaw, no specimens were trapped below dams. Values for water quality variables for each water body are indicated in Appendix A.

This study corroborates reports by the Department of Natural and Environmental Resources that redclaw inhabits several reservoirs (Lago Loíza, Lago Carite and Lago de Cidra reservoirs). At a rate of dispersion of redclaw of 0.5 river systems each year, 5 reservoirs would theoretically become inhabited by redclaw within the next ten years. Even though this species has apparently caused no evident ecological damage to date, they should still be monitored, especially, if redclaw become established in streams, in addition to the reservoirs they now inhabit. Because native streams are slow-moving near the ocean at the mouth of the stream, and because redclaw can withstand salinities of greater than 12 ppt, these areas should especially be monitored for interactions of native shrimp and redclaw.

Future research should include surveys of the fishermen, including their methods of fishing for redclaw and impacts of redclaw on recreational and native fish, and invertebrates, and determination of the ecological impact of redclaw on the intermediate host of *Bilharzia,* as well as in the control snail:(Marisa).

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Appendices

Appendix A. Water quality variables for each water body.

Water Body	pH (± 0.1)	Dissolved Oxygen (± 0.2 mg/L)	Turbidity (± 5 %)(mg/L)	Conductivity (mS/m)	Water Temperature (±1.0 C)	Discharge (m^3/s)
Espíritu Santo Headwater	7.3	8.9	76	12.4	25.4	1.2
Espíritu Santo Reservoir	7.0	8.8	78	12.4	26.2	1.2
Espíritu Santo Tailwater	7.4	8.3	118	24.3	26.7	2.0
Lago de Cidra Reservoir	7.3	8.2	86	23.3	27.5	0.0
Lago de Cidra Tailwater	6.8	7.6	116	24.1	23.8	0.4
Loiza River (Headwater)	6.5	7.1	66	31.2	29.2	2.8
Gurabo River (Headwater)	6.9	6.7	128	43.4	28.2	1.7
Lago Loíza Reservoir	7.5	7.5	75	33.7	28.2	0.0
Lago Loíza Tailwater	8.4	8.7	192	37.3	29.3	1.9
Lajas Drainage Canal	7.4	8.5	30	45.3	26.3	0.1

Appendix B. Fish CPUE (organisms per trap) in each water body. Identification was made with Dawes (2005) and Schliewen (2005).

Water Body	*A. rostrata*	*G. dormitor*	*E. pisonis*	*Oreochromis/Tilapia* spp.	*C. ocellaris*	*L. microlophus*	*C. managuense*	*Poecilia* spp.	*P. tetrazona*	*P. conchonius*	*X. helleri*	*H. bimaculatus*	*G. aymonieri*	*P. multiradiatus*	*A. ocellatus*	*A. nigrofasciatus*	*A. labiatus*
Espíritu Santo Headwater	0.14	0.29	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Espíritu Santo Reservoir	0.10	0.10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Espíritu Santo Tailwater	0.00	0.08	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Gurabo River (Headwater)	0.00	0.00	0.00	1.60	0.00	0.00	0.00	0.05	8.15	1.55	2.00	0.00	0.00	0.00	0.00	0.70	0.05
Lago de Cidra Reservoir	0.00	0.00	0.00	0.00	0.90	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Lago de Cidra Tailwater	0.00	0.00	0.00	0.10	0.00	0.00	0.00	0.20	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Lago Loíza Reservoir	0.00	0.00	0.00	0.15	0.00	0.00	0.00	0.00	1.50	0.35	0.05	0.15	0.00	0.00	0.05	0.70	0.70
Lago Loíza Tailwater	0.00	0.00	0.05	0.15	0.00	0.00	0.00	0.00	2.40	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05
Lajas Drainage Canal	0.00	0.00	0.00	0.15	0.00	0.00	0.10	0.15	0.00	0.00	0.00	0.15	0.00	0.15	0.00	0.00	0.00
Loiza River (Headwater)	0.00	0.00	0.00	0.85	0.00	0.00	0.00	0.25	5.25	2.90	0.05	0.00	0.20	0.00	0.00	2.05	0.15
Average	0.02	0.05	0.01	0.30	0.09	0.00	0.01	0.07	1.73	0.48	0.21	0.03	0.02	0.02	0.01	0.35	0.10
Standard Deviation	0.05	0.09	0.02	0.52	0.28	0.00	0.03	0.10	2.83	0.98	0.63	0.06	0.06	0.05	0.02	0.67	0.22
Other One Day Samples																	
Arecibo River	0.00	0.00	0.00	0.20	0.00	0.20	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Blanco River	0.00	0.00	0.20	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Carite Reservoir	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
La Plata River	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Piedras River	0.00	0.00	0.00	0.10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
UPR Lajas Station	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Average	0.00	0.00	0.03	0.05	0.00	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Standard Deviation	0.00	0.00	0.08	0.08	0.00	0.08	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Appendix C. Coordinates for each sampling station.

