Population and Community Dynamics of Freshwater Decapods in Response to Ecological and Anthropogenic Factors in Subtropical Streams in the Caribbean

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POPULATION AND COMMUNITY DYNAMICS OF FRESHWATER DECAPODS IN
RESPONSE TO ECOLOGICAL AND ANTHROPOGENIC FACTORS IN
SUBTROPICAL STREAMS IN THE CARIBBEAN

by

Omar Pérez-Reyes

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

of

DOCTOR OF PHILOSOPHY

in

Ecology

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UTAH STATE UNIVERSITY
Logan, Utah

2015
ABSTRACT

Population and Community Dynamics of Freshwater Decapods in Response to Ecological and Anthropogenic Factors in Subtropical Streams in the Caribbean

by

Omar Pérez-Reyes, Doctor of Philosophy
Utah State University, 2014

Major Professor: Dr. Todd A. Crowl
Department: Watershed Sciences

Streams have been impacted by human activities in a variety of ways. Over time, these ecosystems become dominated by the most resilient species, with significant losses in the natural components that provide valuable ecosystem services to people. In impacted streams, the loss of ecosystem services often is not recognized until the stream has already been dramatically altered. In this study, I provide data on the natural distribution of freshwater decapods and the status of decapod communities in streams with different land use histories.

I reviewed the decapod distribution for the Caribbean to provide an update of the species that inhabit the freshwater systems. I determined the presence of 18 species of decapods in Puerto Rico and concluded that these decapods follow the island-species relationship in the Caribbean. Also, I present data associated with decapod community dynamics in watersheds with different urban development. As, expected the highly urban watershed had lower diversity and density of decapods than the medium and low urban watersheds. The variations in decapod communities among watersheds correlated with the degradation of the physical-chemical environments and clearing of the riparian zones. I compare the food webs among streams with different human impacts. Specific influences of point/nonpoint sources of N could be
distinguished in food web components. This shows to an effect of human activities on the stream and watershed. In addition, I determined the effect of abiotic and biotic factors on the growth of *A.lanipes* (0.27 mm) and *X.elongata* (0.1 mm) over the 10-year period of study. The results showed that these species transform a wide range of organic materials into their biomass. Finally, I developed a series of education projects which promote the understanding and knowledge of freshwater ecosystems; interactions and the organisms that inhabit these systems. The results showed an increasing interest about freshwater fauna and ecosystems.

I concluded that: a) the distribution of freshwater decapods in the Caribbean islands follows the area-species relationship; b) urbanization represents one of the many distinct land uses that affect habitat structure, energy sources and biotic interactions; and c) it’s necessary to present the results of our research to the general public in ways that are easily understood.

(193 pages)
PUBLIC ABSTRACT

Population dynamics of the freshwater decapods in response to ecological and anthropogenic factors in subtropical Puerto Rican streams: A Caribbean perspective

Omar Pérez-Reyes

Historically, cities were established in close proximity to the richest agricultural lands and freshwater resources. In tropical islands, urbanization occupies a large percentage of land use along streams and rivers and strongly affects the biota and habitat quality. I studied freshwater decapod population and community dynamics in tropical streams of Puerto Rico across human and elevational gradients. I found that: 1) streams with less urbanization had higher decapod species richness and population sizes than the highly urbanized streams; 2) changes in the food webs in the streams are the result of the influence of changes in land use and environmental conditions in their watersheds; 3) *Atya lanipes* and *Xiphocaris elongata* marked and measured bi-annually over a 10 year period have a relatively long lifespan (over 15 years) and slow growth rates (*Atya* grew an average of 0.27 mm per year while *Xiphocaris* only 0.1 mm per year). In order to present the results of our investigations in the Luquillo Forest, we developed an education plan which includes web sites, field exercises, and training program for teachers and students. The results suggested that ecological education and outreach efforts should explore the use of available and trusted methods of dissemination to supplement and encourage use of the internet as a reliable source of information. I conclude that changes in land use have a direct impact on streams components and in the terrestrial corridor near the water body. Alterations of these components can increase the erosion of the stream banks, sedimentation and water flow that impacts the habitat, abundance, diversity and life cycle of organisms in the stream.
DEDICATION

I dedicate my dissertation work to my family and friends.

I want to extend a special feeling of gratitude to my parents,

Ramón Pérez-Vega and Hipólita Reyes-Nieves,

my brother Ramón A. Pérez-Reyes and sister Jessica Pérez-Reyes.

whose words of encouragement led me in this new step.

I also dedicate this dissertation to my many friends

(Fernando A. Villar-Fornes, Francisco J. Pérez-Rivera, and Gladys Nazario) who have

helped me throughout the research process.
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CHAPTER 1
INTRODUCTION

Urbanization represents one of the distinct land uses that disproportionately affect streams. Increases in human population size have often generated an urban sprawl that results in increased pollution, depletion of water resources, and destruction of wilderness and wildlife habitats. Transition from forested to urban landscapes represents a significant threat to sustaining functions of stream ecosystem.

Urbanized streams have been impacted, modified, and often degraded by human activities in a variety of ways. Over time, these freshwater ecosystems become dominated by the most resilient species, resulting in the loss of many natural components that provide valuable ecosystem services to people. In urban and sub-urban streams, the loss of freshwater ecosystem services often is not recognized until the stream has already been dramatically altered or impacted. Numerous anthropogenic stressors and their effects on streams have been identified: channel modification; loss of riparian vegetation; water withdrawal; addition of alien taxa; changing land use; and pollutant generation (Paul and Meyer 2001). These stressors directly impact the physical integrity (loss of large woody debris, canopy opening, stream hydrology, geomorphology, and sedimentation), the physiochemical elements (nutrient enrichment, contaminant pollution, water quality and toxicity) and the biological components (biotic interactions, habitat structure, energy source, and alterations in trophic structure) of the stream (Booth and Jackson 1997, Meyer et al. 2005). As a result, these stressors change the ecological integrity (removal of native species and decline in abundance and richness of macro-invertebrates) and ecosystem services (variation of ecosystem processes and trophic structure that affect water quality); this characteristic pattern is termed the “Urban Stream Syndrome” (Walsh et al. 2005).
The effects of watershed land use on streams and rivers are well-documented and these alterations produced a community structure, sometimes totally or partially degraded, that is significantly different from previous conditions or from similar un-degraded streams. Recent studies have illustrated these effects. For example, there is often a reduction in shade from removal of riparian forest that increases water temperature, promoting algal growth in the stream (Allan 2004). Riparian clearing also decreases bank stability, input of organic matter and increases channel erosion. Other consequences of the removal of land cover are that the soil surface becomes more compacted and impervious, the infiltration decreases and the surface runoff increases. In addition, sedimentation increases turbidity, scouring, abrasion, and changes in the substrate that leads to changes in periphyton and biofilm production, an important food source for most stream communities. The impervious surfaces transport fertilizers and contaminants directly into the streams where the excess nutrients increase the algae production. Contaminants impact the fauna through deformities, disruption of internal systems, and ultimately, mortality rates.

Diverse studies have shown negative relationship among stream communities and land use. Larger deforested patches in the riparian forest have been associated with a decrease in abundance of benthic-dependent species that have been replaced by sediment-tolerant and/or exotic species. Long-term studies have shown the impacts of urbanization on stream through: 1) decreases in the abundance and species diversity; 2) removal of sensitive species and increases in more tolerant species; 3) greater flood frequencies. The magnitude of land use influences on these characteristics depends on slope, soil type, and riparian vegetation of the watershed (Paul and Meyer 2001).

