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Rapid Communication

Records of the Australian redclaw crayfish *Cherax quadricarinatus* (von Martens, 1868) on the island of Puerto Rico

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Abstract

The redclaw crayfish, *Cherax quadricarinatus* (von Martens, 1868), a tropical freshwater crayfish endemic to Northern Australia and Southern Papua New Guinea, was introduced to the island of Puerto Rico in the late 1990's. Redclaw has established populations within man-made reservoirs and ponds across the island, where impoundments have impeded the migration and recruitment of native decapods, potentially opening niche space for the redclaw. We present a case study focused on documenting the presence/absence, sex ratio, size class, and standing stock biomass of redclaw populations from six reservoirs (Carraízo, Cidra, Carite, Güajataca, El Guineo, Dos Bocas), as well as from various holding ponds of an aquaculture facility (Caribe Fisheries) located near the town of Lajas in the southwestern part of the island where the crayfish are considered pests. Crayfish were detected in 5 out of the 7 sample locations (Carraízo, Cidra, Carite, Güajataca, and Caribe Fisheries). A total of N = 150 crayfish were caught during sampling, with 91% being adults (N = 136) and sex counts resulting in a 0.81 male to female ratio. Standard Carapace Length (SCL) ranged from 16 mm (Güajataca) to 82 mm (Carraízo). No significant difference in SCL was found between adult males (48.32 mm ± 1.62 SE) and females (48.17 mm ± 1.47 SE) ($F_{(1,134)} = 0.81$, $P = 0.37$), as well as between SCL in M:F ratio among sample sites ($F_{(4,134)} = 0.84$, $P = 0.50$). However, a significant difference in total mean SCL among sample sites was found ($F_{(4,134)} = 16.96$, $P < 0.0001$). A post-hoc Tukey-Kramer test indicated that individuals in Carraízo, located close to the area of initial redclaw introduction into the headwaters of the Loiza River, had the largest mean SCL (61.38 mm). Mean standing stock biomass per individual ranged from 1.46 g (Güajataca) to 9.71 g (Carraízo). These biomass estimates provide the first insight into the energy supplements that redclaw provides to higher trophic levels (e.g. predatory fish) in these reservoirs. Furthermore, with populations of native decapods having been completely extirpated from most impounded watersheds, introduced redclaw could fill in the empty niche space by processing organic matter and by providing a direct consumption item to recreational fish species. This could reestablish the missing links in the cycling of nutrients and transfer of energy within reservoirs.

Key words: decapod, secondary production, invasive, ecological impacts, fisheries, Caribbean

Introduction

Over the past two decades, concern regarding the intentional or accidental release of the crayfish *Cherax quadricarinatus* (redclaw crayfish) outside of its native range has continued to grow (Williams et al. 2001; Ahyong and

Yeo 2007; Bortolini et al. 2007). Endemic to Northern Australia and Southern Papua New Guinea, redclaw introductions have been recognized worldwide. Due to its vibrant coloration, potential to attain large sizes and stress tolerance, redclaw was an ideal low cost candidate for commercial harvest in multiple countries (Jones et al. 2000). This led to the eventual establishment of introduced populations in South Africa, Mexico, Jamaica, Singapore, Israel, and Puerto Rico (Williams et al. 2001; Ahyong and Yeo 2007; Bortolini et al. 2007; Jaklic and Vrezec 2011). However, few studies have assessed the ecosystem-level effects of redclaw populations within and outside of their native range.