Water body	Latitude	Longitude	Elevation (m)
Arecibo River	18º20'07.20"	66º40'02.19"	135.0
Bayamón Tailwater	18º11'50.10"	66º08'26.68"	402.0
Blanco River	18º13'12.40"	65º47'04.20"	14.9
Caribe Fisheries Drainage	18º01'37.69"	66º58'21.10"	557.5
Carite Reservoir	18º04'34.46"	66º06'22.19"	50.6
Carraizo Reservoir	18º19'35.15"	66º00'56.21"	24.1
Carraizo Tailwater	18º19'41.44"	66º00'56.68"	411.2
Cidra Reservoir	18º11'49.13"	66º08'25.80"	8.2
Espíritu Santo River	18º22'15.80"	65º48'56.84"	22.9
Gurabo River	18º15'21.82"	65º57'59.40"	166.1
La Plata River	18º20'36.41"	66º14'09.44"	29.0
Loco River	17º58'28.55"	66º54'53.13"	8.2
Loiza River	18º13'22.47"	65º00'44.20"	65.8
Mondongo Stream	18º00'40.64"	67º02'59.78"	17.1
Piedras River	18º23'17.71"	66º03'31.02"	18.9
Turabo River	18º13'29.28"	66º01'36.71"	63.7
U.P.R Lajas Station	18º02'14.80"	67º03'50.47"	29.0

Appendix D. Presence (+) of aquatic species captured or observed in each water body.

	Rivers										Stream			Reservoir			Dam		Others		
	Loiza River	Gurabo River	Espíritu Santo	Blanco	La Plata	Turabo	Arecibo	Tanamá	Loco	Río Piedras	Modongo	Francesa	Maizales	Carraizo	Cidra	Carite	Bayamón Below Dam	Loiza Below Dam	Lajas Canal	Caribe Fisheries	UPR-Lajas Station
Aquarium Fish																					
Amphilophus labiatus	+	+					+							+				+			
Archocentrus nigrofasciatus	+	+				+								+							
Astronotus ocellatus														+							
Gyrinocheilus aymonieri	+																				
Hemichromis bimaculatus														+						+	
Poecilia spp.	+	+	+		+												+		+	+	
Pterygoplichthys multiradiatus	+	+			+						+				+		+	+		+	
Puntius conchonius	+	+												+							
Puntius tetrazona	+	+												+				+			
Xiphophorus helleri	+	+				+								+							
Crustacean																					
Callinectes bocourti							+		+												
Cherax quadricarinatus	+	+									+			+	+	+			+		+
Epilobocera sinuatifrons			+								+						+				+
Macrobrachium acanthurus			+	+			+		+	+	+		+	+				+	+		
Macrobrachium carcinus			+				+		+	+								+			+
Macrobrachium crenulatum												+	+								
Macrobrachium faustinum			+	+			+		+	+		+		+	+		+	+	+		+
Panopeus herbstii			+																		
Sesarma roberti			+																		
Xiphocaris elongata												+		+				+			
Native Fish																					
Anguila rostrata			+																		
Agonostomus monticola			+		+						+										
Awaous tajasica					+																
Centropomus undecimalis									+												
Eleotris pisonis				+														+			
Eugerres plumieri									+												
Gobiomorus dormitor			+															+			
Recreational Fish																					
Cichla ocellaris					+										+						
Cichlasoma managuense																			+		+
Dorosoma petenense																			+		+
Ictalurus punctatus	+				+											+					+
Lepomis microlophus							+														
Micropterus salmoides	+																				
Oreochromis / Tilapia spp.	+	+		+	+	+	+			+	+			+	+		+	+	+		+
Mollusc																					
Corbicula fluminea	+	+			+												+	+			
Marisa cornuarietis															+				+	+	+
Nerita fulgurans			+																		
Tarebia granifera	+	+			+		+							+	+		+	+	+	+	+
Others																					
Iguana iguana	+	+			+									+	+						
Rana catesbeiana																			+		
Trachemys stejnegeri						+															