Aquatic insects are the most widely used group of organisms in biomonitoring studies (Allan 2004). Their importance resides in their sensitivity to represent changes in the environment. Moore and Palmer (2005), Cuffney et al. (2010), among many others have
demonstrated a strong relationship between the catchment land cover and the stream biota; taxa richness, abundance and diversity decrease in stream with low riparian forest cover. A decrease in invertebrate diversity can be explained by diverse factors such as: habitat loss (sedimentation and loss of woody debris); pollution and chemical contamination (nutrient inputs from agriculture in riparian zones, toxins and reduction in dissolve oxygen concentration) (Allan 2004); and replacement of species (shifts and eliminates important species in the food web for non-necessary ones) (Sudduth and Meyer 2006).

This study had 5 objectives. In the first chapter, I describe the distribution of freshwater decapods in Puerto Rico and the Caribbean. In Chapter 2, I examined changes in decapod assemblages, water quality, and habitat quality along two streams with varied land uses and one forested stream that served as a reference stream. I predicted that decapod diversity and abundance would be greater in streams within high percentages of forest cover compared to sites with limited forest. In Chapter 3, I evaluated the decapod and fish communities in forested and urban streams in Puerto Rico in order to compare food webs from streams with different degrees of human impact. I hypothesized that the effects of anthropogenic stressors on freshwater food webs would be less dramatic in forested streams compared to urban ones. In Chapter 4, I reported the growth rates of marked shrimp in the headwaters of the Luquillo Mountains. Comparisons in growth were observed in long-term changes under natural conditions, in response to hurricane-driven disturbances, temperature, and seasonal inputs of leaf litter. Finally in Chapter 5, I proposed and developed some educational tools (e.g., web sites, workshops, field activities) to present the ecological information derived from research in Luquillo Experimental Forest to the general public.
LITERATURE CITED


CHAPTER 2
FRESHWATER DECAPODS OF PUERTO RICO: A CHECKLIST
AND REPORTS OF NEW LOCALITIES

Abstract
An updated checklist of the freshwater decapod fauna of Puerto Rico is presented based on records of shrimp and crab species whose presence has been confirmed in Puerto Rico as a result of extensive field collections, examination of carcinological collections, literature review, and personal communications from researchers. The freshwater decapod fauna of Puerto Rico consists of 18 species of shrimp belonging to eight genera and three families, and one species of crab belonging to the family Pseudothelphusidae.

Introduction
The freshwater decapod fauna of Puerto Rico is relatively well known for their role in the ecological process as shredders and for nutrient cycling (Crowl et al. 2001). However, relatively little work has been done on shrimp and crab diversity, distribution and inventory in a systematic way in Puerto Rico.

Juan Gundlach (1887) reported many species of decapods on the island but Schmitt (1935) in the Scientific Survey of Porto Rico and the Virgin Island, was the first to report the presence of freshwater decapods. Macrobrachium acanthurus (Weigmann), M. carcinus as “Periclimenes portoricensis” (Linnaeus 1758), and M. faustinum (De Saussure), Xiphocaris elongata (Guérin-Méneville), Atya scabra (Leach, 1815), A. innocuous (Herbst) and Micratya poeyi (Guérin-Méneville) were reported by Schmitt. In 1954, Chace reported the first troglobitic

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1 Coauthored by Omar Pérez-Reyes, Todd A. Crowl, Pablo J. Hernández-García, Ricardo Ledesma-Fusté, Fernando A. Villar-Fornes, and Alan P. Covich
Typhlatya has been reported in caves on Mona Island, Guánica Dry Forest-Puerto Rico, Dominican Republic, Curacao, Barbuda and Lesser Antilles (Debrot 2003). In 1967, Vélez made the first checklist of freshwater and terrestrial decapods of Puerto Rico and reported the presence of *Atya innocuous* as “*A. occidentalis*” and *Atya scabra* as “*Atyia scabra*”. Based on their own collections in 1964-1966 and material provided by others, Chace & Hobbs (1969) documented distribution, ecology and taxonomy of the freshwater decapods of the Caribbean; but they did not identify the precise location or collection date of the specimens. Canals (1977; 1979) reported collecting specimens of *Macrobrachium crenulatum* (Holthuis) in the Espíritu Santo River and classified this location as the only one in the island for this shrimp. Villamil and Clements (1976) working in the same river described the ecology and distribution of the freshwater shrimp in the upper parts of the river. In their report, Villamil and Clements concluded that some species of atyids showed intra-specific habitat selection based on water flow, type and size of the substrate. The effects of abiotic factors on distribution and development of palaemonids were studied by Santiago (1979), and Ching and Vélez (1985).

Hobbs and Hart (1982) did a comprehensive analysis of the distribution, taxonomy and classification of the *Atya* genus globally. Their report of *Atya* included the three species of *Atya* present in Puerto Rico: *A. lanipes*, *A. innocuous* and *A. scabra*, but the report was incorrect in relation to the locations for these shrimp in the island. They reported these species only in 10 streams and rivers around the island.

lanipes at the Luquillo Experimental Forest and associated the egg production with high flows and high food availability. Pérez-Reyes (1999) in his work regarding the abundance, diversity and life histories of freshwater decapods in Puerto Rico, concluded that there were no differences in species diversity, fecundity and density in rivers that flow through different ecological life zones. In addition, Pérez-Reyes reported new localities for Macrobrachium crenulatum Tanamá, Cerrillos, Loco and Camuy rivers. The upstream migration of Xiphocaris elongata, Macrobrachium spp., and Atya spp. was studied by Kikkert (2009) at the Espiritu Santo River. He reported that massive migration occurs at night and when the water flow is minimal. New records on Potimirim and a new species of Micratya were reported by Holmquist et al. (1998) (Potimirim glabra Kingsley 1878) and Pérez-Reyes (1999; 2010 unpublished data) (Potimirim americana Guérin-Méneville 1855), and Karge et al. (2013) (Micratya cooki) respectively. Recently a new Potimirim species from the Guayanes River in the municipality of Yabucoa was discovered by Fernando Mantelatto, they are working in the molecular and morphological description (F.Mantelatto pers. com.).

The endemic potamonid crab, Epilobocera sinuatifrons (A.Milne-Edwards, 1866) was described by Milne-Edwards (1866) and Rivera (1996), who when describing the distribution of this freshwater crab found that Epilobocera occurs in all kinds of habitats, elevations and environments. The distribution of the Buruquena in the Luquillo streams was studied by Zimmerman and Covich (2003) reporting that the distribution and abundance of Epilobocera correlated with the physical habitat (pool depth, volume, high water velocity, substrate type and size, and high water flow) and previous use of the forest. The growth rate and diets of this freshwater crab were described by Fraiola (2004). He found that E. sinuatifrons feeds on a wide variety of plants and animals in the stream and in the riparian forest, where the growth rate was limited to 0.02 mg mg⁻¹ per day, and that they reached reproductive maturity in their 7th year. The
genetic status of *E. sinuatifrons* was described by Cook *et al.* 2008a. They reported that the populations are differentiated among rivers but have a natural history to be recently derived, since these species have not experienced population expansions or bottlenecks.