Redclaw was first imported into Puerto Rico in a commercial shipment of 3000 individuals in 1997 for experiments in aquaculture. These individuals were stocked in outdoor earthen ponds at an aquaculture facility in the northeastern part of the island near the town of San Lorenzo (Williams et al. 2001). Following hurricane Georges in 1998, these ponds became inundated and accidental introduction of redclaw occurred into the Rio Grande de Loiza River basin. Stable populations now occur in the Carraízo Reservoir, a manmade reservoir and main dam on the Rio Grande de Loiza River, as well as the headwater tributaries above the impoundment. Williams et al. (2001) suggest that several other shipments of redclaw have been illegally imported into the island. For example, in 1998, the Puerto Rico Department of Agriculture received permission to import an undisclosed amount of redclaw to evaluate their potential as a commercial stock (Williams et al. 2001; Garcia-Vazquez 2008). These individuals were placed at the University of Puerto Rico's Aquaculture Field Station in Lajas, in the southwestern part of the island. Individuals were held in earthen ponds and precautions were taken to limit escapes (e.g. concrete borders). However, some individuals escaped during a flood in the early 2000's. This escape was confirmed in 2004, when individuals were collected downstream from the station's drainage canal. Small populations now occur throughout the Lajas Valley (Garcia-Vazquez 2008).

The topography of Puerto Rico is characterized by a central mountain range leading to a relative steep gradient of elevational change within a small spatial scale. Variability in river discharge and the absence of natural lakes made it necessary to build catchment reservoirs to support the water demands of a growing population (Neal et al. 2009). These impoundments have restricted native diadromous decapod and fish species from reaching headwater streams above these structures, leading to their extirpation in streams (Holmquist et al. 1998; Pringle 2001; March et al. 2003) and substantial ecosystem-level effects (e.g. increased benthic algae, nutrients, and organic matter; Greathouse et al. 2006). Native shrimps on the island include 18 species from three families: Atyidae, Palaemonidae, and Xiphocarididae (Perez-Reyes 2013). Native shrimp provide a wide range of ecosystem services and fill multiple trophic levels within their native range

(Perez-Reyes 2015). The lack of native decapods in these reservoirs may have reduced competition pressure and opened niche space for the redclaw, representing an opportunity for crayfish to become established in reservoirs around the island (Williams et al. 2001; Garcia-Vazquez 2008). Within reservoirs, redclaw could be playing a key role in aquatic food webs, as a subsidy for larger consumers in the absence of native decapod species.

As reservoirs are usually stocked with multiple recreational fishery species (e.g. black bass, sunfish, catfish, tilapia, threadfin shad), there is a high predation pressure upon redclaw in these habitats. Many of these fish species are primarily piscivorous. However, interspecies competition may lead to changes in resource consumption (Neal et al. 2009). In Western Australia, a similar crayfish species (*Cherax cainii* Austin, 2002) was observed to supplement 61% of the stomach contents of stocked rainbow trout (*Oncorhynchus mykiss* Walbaum, 1792) in Churchman Brook Reservoir (Tay et al. 2007). In the absence of native decapods, standing stock crayfish biomass could supplement higher levels of the lentic (reservoir) food webs, where overall production is generally low (Kröger et al. 2010).

Within their native range, crayfish play critical roles in lotic and lentic communities (Charlebois and Lamberti 1996; Creed and Reed 2004; Magoulick and DiStefano 2007). Crayfish act as a food resource for fish, birds and mammals, aid in the processing of organic matter, and regulate benthic macroinvertebrate communities through direct predation or indirect competition (Hill and Lodge 1999; Correia 2001; Creed and Reed 2004). Alternatively, as non-native species, crayfish can have detrimental effects on a receiving area. Crayfish introductions influence ecosystem processes through changes in local habitat, reduction in macrophyte populations, as well as negatively affecting fish, amphibians, and macroinvertebrates assemblages through competition for resources and habitat, and/or introducing pathogens to the receiving area (Kershner and Lodge 1995; Guan and Wiles 1997; Johnson et al. 2009).

Here we present a project with the following goals: 1) provide accounts of redclaw presence or absence in different impoundments and one aquaculture facility representative of major geographical regions the island of Puerto Rico; 2) document sex ratios and size class frequencies of established populations in those areas; and 3) develop a linear regression model to estimate redclaw standing stock biomass within reservoirs.