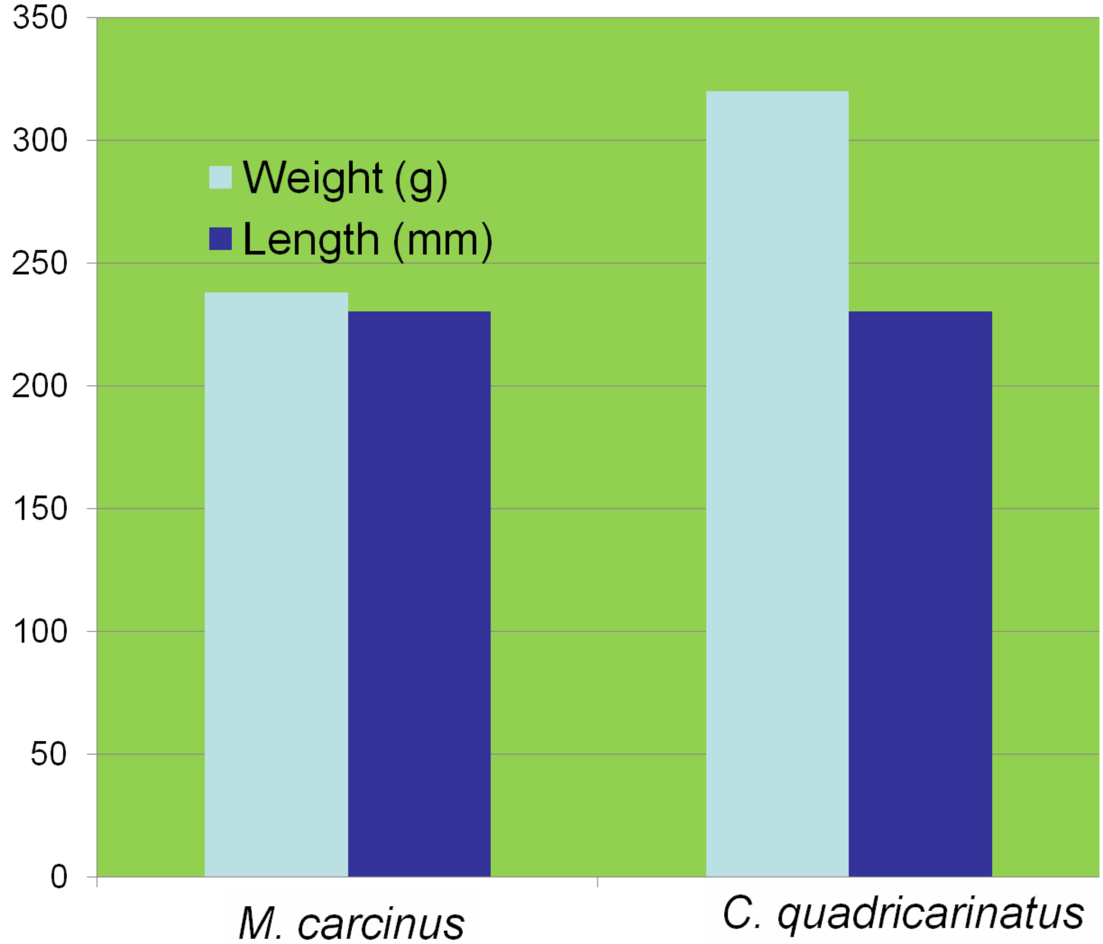
Appendix E. Total number and mean number of *Cherax quadricarinatus* per month.