Knowledge of freshwater decapods diversity in the Caribbean has increased rapidly in recent years as a result of studies that describe their role in aquatic ecosystems, as part of the food chain and as recyclers of organic material. The most recent works and the long term experiments on the ecology of the freshwater decapods from Puerto Rico have been done at Luquillo Experimental Forest. The research has focused on the ecological interactions of the decapods with other species (Pringle *et al.* 1993; 1996; Crowl & Covich 1994; Johnson *et al.* 2000; March *et al.* 1998; 2002; Cook *et al.* 2008b; Covich *et al.* 2009; Hein *et al.* 2010), the effects of natural (Covich *et al.* 1991; 1996; 2003; 2006) and anthropogenic disturbances on the populations (Benstead *et al.* 1999; 2000; Greathouse *et al.* 2005; 2006; Hein *et al.* 2010; March *et al.* 1998; 2003), and in the nutrient recycling importance for the species (Pyron *et al.* 1999; March *et al.* 2001; March & Pringle 2003; Wright & Covich 2005; Covich & McDowell 1996, Crowl *et al.* 2001; 2006; Cross 2008; Benstead *et al.* 2010).

The goal of this study is to contribute knowledge of the freshwater decapod fauna found in the Puerto Rico archipelago describing their distributions, and to clarify which are the valid shrimp and crab species in the island. The list contained herein is a comprehensive list of the decapod fauna found in Puerto Rico based on a revision of previously published data, museum collections, personal collections and research. Additionally, in this study a newly taxonomic key, distribution maps and recorded species have been added to the information of the freshwater decapod fauna of the island. Representative specimens were deposited in the Zoology Museum at the University of Puerto Rico, Río Piedras Campus, Museo Nacional de Historia Natural de República Dominicana and in the reference collection at El Verde Field Station, University of Puerto Rico.
Study Area

The Archipelago of Puerto Rico is located in between the Atlantic Ocean and the Caribbean Sea and comprises 3 inhabited islands; Puerto Rico, Vieques and Culebra, 4 natural reserve islands (Mona, Monito, Desecheo, and Caja de Muerto) and more than 100 cays. With an area of 9,104 km$^2$, Puerto Rico is the third largest island in the United States. Six ecological life zones have been described for Puerto Rico and ranging from dry to rain forest (Ewel & Whitmore 1973; Helmer et al. 2002). Subtropical Lower Montane Rain Forest occupies the smallest area with 12.3 km$^2$ while the Subtropical Moist Forest is the prevailing life zone, covering more than 5,482 km$^2$ (Ewel & Whitmore 1973; Helmer et al. 2002). Numerous rivers and streams flow down from the mountains of the Cordillera Central but only 41 reach the coastal plains; rivers from the north coast are larger, with tranquil waters, and have higher flow capacity in comparison to the southern rivers that have extensive drought periods. The characteristics present on each river, in combination with the conditions of the ecological life zones, provide the environment for diverse mesohabitats that the different species of decapods can exploit.

Material and Methods

The following list is based on preserved specimens for most species. Sporadic collecting was mainly undertaken from 1970–2011. Decapods were sampled by hand using aquatic nets, minnow traps or electroshocker. The material collected was identified by one of us (OPR) and is housed in the Zoological Collections of the Biological Museum at the University of Puerto Rico, Río Piedras Campus and El Verde Field Station, University of Puerto Rico, Río Piedras Campus. In addition, parts of the data that formed the basis of the checklist were obtained from the literature cited in the introduction and collections at the National Museum of Natural History, Smithsonian Institution, and Museum of Comparative Zoology of Harvard University.
Nomenclature, classification and common name (McLaughlin et al. 2005) of taxa follows the Chace and Hobbs (1969), Chace (1972), Holthuis (1980), Hobbs and Hart (1982) descriptions. Some common names are derived from the native Taíno languages or local fisherman.

**Results and Discussion**

A total of 18 species of freshwater decapods from 4 families were found to inhabit the freshwater systems of the Puerto Rico Archipelago (Table 2-1; Fig. 2-1, 2-2, and 2-3). The families represented include Atyidae (10 taxa or 56% of the biota), Palaemonidade (6 taxa or 33%), Xiphocarididae (1 taxa or 5%), and Pseudothelphusidae (1 taxa or 5%) (Table 2-1). Three species of shrimp, *Potimirim glabra*, *Potimirim americana*, and *Palaemon pandaliformis*, are new records for the island. *Micratya cooki* represents the new species for Puerto Rico.

The diversity of freshwater carcinological fauna is expected for an island of its size (Table 2-2; Fig. 2-4), although the list is expected to grow with more intensive surveys, particularly in the estuarine portions of the rivers and subterranean streams in the karst area of the island. Decapod species richness and composition of the area surveyed suggest healthy stream environments. The diversity here reported is comparable to that of Hispaniola (Pérez-Gelabert 2008), which has 19 taxa reported and Jamaica with 21 species of freshwater decapods (Schubart & Koller 2005). Detailed examination indicates that the species-area relation among the Greater and Lesser Antilles results because larger islands have more number and diverse habitats in contrast with the smaller ones (Losos & Losos 1996). The diversity of the freshwater decapod group in the Caribbean Archipelago tends to be controlled primarily by the size of the island and the dispersion of the organisms. Habitat and vegetation types in the Lesser Antilles are primary catalogued as xerophytic and mesophytic, only Guadeloupe, Dominica, Martinique and St. Lucia (Isaac & Bourque 2001) have abundant rainfall and higher densities of streams and rivers capable
to sustain hydrophytic vegetation and abundant freshwater fauna (Ricklefs & Lovette 1999). Similar distribution, diversity and abundance has been observed in lizards (*Anolis*) (Losos & Losos 1996; Losos & Schluter 2000), birds (*Coereba*) (Ricklefs & Lovette 1999; Ricklefs 2000), bats (Ricklefs & Lovette 1999), butterflies (*Heliconious* & *Dryas*) (Davies & Spencer-Smith 1998; Ricklefs & Lovette 1999; Davies & Bermingham 2002) (McDowell et al. 2012). The life cycle histories of these species influence the distribution and abundance through the Caribbean Archipelago. All freshwater shrimp in the Caribbean exhibit an amphidromous life cycle where adults reproduce in the high elevation sections of the stream and the larvae need to spend time in the estuary until metamorphose and migrate to the upper locations of the freshwater bodies. This results in a common species pool in the estuaries and the sea capable to colonize and migrate among the islands.

Freshwater decapods were found across all ecological life zones, with the richest systems (Río Bayamón, Río Mameyes and Río Sabana) were located in the north part of the island or in the Subtropical Moist Forest. What is more significant, however, is the presence of all the seventeen native species in most of the rivers specifically in the highly forested streams of El Yunque National Forest (Río Mameyes, Río Sabana & Río Espíritu Santo) and in the highly urbanized Río Bayamón (Table 2-1; Fig. 2-2 & 2-3). The relatively rich and unaltered environment, presence of organic matter, longitudinal connectivity and the physical-chemical variables may provide the conditions for which these streams are important areas for the conservation of these aquatic animals.

Although this checklist is richer in Atyidae and Palaemonidae species than previously reported by Vélez (1967) and Chace and Hobbs (1969); the reports by Holmquist *et al.* 1994, Pérez–Reyes (1999), and Kwak *et al.* 2007, which were largely from field collections, appear to reveal a bias towards big and larger species.
Checklist of freshwater decapods species collected in Puerto Rico.