Materials and methods

Presence of redclaw were sampled during June–August of 2012 from six reservoirs located throughout the island of Puerto Rico (Figure 1, Table 1) and in one aquaculture facility (Caribe Fisheries Inc., Lajas, PR) where redclaw is considered a pest in artificial earthen holding ponds used for cultivation of *Macrobrachium* sp. Sampling points were chosen based on geographical positioning on the island (the mountainous interior, the coastal

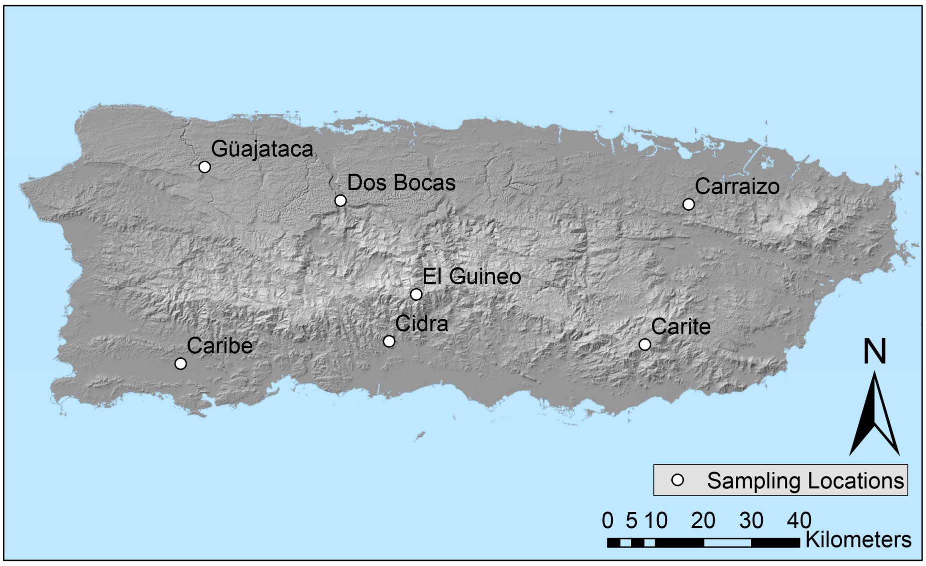

Figure 1. Map of reservoir sampling locations across the island of Puerto Rico.

Table 1. Sampling sites, region, municipality, and WGS84 coordinates (as decimal degrees; DD) within the island of Puerto Rico, total drainage area of reservoirs (km^2), physicochemical characteristics measured (Temp = temperature: pH = alkalinity: DO = dissolved oxygen), number of individuals collected (N), and Catch per Unit Effort (CPUE) at each location. Regions are classified as NE= Northeast, NW= Northwest, SE= Southeast, SW= Southwest, and MI = Mountainous Interior. ** Caribe Fisheries is an aquaculture farm and not a reservoir.

Sites	Region	Municipality	Coordinates (DD)	Area (km^2)	Temp (C^o)	pH	DO (mg/L)	N	*CPUE*
Carraizo	NE	Trujillo Alto	18.328, −66.016	538.0	30.0	7.5	4.2	29	0.5
Cidra	NE	Cidra	18.071, −66.578	21.0	30.2	8.1	4.5	32	2.0
Carite	SE	Guayama	18.065, −66.098	21.2	27.6	8.0	4.6	25	0.5
Güajataca	NW	Quebradillas	18.398, −66.924	60.4	28.8	7.9	4.0	31	1.0
El Guineo	MI	Villalba	18.159, −66.527	4.1	24.5	7.9	5.3	0	0.0
Dos Bocas	MI	Utuado	18.335, −66.669	420.1	30.6	7.9	–[a]	0	0.0
Caribe **	SW	Lajas	18.029, −66.969	–	31.5	8.4	3.9	33	–

[a] Dissolved oxygen (DO) probes were inoperable at the Dos Bocas site.