Month	*C. quadricarinatus*	No. of Samples	Mean per month
Jan	6	1	6.0
Feb	8	2	4.0
Mar	6	1	6.0
Apr	0	0	0.0
May	3	2	1.5
Jun	17	2	8.5
Jul	18	2	9.0
Aug	17	1	17.0
Sep	20	2	10.0
Oct	0	0	0.0
Nov	6	1	6.0
Dec	29	4	7.3

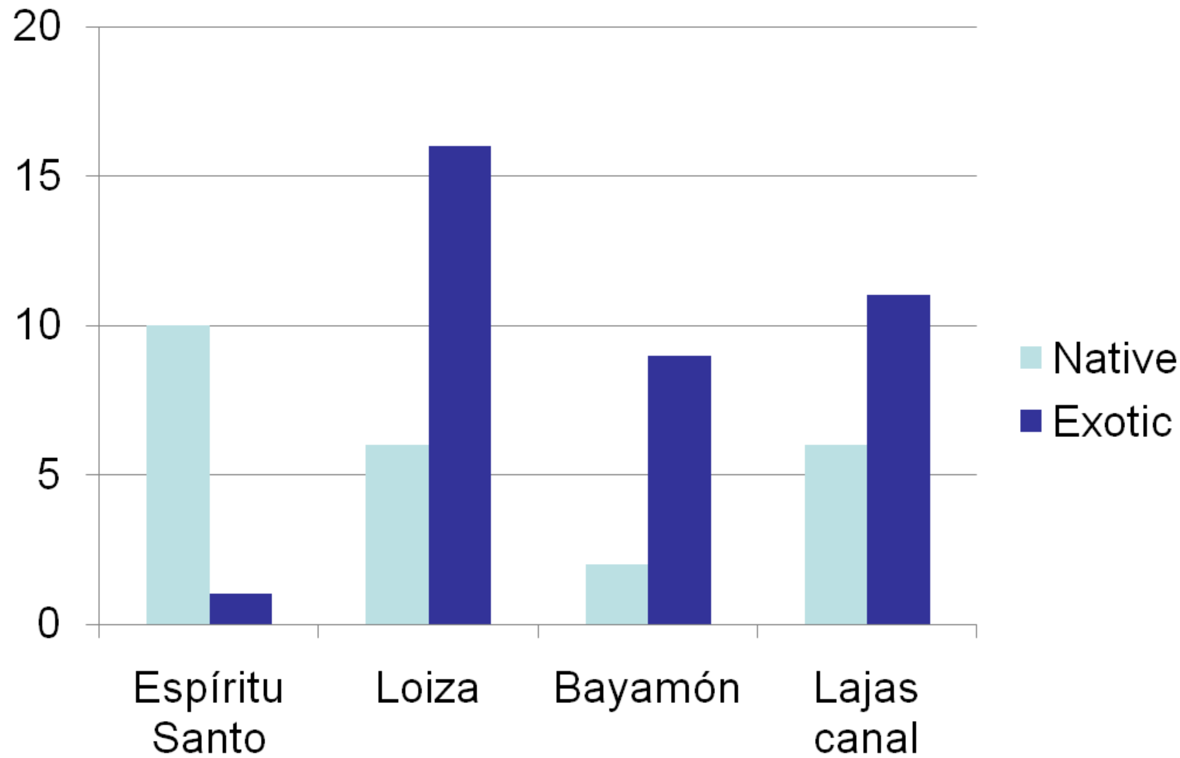
Appendix F. Crustacean CPUE in each water body (mean numbers per trap). Identification was made with Coward (2007) (crayfish) and Chace and Hobbs (1969) (native shrimp).

Water Body	*C. quadricarinatus*	*M. acanthurus*	*M.carcinus*	*M. faustinum*	*M. crenulatum*	*X. elongata*	*E. sinuatifrons*	*C. bocourti*	*P. herbstii*
Espíritu Santo Headwater	0.00	0.29	0.00	1.57	0.00	0.14	0.00	0.00	0.00
Espíritu Santo Reservoir	0.00	0.60	0.10	0.90	0.00	0.10	0.00	0.00	0.00
Espíritu Santo Tailwater	0.00	0.08	0.00	0.08	0.00	0.00	0.00	0.00	0.17
Gurabo River (Headwater)	1.35	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Lago de Cidra Reservoir	1.45	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Lago de Cidra Tailwater	0.00	0.00	0.00	0.05	0.00	0.00	0.20	0.00	0.00
Lago Loíza Reservoir	1.85	0.05	0.00	0.80	0.00	0.05	0.00	0.00	0.00
Lago Loíza Tailwater	0.00	0.70	0.70	2.65	0.00	0.15	0.00	0.00	0.00
Lajas Drainage Canal	1.00	0.50	0.05	0.20	0.00	0.00	0.20	0.05	0.00
Loiza River (Headwater)	0.55	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Average	0.62	0.22	0.09	0.63	0.00	0.04	0.04	0.01	0.02
Standard Deviation	0.73	0.28	0.22	0.89	0.00	0.06	0.08	0.02	0.05
Other One Day Samples									
Arecibo River	0.00	2.40	1.00	2.00	0.00	0.00	0.00	0.40	0.00
Blanco River	0.00	0.40	0.00	1.60	1.80	2.00	0.00	0.00	0.00
Carite Reservoir	1.60	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
La Plata River	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Piedras River	0.00	0.70	0.10	0.60	0.00	0.00	0.00	0.00	0.00
UPR Lajas Station	1.40	0.00	0.00	0.00	0.00	0.00	0.40	0.00	0.00
Average	0.50	0.58	0.18	0.70	0.30	0.33	0.07	0.07	0.00
Standard Deviation	0.78	0.93	0.40	0.89	0.73	0.82	0.16	0.16	0.00