Family **ATYIDAE**

Genus *Atya* Leach, 1816

1. *Atya scabra* (Leach, 1815) - Gata shrimp, camacuto shrimp, Gata, Guábara
2. *Atya innocuous* (Herbst, 1792) - Basket shrimp, Gata, Guábara
3. *Atya lanipes* Holthuis, 1963 – Spinning basket shrimp, Guábara

Genus *Jonga* Hart, 1961a

1. *Jonga serrei* Hart, 1961a– Estuarine tiny basket shrimp, Guabarita

Genus *Micratya* Bouvier, 1913

1. *Micratya poeyi* Bouvier, 1913 - Caribbean dwarf filter shrimp, Guabarita

Genus *Potimirim* Holthuis, 1954

1. *Potimirim americana* (Guérin-Méneville, 1855) – American potimirim, Guabarita
2. *Potimirim mexicana* (De Saussure, 1857) – Mexican potimirim, Guabarita
3. *Potimirim glabra* (Kingsley, 1878) - Smooth potimirim, Guabarita

Genus *Typhlatya* Creaser, 1936


Family **XIPHOCARIDIDAE**

Genus *Xiphocaris* Ortmann, 1895

1. *Xiphocaris elongata* (Guérin-Méneville, 1856) - Yellow-nose shrimp, Salpiche, Piquines
Family **PALAEMONIDAE**

Genus *Macrobrachium* Bate, 1868

1. *Macrobrachium carcinus* (Linnaeus 1758) – Painted river prawn, Big claw river shrimp, Camarón Palancú
2. *Macrobrachium acanthurus* (Wiegmann, 1836) - Cinnamon river shrimp, Tuberculoso
3. *Macrobrachium heterochirus* (Wiegmann, 1836) - Cascade river prawn, Camarón Palancú
4. *Macrobrachium faustinum* (De Saussure, 1857) - Caribbean long arm shrimp, Zurdito, Camarón Bocú

Genus *Palaemon* Weber, 1795

1. *Palaemon pandaliformis* (Stimpson, 1871) - Grass shrimp, Potitinga shrimp

Family **PSEUDOTHELPHUSIDAE**

Genus *Epilobocera* Stimpson 1860

1. *Epilobocera sinuatifrons* (A. Milne-Edwards, 1866) - Puerto Rican freshwater crab, Buruquena (Taino name), jaiba
Taxonomic Key for the Atyidae and Xiphocarididae families in Puerto Rico
(Modified from Chace & Hobbs 1969; Chace 1972)

1 Chelae of first and second pereiopods without tufts of long hairs at ends of fingers

**XIPHOCARIDIDAE ... Xiphocaris elongata**
- Chelae of first and second pereiopods with tufts of long hairs at ends of fingers **ATYIDAE...2**

2 Eyes reduced, cornea limited to distolateral pigment spot on eyestalk; subterranean species ...

*Typhlatya monae*
- Eyes normal, cornea nearly as broad as or broader than eyestalk; pereiopods without exopods …

3

3 Compressed rostrum with teeth on the dorsal margin ... 4

- Depressed rostrum without teeth on the dorsal margin ... 5

4 Appendix masculina with spinulation near the distal end, tip of appendix interna does not reach the spinulated part of the appendix masculine ... *Micratya poeyi*

- Appendix masculina with spines extending more proximally, tip of the appendix interna reaches the spinulated part of the appendix masculine ... *Micratya cooki*

5 Carpus of second pereiopod broader than long ... 6

- Carpus of second pereiopod much longer than broad ... 8

6 Adults without horizontal lateral lobe or tooth on either side of rostrum; third pereiopod not bearing horny scales or tubercles and only slightly more robust than fourth pereiopods ... *Atya lanipes*

- Adults with distinct horizontal lateral lobe or tooth on either side of rostrum; third pereiopod bearing prominent horny scales or tubercles and considerably larger and more robust than fourth pereiopods ... 7

7 Lateral lobes of adult rostrum obtuse; pleuron of second abdominal somite without blunt marginal spines although pleura of third to fifth somites may bear acute marginal denticles …
Atya innocuous

- Lateral lobes of adult rostrum subacute and directed anteriorly; ventral margins of pleura of second to fifth abdominal somites armed with row of small blunt spines … Atya scabra

8 Orbital margin minutely serrate; appendix masculina on second pleopod of male slender, terminating in sharp point … Jonga serrei

- Orbital margin not serrate; appendix masculina on second pleopod of male broad, rounded distally … 9

9 Appendix masculina widening distally, about three-fourths as wide as long, posterior margin slightly and evenly convex … Potimirim americana

- Appendix masculina widest proximally, not more than half as wide as long, posterior margin sinuous ... 10

10 Dorsal margin of rostrum curving downward at tip; appendix masculina with deep, unarmed sinus in posterior margin … Potimirim glabra

- Dorsal margin of rostrum nearly straight; appendix masculina without deep, unarmed sinus in posterior margin … Potimirim mexicana
Taxonomic Key for the Palaemonidae family in Puerto Rico
(Modified from Chace & Hobbs 1969; Chace 1972)

1 Carapace with two spines on anterolateral margin, antennal and branchiostegal … *Palaemon* *(Palaemon) pandaliformis*
   - Carapace with hepatic spine on lateral surface and with no more than one spine on anterolateral margin, branchiostegal and rarely antennal spines absent; rostrum with ventral teeth … 2

2 Rostrum long, unramed throughout dorsal length, posterior tooth usually separated from second by distance greater than that between second and third, usually reaching beyond end of antennal scale, with 5-11 dorsal teeth, no more than 2 of which originate on carapace posterior to level of orbital margin; second pereiopod of adult male spinulose, carpus shorter than chela, fingers densely furred … *Macrobrachium acanthurus*
   - Rostrum short, reaching at most slightly beyond end of antennular peduncle, with 10-15 dorsal teeth, at least 4 of which originate on carapace posterior to level of orbital margin; second pereiopods robust, chela less than seven times as long as broad … 3

3 Rostrum with sinuous dorsal margin, tip slightly upturned; second pereiopods of adult subequal in form but not in size, with short pubescence and short spines along outer margin of fixed finger and continued onto palm, but spines not forming distinct crest and not hidden by pubescence … 4
   - Rostrum with nearly straight dorsal margin, tip not upturned; second pereiopods of adult unequal in both form and size with dense long fur partially concealing crest-like row of long spines on margin of palm … 5

4 Posterior teeth of dorsal rostral series not especially erect or noticeably more widely spaced than others; second pereiopods of adult subequal, carpus shorter than merus and about half as long as palm, fingers only slightly shorter than palm, prominent tooth near end of proximal third of opposable margin of fixed finger … *Macrobrachium carcinus*
   - Three or four posterior teeth of dorsal rostral series more erect and more widely spaced than
anterior ones; second pereiopods of adult usually unequal in length, major one with carpus about as long as merus and about three-fourths as long as palm, fingers about two-thirds as long as palm, none of teeth on opposable margin of fixed finger greatly enlarged … Macrobrachium heterochirus

5 Major second pereiopod of adult male with carpus usually longer than merus and fingers distinctly longer than palm, row of spines along mesial margin of palm and fixed finger rather long on proximal portion of palm, becoming shorter near middle of palm, longer near base of finger, and decreasing again distally on finger … Macrobrachium faustinum

- Major second pereiopod of adult with carpus shorter than merus and fingers slightly longer or slightly shorter than palm, row of spines along mesial margin of palm and fixed finger forming regular series, not decreasing in length along middle portion of palm … Macrobrachium crenulatum

Pseudothelphusidae
(Modified from Chace & Hobbs 1969)

Carapace not very convex longitudinally or transversely, broad, less than three-fifths as long as wide; cervical groove distinct, concave forward; anterolateral margin denticulate, marked by two obscure notches, one at end of cervical groove, one near outer orbital angle; front delimited dorsally by strong transverse crest hiding entire true frontal margin from dorsal view. Third maxilliped with merus subquadrate, lateral margin feebly convex, distal margin somewhat concave; exopod extending beyond ischiomeral articulation. Pereiopods not unusually long or slender. Chela without prominent, swollen protuberance on outer surface near base of fingers ...