lowlands, and the karst area), previous records (Carraizo and Carite) in the literature (Williams et al. 2001; Garcia-Vazquez 2008), accessibility, and overall safety of personnel and equipment for deployment. We sampled for crayfish using baited, cylinder, minnow traps (Wildlife Supply Company, Yulee, FL) at each location. Trap openings were modified (3–5 cm) to accommodate for the large size potential of redclaw. A total of 15–20 traps (42 × 23 cm, 6.4 mm galvanized wire mesh) were baited with cat food pellets and each of them set every 10 m of 150–200 m transects, at depths ranging from 0.15 m – 3.0 m. Traps were left in the water for 24–48 h, depending on distance and accessibility between sites. Substrates at trap locations were characterized using a modified Wentworth scale (Wentworth 1922; Cummins 1962) and ranged from soft silt (< 0.063 mm) to large boulder (> 254 mm). Water chemistry parameters (e.g., Temperature, pH, Dissolved Oxygen) were measured at three locations of each site using a handheld YSI Professional Plus multi-parameter probe (YSI Incorporated, Yellow Springs, Ohio), and an average of those measurements was calculated for each site (Table 1).

Individual crayfish were sexed and measured to the nearest mm for standard carapace length (SCL i.e., from the tip of rostrum to the posterior median margin of the cephalothorax). Gender and life stage (adult *vs* juvenile) of crayfish was determined by the presence or absence of gonopores at the base of the third periopods for females and at the base of the fifth periopod in males or presence of gonopores to distinguish life stage (Ghanawi and Sauod 2012). Redclaw gains its name from a soft, red patch on the chelae of males; intersex individuals have been described having this red patch, but also displaying gonopores at the base of the third periopod. However, no individuals exhibiting both of these characteristics were surveyed during the duration of this study. A Catch-Per-Unit-Effort (CPUE = number of individuals per trap night; ~ 24 hrs) approach was used to estimate relative abundance of subpopulations. Limitations with a CPUE approach are associated with bias of baited traps towards larger individuals (> 50 mm) (Westman 1999). Using CPUE to estimate relative abundance can underestimate the overall population density because estimates are determined from a small subsample which is not representative of the entire reservoir.

Overall averages of mean SCL were compared using a Two-Way Analysis of Variance (ANOVA) with independent variables being sex and location. Data met homogeneity of variance assumptions for ANOVA. All statistical analyses were completed using JMP Pro 10 (SAS Institute Inc., Cary, N.C.).

The use of a length-mass relationship has been described as a rapid and precise approach to calculate biomass (Benke et al. 1999). Individuals representing the full size range of redclaw, while maintaining natal chelae and walking legs (N = 30), were scrubbed of all debris, preserved in ethanol (95%) and transported back to the laboratory. Crayfish were allowed to air dry for 30 minutes, then placed in an oven to dry at 60 °C for 24 h. Redclaw were weighed to the nearest mg for dry-mass (DM). Biomass was estimated by log10 transforming our data as described in (Methot et al. 2012) and using the length-mass regression equation described in Benke et al. (1999), which predicts mass as power function of a linear dimension,

$$M = aL^{b}$$

where M is the organism dry-mass (mg), L is the linear dimensions of the SCL (mm), and a and b are constants. Developing a predictive model for redclaw biomass can aid in future estimates of redclaw secondary production and trophic dynamics within these and similar systems (Benke et al. 1999; Sabo et al. 2002; Methot et al. 2012).

Results

Crayfish were detected in 5 out of the 7 sample locations (Carraízo, Cidra, Carite, Güajataca, and Caribe Fisheries). Crayfish were absent from our traps in Dos Bocas and El Guineo reservoirs. A total of N = 150 crayfish were