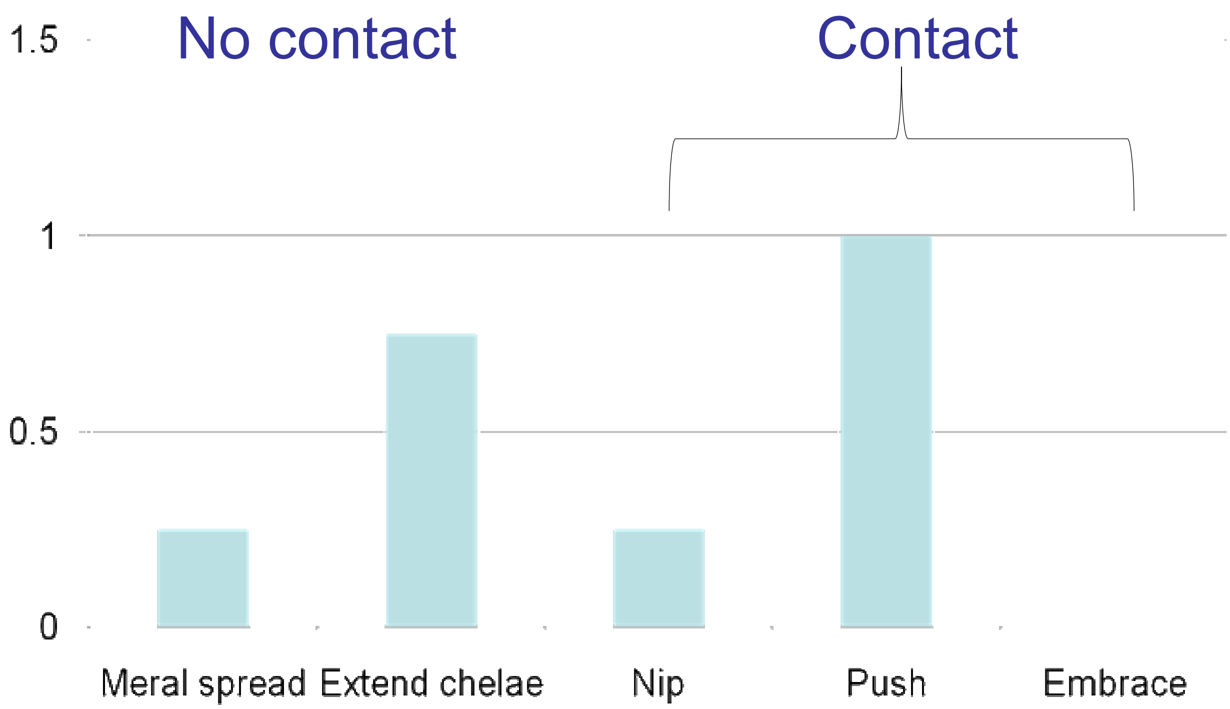
Appendix G. Weight and length comparison between *M.carcinus* (one specimen) and *C.* quadricarinatus (one specimen).



Appendix H. Native and Exotic species captured or observed in each river system.



Appendix I. Agonistic trial (*Macrobrachium carcinus* act vs. *Cherax*).



Appendix J. Agonistic trial (*Cherax* act vs *Macrobrachium carcinus*).