Epilobocera sinuatifrons
References


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Leach, W.E. (1815) A tabular view of the external characters of four classes of animals, which linn arranged under insecta: with the distribution of the genera composing three of these classes into orders, and descriptions of several new genera and species. *Transactions of the Linnaean Society of London*, 11, 306-400.


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Caribbean Journal of Science, 7, 41-44.


Table 2-1  Distribution of the 18 freshwater decapod species sampled at the 43 freshwater bodies (rivers, streams, rivulets, and caves) in Puerto Rico.

<table>
<thead>
<tr>
<th>Species</th>
<th>Atya lanipes</th>
<th>Atya innocua</th>
<th>Atya scabba</th>
<th>Janga varii</th>
<th>Macrobrachium pseudobrachium</th>
<th>Macrobrachium onsumim</th>
<th>Macrobrachium compressum</th>
<th>Macrobrachium faustinum</th>
<th>Palaemon pandaliformis</th>
<th>Xiphocaris elongata</th>
<th>Epilobocera sinuatifrons</th>
<th>Total Species/Location</th>
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Table 2-2  Antillean islands, area, and number of families, genera and species of freshwater decapods included in the study. Primary data sources for the decapod species presence in the studied Caribbean islands.

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- Bass 2004 a
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- Barnish 1984
- Thorpe and Lloyd 1999
- Rodríguez and López 2003
- Debrot 2003
- Bass 2005
- Hobbs and Hart 1982
- Felix 1991
- Bass 2003a
- Hobbs and Hart 1982
- Bass 2004 b
- Hobbs and Hart 1982
- Nemeth and Platenberg 2007
- Rodríguez and López 2003
- Hobbs and Hart 1982
- Hynes 1971
- Bass 2003 b
- Chace and Hobbs 1969
- Bass 2006
- Chace and Hobbs 1969
- Hobbs and Hart 1982
| Bermuda  | 53 | 3 | 3 | 3 | Chace and Hobbs 1969 |
Fig. 2-1 Geographic distribution of shrimp species from the family Atyidae sampled and reported for the major rivers of Puerto Rico and their tributaries. The number in the triangle represents the number of atyid species collected in the river. *Typhlatya monae* was recorded in caves from the Mona Island Reserve and in the xerophytic forest of Guánica. Numbers outside the map represent the number of rivers in the island.
Fig. 2-2 Geographic distribution of shrimp species from the family Palaemonidae sampled and reported for the major rivers of Puerto Rico and their tributaries. The number in the diamond represents the number of palaemonid species collected in the river. Numbers outside the map represent the number of rivers in the island.
Fig. 2-3 Geographic distributions of *Epilobocera sinuatiformis* and *Xiphocaris elongata* in the major rivers of Puerto Rico. Open triangles represent *Epilobocera sinuatiformis*, closed triangles represent *Xiphocaris elongata* and open-close triangles the occurrence of both species. Numbers outside the map represent the number of rivers in the island.
Fig. 2-4 Species-area relationships of freshwater decapods in the Antilles. Species richness of decapods as a function of island area shows a species–area (LN–LN) relationship with a slope of 0.264±0.05 ($R^2$=0.3908). Solid line represents the regression line for all islands in the Caribbean. Closed diamonds represent Lesser Antilles and open diamonds Greater Antilles.
CHAPTER 3

COMPARISON OF DECAPOD COMMUNITIES ACROSS AN URBAN-FOREST LAND USE

GRADIENT IN PUERTO RICAN STREAMS

Abstract

Urbanization influences a range of factors related to stream health, including the hydrologic regime, water quality, and riparian conditions that lead to negative effects on terrestrial and aquatic ecosystems. However, impacts on freshwater decapods from urbanization of tropical streams have not been reported. We hypothesized that changes in decapod communities in watersheds with different levels of urbanization are related to changes in physical stream habitats caused by different land uses and their effects on water discharge. The impacts of land use on the physico-chemical characteristics of streams and freshwater decapod communities were evaluated in three watersheds characterized by low, moderate and high-intensities of urbanization in Puerto Rico. For the low and moderately developed urban watersheds, decapod species richness ranged from 10-11 species; the highly urbanized watershed only had 4 species. *Macrobrachium faustinum* and *Xiphocaris elongata* were the most ubiquitously species and were found in all watersheds. Multivariable analysis of physical characteristics and densities of the decapod families resulted in one axis that explained 80% of the total variation among the watersheds and was correlated with stream discharge. The effect of discharge is likely a result of frequent high flows that sustain habitats with high concentrations of dissolved oxygen and low concentrations of pollutants. An increase in physico-chemical parameters were observed from the LUW to the HUW. These results indicate that the decapod communities were most likely influenced by land use and environmental conditions that affected erosional aspects related to water discharge and water quality in the highly impacted watersheds.

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2 Coauthored by Omar Pérez-Reyes, Todd A. Crowl, and Alan P. Covich
Keywords Atya, Epilobocera, Macrobrachium, species diversity, urban streams, Xiphocaris

Introduction

Urbanization can disproportionately affect flow regime (Walsh et al. 2012; Braud et al. 2013), water quality (Mallin et al. 2009; Line 2013; Wang et al. 2013), energy sources (Zeni and Cassati 2014), habitat (Engman and Ramírez 2012; Fogaca et al. 2013), and biotic interactions (Wenger et al. 2010; Kaushal and Belt 2012; McDonald et al. 2013). Collectively, changes in these aspects alter the stream health and modify ecosystem goods and services provided by biotic communities. Over time, freshwater ecosystems in urban watersheds generally become dominated by the most resilient species. These patterns are described as the “Urban Stream Syndrome” (Meyer et al. 2005; Walsh et al. 2005).

Tropical streams are rarely studied across urbanization gradients (Victor and Ogbeibu 1991; Buckup et al. 2007; Nemeth and Platenberg 2007; Zhang et al. 2010; Valle et al. 2013). Most previous studies in tropical streams have focused on terrestrial-aquatic interactions and the roles of diverse freshwater species in forested areas (Pringle et al. 1993; Covich et al. 1996; March and Pringle 2003; Crowl et al. 2001; Greathouse et al. 2006a, 2006b; Covich et al. 2009).

In general, abundance and species diversity decrease in streams with loss of riparian forest cover. Aquatic insects are most frequently used in stream biomonitoring studies to assess land-use impacts because of their sensitivity to changes. A strong relationship between watershed land cover and stream insect biota is well established (Chinnayakanahalli et al. 2011; Chadwick et al. 2012; Vander Laan et al. 2013). Although previous studies of Caribbean urban streams have evaluated species responses of aquatic insects to environmental changes (e.g., de Jesús and Ramírez 2011; Ramírez et al. 2012), none have focused on freshwater decapod community structure or their roles in urban stream ecosystems.
Tropical island streams, in contrast to continental streams, are often dominated by diadromous decapod species rather than by aquatic insects (Covich and McDowell 1996; Crowl et al. 2012). Caridean shrimp (Atyidae, Palaemonidae, and Xiphocarididae) and crabs (Grapsidae, Pseudothelphusidae) are potentially vulnerable to the physical and ecological effects of urbanization. A decrease in decapod diversity can result from: habitat loss (sedimentation and loss of woody debris); pollution and chemical contamination (nutrient inputs from agriculture in riparian zones, toxins and reduction in dissolved oxygen concentration); replacement of native species by exotics; and a decrease in allochthonous food resources that shift the trophic structure from allochthonous to autochthonous food resources and consumers. These decapod species (Atya, Macrobrachium, Xiphocaris and Epilobocera) influence primary production, leaf-litter breakdown, and the benthic community structure (Pringle et al. 1993; Covich et al. 1999; Crowl et al. 2001; Synder et al. 2011, Crowl et al. 2012). Moreover, these consumers are important food sources for predators including large species of freshwater shrimp and crabs, fish, aquatic birds, snakes and turtles (Hein et al. 2010).