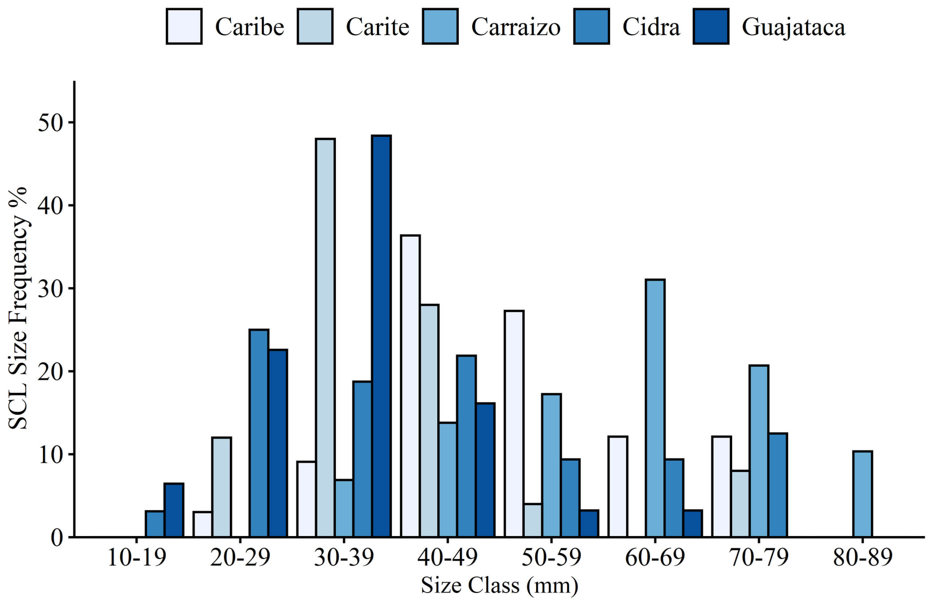

Figure 2. Size frequency (%) distribution based on standard carapace length (SCL) at the Carraízo, Cidra, Carite, Guajataca reservoirs and Caribe Fisheries site. Size estimates are provided in millimeters (mm) and percentages are based on total number of individuals caught at each location.

collected from sample sites representing the three major regions of the island (the mountainous interior, the coastal lowlands, and the karst area). Size frequency percentages of measured SCL showed various distribution curves among sample sites (Figure 2). SCL from all individuals sampled (N = 150) ranged from 16–82 mm (Figure 2). The vast majority (91%, N = 136) of the crayfish captured were adults; only 14 juveniles were caught. Cidra and Güajataca had the highest observed juvenile numbers, with 5 individuals caught at both sites. A significant difference was found in the overall adult mean (juveniles omitted) SCL among sample sites ($F_{(4,134)} = 16.96$, $P < 0.001$), and a post-hoc test (Tukey-Kramer) indicated individuals in Carraízo to have the largest mean SCL (Figure 3). No significant difference in SCL was found between adult males (48.32 mm ± 1.62 SE) and females (48.17 mm ± 1.47 SE) ($F_{(1,134)} = 0.81$, $P = 0.37$), as well as between SCL within either sex among sample sites ($F_{(4,134)} = 0.84$, $P = 0.50$).

Plotting the relationship between SCL to dry-mass (Figure 4) produced a power equation ($M = 0.0057\ L^{3.4451}$; $R^2 = 0.971$) to estimate biomass for all individuals at sample sites. Individual biomass ranged from 22.3 to 80.0 mg. Significant variation in overall mean biomass was observed among sample sites ($F_{(4,145)} = 15.59$, $P < 0.001$), with crayfish collected at the Carraízo reservoir having the highest overall mean biomass (9.713 ± 1.090 mg; mean ± SE), followed by individuals collected in Caribe Fisheries, Cidra, Carite, and Güajataca reservoirs, respectively (Figure 5). Furthermore, no differences in biomass were found between crayfish collected at Carite, Caribe, or Cidra. However, crayfish collected at Caribe Fishery had a significantly greater biomass than Güajataca.

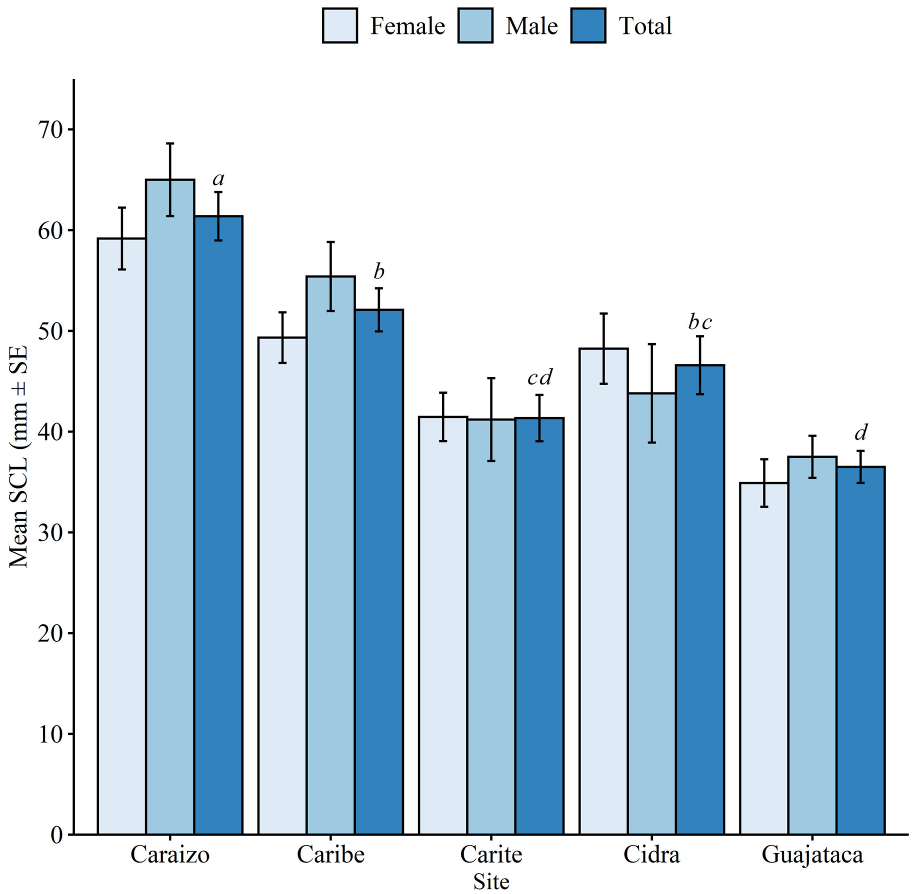

Figure 3. Mean individual size as standard carapace length (SCL ± SE) of redclaw crayfish collected at each sampling location. Estimates are presented for all individuals collected (overall), as well as for males and females separately. Significant differences in overall SCL among sample sites (P < 0.0001) post hoc test (Tukey-Kramer) are depicted by different italicized letters.