The diadromous shrimp in this study have larval stages that complete their development in estuarine or marine environments. Consequently, these species are vulnerable at different stages of their complex amphidromous life cycle to a range of stressors such as low dissolved oxygen or toxins as well as fish, decapod and bird predators. Individuals grow, mate, and spawn in the river but the planktonic larvae develop in brackish estuaries or marine waters. After completion of larval metamorphoses, the post-larvae migrate upstream to the headwaters and migrate back to the headwaters to complete their life cycle (Benstead et al. 2000; Kikkert et al. 2009; Bauer 2011a, 2011b, 2013).

We hypothesized that species loss in watersheds with different degrees of urbanization would result because different taxa could be affected by changes in their habitat as consequence of the land use. We compared the freshwater decapod community composition among
watersheds with different urban land cover levels (low, moderate, and high) and between different periods of rainfall [Low Rainfall- (LRF) and High Rainfall- (HRF)]. We expected to find lower abundance and diversity of decapods in watersheds with a higher percentage of urban land cover than in watersheds with moderate and low urban impact because of lower water quality and high peak flows characteristic of most urban ecosystems. We also hypothesized that the effects of the low rainfall would further reduce the abundance and diversity of decapods in watersheds with moderate and high percentage of urban land use by exacerbating the physical and chemical effects of urbanization such warmer water and lower dissolved oxygen.

Material and Methods

Site selection and classification

Three watersheds that represent different gradients of human impact in Puerto Rico were selected to test our hypotheses. The Sabana, Bayamón and Río Piedras watersheds represent low, moderate and high levels of urbanization based on the percentage of urban cover, respectively (Fig. 3-1). The streams were classified by the percentage of urban land use in their watersheds based on the results obtained by the Puerto Rico Gap Project (Gould et al. 2008) (Fig. 3-2). The drainage areas for these watersheds were 10.3 km² in the low urban watershed, 108.3 km² for the moderate and 39.7 km² for the highly urban. In each watershed, three sampling sites were selected from the river mouth to the headwaters to maximize the diversity of habitat types (i.e. pools, runs, and riffles) in different land use settings. At each site, three, 10m sampling reaches were randomly selected to sample decapod communities and measure the physico-chemical data (9 sampling location across watersheds). All the sampling reaches were located downstream the reservoirs in the Bayamón and Río Piedras streams. The two small dams in the coastal valleys of Río Piedras and Río Bayamón do not represented a barrier or have any direct impacts on
freshwater species because they are inundated during floods and post-larval shrimp can migrate around and over these low dams (Fig. 3-1).

The Río Sabana watershed (with low level urbanization- LUW) is located in the northeastern portion of the Luquillo Experimental Forest (LEF), where there is little seasonal variation in rainfall. The river’s headwaters are located in the eastern portion of El Yunque National Forest (also known as the Luquillo Experimental Forest) and this watershed (28,000 ha) is managed by the U.S. Forest Service to sustain the riparian forest cover. The Puerto Rico Environmental and Natural Resources Department manages the suburban and urban reaches of this watershed (approximately 1,083 ha). Humans have impacted the meanders and valleys in the middle and lower watershed for hundreds of years (Thomlinson and Rivera 2000). The headwater portion of the Río Sabana watershed is dominated by patches of secondary forest with some sections considered primary forests (51 %) (Fig.3-2). The middle elevations have moderate densities of native and introduced trees in contrast with the lower sections where the valleys have high densities of non-native grasses and fruit trees. Non-native species are scarce in the forested sites but increase downstream to the urban reaches. Urban reaches (6.2 %) are characterized by riparian zones primarily composed of grasses where the most common species are Panicum aquaticum and Bambusa vulgaris rather than forested riparian buffers.

The Río Bayamón watershed (with moderate level of urbanization- MUW) is one of the largest in Puerto Rico. The river’s headwaters are located in the Cordillera Central at an elevation of 500 m above sea level and flow through Subtropical Moist and Subtropical Wet Forests (Ewel and Whitmore 1973; Helmer et al. 2002). The land cover for the Bayamón watershed consists of 41 % secondary forests, 26 % grassland, 7 % suburban and 24 % urban development (Gould et al. 2008) (Fig. 3-2). The vegetation communities in the forested sections of the watershed are dominated by exotic trees species and the urban sections by grasses. The
meanders in the lower and coastal valleys have been heavily modified due to construction of earthen channels with raised levees for flood control.

The Río Piedras watershed (with high level urbanization- HUW) has several tributaries and flows through the center of the metropolitan area of San Juan. This watershed has more than 60% of urban cover, 5% suburban development, and 18.5% of secondary forest (Fig. 3-2) (Ortíz-Zayas et al. 2006; Gould et al. 2008; de Jesus and Ramírez 2011). The headwaters are located 70 m above sea level and regulated by outflow from the Las Curias Reservoir. The Río Piedras flows from Las Curias Reservoir (200 m above sea level) through several residential areas, the Botanical Garden of The University of Puerto Rico, and into San Juan Bay. Within the city of Río Piedras, some reaches and tributaries have been modified by channelization or reinforced with rock embankments. The riparian vegetation is characterized by exotic species of trees and grasses.

Data Collection

Stream Habitat Data

Each stream was visited in random order and sampled twice each year for 2 years (2010-2011), during the Low Rainfall (LRF) period (December-May), and the High Rainfall (HRF) period (June-November). To characterize the habitat at each sampling reach, several physical characteristics of the pools (length, width, depth, maximum depth, and substrate), and biotic factors (organic matter in the stream, pool canopy cover, and riparian canopy cover) were measured. Composition of the substrate was characterized from a location near each sampling site where decapods were collected. One hundred rocks from four samples of 0.5 m² were selected randomly to characterize the substrate composition using a gravelometer. The categories were expressed as percent bedrock, boulders, cobble, coarse gravel, fine gravel, and sand/fines. The percentage categories were converted to a Substrate Index (SI) using the following formula:
\[ SI = [(0.08) \text{ (\% bedrock)} + (0.07) \text{ (\% boulder)} + (0.06) \text{ (\% coble)} + (0.05) \text{ (\% gravel)} + (0.04) \text{ (\% fine gravel)} + (0.03) \text{ (\% sand and fines)}]. \]

The composition of the dominant riparian vegetation was determined by recording the most abundant species along the banks of the streams. The riparian and pool canopy cover were measured six times annually (three times during the two periods per year) using a spherical densitometer directly in the middle of the stream and in the riparian forest (10 m from the stream). Four samples of 0.5 m² of submerged organic matter in the selected pools were collected every time the pools were visited. The organic matter was collected in labeled plastic bags, frozen, dried in an oven at 25 °C for 24 h. Once dried, the organic matter was weighted to determine the total amount of organic matter in the pool. The water discharge for each watershed was obtained from the United States Geological Service (USGS) gauging station located nearest the stream sampling sites (Sabana- USGS 50067000; Bayamón- USGS 50047850; Río Piedras- 50049100). The discharges for each watershed were standardized by drainage area. Standard water parameters (conductivity, pH, DO, turbidity, and temperature) were recorded during 24-h with three DS 5X Hydrolab Multiparameter Sondes (Hatch Hydromets Colorado, USA) set at each sampling site (river mouth, mid location and headwaters) (Fig. 3-1) Additional chemical data from the LUW and the HUW were obtained from the long-term data sets of the Luquillo Long Term Ecological Research program, the Sabana Station- Forest Service, and the San Juan Urban Long Term Research Area Project.

Decapod sampling and processing

Decapod distributions were collected from all sites using a backpack electrofisher (Model 12-B, Smith-Root, Vancouver, Washington, USA). Collections consisted of three upstream electrofishing passes in each sampling reach that was bounded by a 6.4 mm mesh net to limit the emigration or immigration of decapods and fish during sampling. Hand nets were used to collect the organisms; macro-invertebrates (small decapods, insects, and mollusks) were transferred to
labeled plastic bags and placed on ice for transport to the laboratory. The habitats sampled included riffle, run, pool and the aquatic vegetation. Decapods were identified and classified according to species, counted, and their reproductive condition was recorded (gravid or non-gravid). Large decapods were measured in the field and released. Small specimens were identified by the reproductive appendages (1st and 2nd pleopods). When the individuals were too small or immature to be identified, they were classified to genus or family. Taxonomic identification followed Chace and Hobbs (1969) and Pérez-Reyes et al. 2013. The cephalothorax length (CL) of each decapod was measured from the post-orbital region to the end of the carapace with a dial caliper (0.01 mm precision); the measurement from the tip of the rostrum was not used because the rostrum was missing in some individuals. Length of the rostrum among Xiphocaris elongata varies among individuals related to the presence of fish predators below waterfalls (Covich et al. 2009; Ocasio-Torres et al. 2014; 2015).

Eggs from ovigerous females were stripped from the pleopods using fine forceps; setal material and extraneous matter was removed. The egg mass was placed in a square Petri dish with water and split into 36 equal portions. Eggs from 8 of 36 squares from the Petri dish were counted and the total number of eggs from each female was calculated using the following formula: Total egg number = ((Σ X)/8) (36); where X= number of eggs on each sub-sample.

**Freshwater shrimp larval drift**

Invertebrate drift at each watershed was sampled at 30 min intervals over a 24 hr period, at the lowest reach of each river. Drifting decapod larvae were collected by placing 3 plankton nets (153 µm mesh with dimensions of 30 cm mouth diameter x 90 cm length) in the channel; one in the middle and two equidistant on each side of the stream (25% and 50% of the stream width taken from each bank). The nets were located in sites where water depth was sufficient to completely cover the net opening and were set for periods of 30 min. Depth and flow velocity
were measured to calculate the volume of water that passed through each net. Depth was measured to the nearest 0.5 cm and the water flow was measured (to the nearest 0.01 m s⁻¹) at a point directly in front of each net using a Marsh McBirney 2000 Flo-Mate Flow Meter. Samples were labeled and preserved immediately in 4% formalin and transported to the laboratory, where they were counted using a dissecting microscope. Samples with high larval densities were subsampled and the total number of larvae was estimated by volume. Preserved samples were diluted in water until reaching 100 ml; then 5 sub-samples of 1 ml were extracted and the larvae counted. The number of larvae in the sub-samples was averaged and multiplied by the total volume (ml) in order to estimate total number of larvae in the sample. The drift densities of shrimp larvae (number of larvae m⁻³) were calculated by dividing the number of organisms collected in the net by the amount of water that passed through the net. The volume of water sample in a 30-min survey period was calculated as \( V (m^3) = S(m^2) \cdot (v(m/s)) \cdot (1800 (s)) \), where \( S \) is the area of the net mouth submerged in the water and \( v \) is the average flow velocity measured in front of the net. The sampling of shrimp larvae was conducted in random order in July 2009 during the HRF period.

**Data analysis**

*Community composition in streams*

The environmental variables and the physico-chemical measurements (24-hr sampling) from the three sampling sites in each stream were compared among watersheds using one-way ANOVAs. The totals of these variables were also compared with pairwise comparisons tests (Tukey) among watersheds. Species diversity was characterized by the number of taxa (\( S \)), Shannon-Weiner Index of Diversity (\( H' \)), evenness (\( J \)) (Magurran 2003), total density, and densities of decapod family groups (Atyidae, Palaemonidae, Xiphocarididae, and Pseudothelphusidae). Differences in decapod community diversity, richness, evenness, and total
density among watersheds (LUW, MUW, HUW) and between the two rainfall periods (LRF and HRF) were examined using nested ANOVAs and a Tukey post-hoc test. The average and standard error (SE) of each variable measured by each land use reach and rainfall period were calculated as a way to characterize their variability previous the analyses. Density data were transformed (LN X+1) prior to being compared among watersheds. Non-metric multidimensional scaling (NMDS) was used to describe the relationship among densities of decapod family groups and environmental variables (pool area, pool volume, pool cover, riparian cover, standardized discharge, substrate index, organic matter in the stream, and maximum depth). The densities of the decapod families and the corresponding environmental variables were averaged for each sampling site in each watershed prior to analysis. Family densities of the primary vector representing environmental variables were plotted with the ordination configuration. Prior to analysis, the environmental and decapod abundance data were SQRT(X) transformed. Densities of family groups were used instead of total density per specie due to some of the specimens could not be fully identified because they were juveniles. The Bray-Curtis Dissimilarity Index (Bray and Curtis 1957) was used as the distance variable for NMDS ordination.

*Drift density and Fecundity*

Statistical differences in aquatic drift density among sites were tested using one-way ANOVA with a Tukey post-hoc test. Drift densities were (LN X+1) transformed before the analysis. Linear regressions were used to examine possible relationships between egg production and shrimp size. We used analysis of covariance (ANCOVA) to test for differences in the mean numbers of embryos among females of the same species but from different streams. In order to evaluate possible differences in fecundity among populations, an ANCOVA (with CL as the
covariate) was applied to the slopes for the relationship between egg number and body size (Zar 1999).

**Results**

*Characteristics of the watersheds*

The one way ANOVAs comparing water discharge from the watersheds demonstrated significant differences among streams (F$_{2,33}$=10.4; p<0.0001). The pairwise comparison test showed that the LUW (0.06±0.01 m$^3$s$^{-1}$) and HUW (0.05±0.01 m$^3$s$^{-1}$) had high, similar mean discharge compared to the MUW where the mean discharge was 0.02±0.002 m$^3$s$^{-1}$. The lowest monthly mean discharges were observed during the LRF period (February and January) as expected. One-way ANOVAs comparing pool area, pool volume, riparian and pool canopy cover, maximum depth, and the substrate index among watersheds showed no significant differences among watersheds. One-way ANOVAs comparing pool area, pool volume, riparian and pool canopy cover, maximum depth, and the substrate index among watersheds showed no significant differences among watersheds.

One-way ANOVAs for the 24-hr physico-chemical parameters of water showed significant differences in water temperature, salinity, pH and conductivity among the watersheds (Table 3-1). Water temperature increased from the LUW to the HUW. The lowest average water temperature was recorded in the LUW (26±0.08 °C) while the MUW and HUW had average values of 28.3±0.1 °C and 27.5±0.1 °C, respectively. Concentrations of the dissolved oxygen varied among streams (Table 3-1). The DO concentrations in the LUW ranged between 111.7±0.5 to 78.2±0.5 mgL$^{-1}$, in the MUW between 140.0±1.0 to 55.2±1.0 mgL$^{-1}$, and in HUW between 94.6±0.5 to 71±0.5 mgL$^{-1}$. Significant differences in TDS were observed among watersheds (Table 3-1). The LUW had the lowest concentrations in TDS with an average value of 0.07±0.002 g L$^{-1}$ while the highest values were observed in the MUW (0.3±0.003 g L$^{-1}$).
Conductivity and salinity also showed significant differences among streams (Table 3-1). The MUW and HUW showed higher conductivities and salinities than the LUW (Table 3-1).