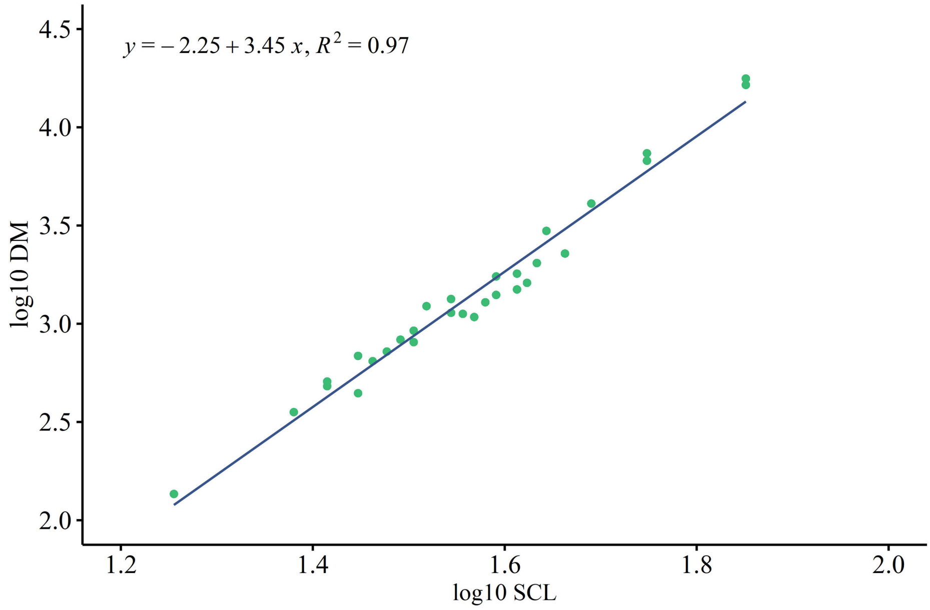

Figure 4. Relationship between standard carapace length (SCL; mm) and Dry-Mass (DM; mg) of redclaw crayfish collected across all study locations (N=150).

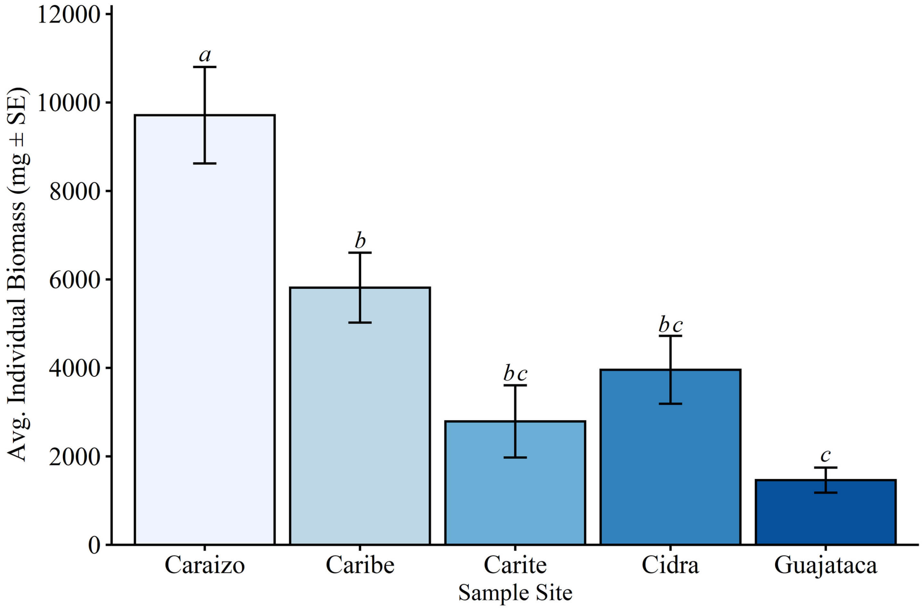

Figure 5. Mean individual biomass estimate per sample site using the power equation ($M = (0.0057) L^{(3.4451)}$). Significant differences in mean individual biomass among sample sites ($P < 0.0001$) post hoc test (Tukey-Kramer) are depicted by different italicized letters.

Discussion

The results of this study are the first to document the presence throughout a wide area and the length-mass relationship of redclaw crayfish established on the island of Puerto Rico. Although introduction of redclaw (Williams et al. 2001) and the presence of established populations had already been reported for parts of the island (Garcia-Vazquez 2008), our study is the first to document an established population at the Güajataca reservoir, a site in the northwest region of the island where it had not previously been reported. This supports the potential for redclaw to be expanding their previously documented range, a possibility which had been suggested by the Puerto Rico Department of Natural and Environmental Resources (Williams et al. 2001). However, no redclaw were collected at two of our sampling locations (Dos Bocas, El Guineo) near the mountainous interior of the island, despite what appears to be favorable conditions (e.g., temperature, pH).

Many studies have documented life history attributes, such as growth rates, of redclaw, as it pertains to aquaculture practices (Gu et al. 1995; Barki et al. 1997; Jones et al. 2000; Meade et al. 2002; McPhee et al. 2004; Naranjo-Paramo et al. 2004; Tropea et al. 2010). It is common within aquaculture to monitor growth, biomass, and production through measuring morphometrics of individuals. Developing a species specific relationship between length and dry mass of collected specimens over a wide range of size classes will eliminate error caused by varying water mass and allow for a more accurate measurement regime. Moore et al. (2013) emphasizes the lack of life-history studies conducted on crayfish native to USA and Canada; however, this lack of knowledge can also be expanded for crayfish introductions. Power functions developed from length-mass relationships provide a standardized method in estimating biomass of not only introduced redclaw, but of crayfish in general (Benke et al. 1999; Moore et al. 2013).

Multiple studies have documented the establishment of redclaw outside of its native range (Williams et al. 2001; Ahyong and Yeo 2007; Bortolini et al. 2007; Jaklic and Vrezec 2011; Marufu et al. 2014; Tyser and Douthwaite 2014; Pienkowski et al. 2015). Introduction of redclaw outside of its native range is predicted to increase due to increased harvesting for aquaculture, the ability to be easily reared in outdoor ponds, and tolerance of stressful environments (Jones et al. 2000; Doupe et al. 2004; Larson and Olden 2013). Our length-mass relationship will be useful for a rapid conversion into dry mass per m^2 when monitoring introduced populations from length measurements taken in the field. Estimating biomass, as compared to measuring absolute or relative abundance, provides a better measure of the energetic resources available for use in higher trophic levels (Jackson and Britton 2014). Estimating biomass in tangent or in lieu of absolute abundance provides a better representation of energy availability for higher trophic pathways within a system (Benke et al. 1999; Sousa et al. 2013; Jackson and Britton 2014). Our equation will also be useful for further inquiry into life history changes associated with introduction events (Doupe et al. 2004; Garcia-Vazquez 2008; Pattillo 2010).

Doupe and colleagues (2004) assessed possible predation pressures which could be influencing invasion success of an established population of redclaw within Lake Kununurra located in Western Australia. Researchers wanted to document direct predation of redclaw by various recreational fish species present within the lake. Diet analysis of 19 fish species revealed that redclaw only contribute a relatively low amount (4–8%) to overall gut content. The authors concluded that the redclaw density within Lake Kununurra could also be low and any predation by fish species could be purely opportunistic. These results do indicate evidence of direct predation, although relatively low levels, from fish species within the introduced range of redclaw. Our length-mass equation for redclaw biomass could be used within systems like Lake Kununurra to estimate how much energy reserves from crayfish mass may be readily available for transference to higher levels of the food web.

Redclaw populations within reservoirs on the island of Puerto Rico may be utilized as a food resource and could be beneficial for recreational fisheries. Pienkowski et al. (2015) provides evidence that redclaw are an important fishery in Jamaica and is a substantial source of income during periods when catches of native decapod shrimp decline. Pienkowski et al. (2015) concluded that redclaw provided approximately 15% of total catch value for fishermen, a significant portion of fishermen's gross revenues. The authors made personal observations that redclaw was being caught by local fisherman which suggests that small scale fishing efforts for invasive crayfish could continue to be observed when native decapod catches decline in reservoirs and has yet to be explored. Our predictive model could provide rapid and useful information for the amount of redclaw biomass available for utilization as a recreational fishery species or inquiry into the ecological impacts of redclaw on Puerto Rico and abroad.

The existence of redclaw populations in reservoirs throughout multiple watersheds across the island supports the need for further assessment of their populations throughout other waterbodies. As a follow-up to previous reports (Williams et al. 2001; Garcia-Vazquez 2008), our data suggest that introduced redclaw populations are growing and spreading, as other introduction events may be taking place and they continue to find a niche and become established. If this trend continues, redclaw has the potential to become a significant part of the aquatic ecosystem in terms of structure and function. Future studies should focus on directly assessing the ecological role that these introduced crayfish are playing and how redclaw are affecting local ecosystem processes and food web dynamics.

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