**Decapod diversity and abundance**

A total of 14,833 specimens from the Atyidae, Palaemonidae, Pseudothelphusidae, Xiphocarididae, and Grapsidae were collected in the watersheds (Table 3-2). The most common species found in all of the streams were *Xiphocaris elongata* (*n*=5164), *Macrobrachium faustinum* (*n*=1276), and *Epilobocera sinuatifrons* (*n*=11). *Micratya poeyi*, *Atya lanipes*, *Potimirim glabra*, *Macrobrachium carcinus*, and *Epilobocera sinuatifrons* were present in larger proportions in the LUW compared to the other watersheds. Conversely, *X. elongata*, *M. faustinum*, and *Atya scabra* were present in larger proportions in the MUW. *Palaemon pandaliformis* was the most abundant shrimp in the HUW (Table 3-2); this species represented the 77% (530) of all the individuals collected in this watershed during study.

Thirteen species of the 18 native freshwater decapods that are known to occur on the island (Pérez-Reyes et al. 2013) were collected during the study. The LUW and MUW had similar numbers of species (11 and 10 respectively) in comparison with the HUW with only 4 species. The nested ANOVA comparing the number of species among watersheds and between rainfall periods showed significant differences in species richness among watersheds (*F*$_{2,3}$=35.3; *p*<0.008), but not between rain periods (*F*$_{2,3}$=0.3; *p*>0.825) (Fig. 3-3a). The highest mean number of species was observed in LUW (7.0±1.1), while the MUW and HUW had 5.0±1.0 and 2.5±0.2 species, respectively. The Tukey pairwise tests to compare average of species number among watersheds showed that the LUW- HUW differed significantly in their number of species (*p*<0.001) than the LUW-MUW (*p*<0.063) and the MUW-HUW (*p*>0.09). The most diverse watershed was LUW with a mean diversity indices of 1.3±0.04 and 1.2±0.1 during the LRF and HRF, respectively. The mean diversity indices in the HUW were 0.09±0.03 (LRF) and
The nested ANOVA to compare the diversity index (H') per rainfall period and watersheds showed significant differences among watersheds ($F_{2,3}=44.6; p<0.006$), but was not significant among rain periods ($F_{2,3}=0.6; p<0.718$). Higher values in evenness were observed in the LUW in comparison with the MUW and the HUW (Fig. 3-3c). The nested ANOVA showed no significant differences in evenness were observed between rainfall periods or watersheds (Fig. 3-3c). A post hoc Tukey test for evenness showed that the LUW-HUW group differed from the LUW-MUW and MUW-HUW; no differences in evenness were observed between seasons.

Higher mean densities of decapods were observed in the LUW and MUW than HUW. The LUW had a highest average density of decapods ($1.7\pm0.7$ decapods m$^{-2}$) during the LRF in comparison with the MUW ($1.1\pm0.4$ decapods m$^{-2}$) where the highest average density was observed in the HRF (Fig. 3-3d). The lowest abundance of decapods was observed in HUW during the HRF with $0.5\pm0.2$ decapods m$^{-2}$. Significant differences in decapod densities were found among watersheds ($F_{2,3}=101.2; p<0.002$), but no significant differences in decapod densities were found between rain periods ($F_{2,3}=0.054; p>0.983$) (Fig. 3-3d). The most abundant species in the LUW were *Micratya poeyi* and *Xiphocaris elongata* with average densities of $1.0\pm0.2$ and $1.1\pm0.1$ shrimp m$^{-2}$ respectively. The LUW had the largest density of atyids ($1.2\pm0.1$ atyids m$^{-2}$) and xiphocarids ($0.7\pm0.1$ *Xiphocaris* m$^{-2}$). Palaemonids were abundant in HUW ($0.6\pm0.2$ palaemonids m$^{-2}$), while the largest average densities of *Epilobocera* were observed in LUW ($0.004\pm0.003$ crabs m$^{-2}$) (Table 3-2). Highly significant differences in atyid densities were observed among watersheds ($F_{2,3}=14.7; p<0.0001$), but not between LRF/HRF periods. Significant differences in xiphocarid densities were found between seasons ($F_{2,3}=4.6; p<0.02$) but not among watersheds. Higher densities of xiphocarids were observed during the LRF period in the LUW in contrast with the MUW and HUW where the highest densities were observed in the HRF period (Table 3-2). The post-hoc test showed no differences among watersheds or rain
season. No significant differences in palaemonids, xiphocarids and pheudothelphusids were observed between rainfall periods or watersheds.

**Multivariable Analysis**

NMDS ordination of decapod abundance assemblages yielded 2 major axes; Axes 1 and 2 explained most of the variation. Axis 1 and 2 were highly related to the discharge (0.8) and pool volume (0.03), respectively (Fig. 3-4). Stream with positive values on NMDS axis 1 and 2 were located in the HUW. Discharge represented the environmental variable with better explained the variation in species abundance. The environmental variable that best explained the variation on axis 2 was pool volume. The sites with larger pools were observed in the MUW (10.7 m$^3$) and low (10.3 m$^3$) HUW. The pool area and the maximum depth of the pools were also important factors with direct influence in the decapod densities.

**Fecundity and Drift density**

Ovigerous females of *Atya innocuous*, *Micratya poeyi*, *Macrobrachium faustinum*, and *Xiphocaris elongata* were collected in all the watersheds. Ovigerous *Palaemon pandaliformis* were collected in the HUW. The largest brood sizes were reported for *Atya innocuous* where the maximum number of eggs were observed in the MUW (6,587 eggs) and LUW (1,256) and the smallest was for *Micratya poeyi* from LUW with 12 eggs. Positive linear regressions between cephalothorax length and fecundity were observed for the species in all the watersheds (Fig. 3-5). No significant differences in the slopes between body size and fecundity among watersheds in *Micratya poeyi*. The ANCOVA analyses demonstrated no significant effect of locality on female fecundity for *Atya innocuous* (F=1.4; df=1; p>0.2) and *Xiphocaris elongata* (F=1.6; df=1; p>0.2), but were significant for *Macrobrachium faustinum* (F=17.8; df=2; p<0.001) (Fig 3-2b, c, d). A post-hoc Tukey test for comparison of fecundity among watersheds in *M. faustinum* showed similar fecundities between the LUW-HUW than with the LUW-MUW or MUW-HUW.
The analyses of covariance detected effects of female CL on fecundity in *Atya innocuous* (F=214; df=1; \( p \leq 0.0001 \)), *Macrobrachium faustinum* (F=52; df=1; \( p \leq 0.0001 \)) and *Xiphocaris elongata* (F=53; df=1; \( p \leq 0.0001 \)).

Lower mean hourly drift densities (larvae m\(^{-3}\)) were observed at 10:30 hr and 13:30 hr in the LUW (2.0±0.36 larvae m\(^{-3}\)) and HUW (2.0±0.65 larvae m\(^{-3}\)), respectively. The largest mean drift density occurred in the MUW with 2552±7.8 larvae m\(^{-3}\) (Fig. 3-6). Mean drift density in the LUW over the course of the study was 370±133.2 larvae m\(^{-3}\), while the mean for the MUH and HUW were 263±105.6, and 344±111.1 larvae m\(^{-3}\). No significant differences in mean drift densities were observed among watersheds (F\(_{2,68}\)=2.06, \( p=0.13 \)). Diel periodicity in the drift densities was observed where a reduction in larvae release occurred from 6:30 to 16:30 (Fig. 3-6).

**Discussion**

Our results show a general negative impact of urbanization on species richness and abundance of freshwater decapods along the urban-forested gradient in the tropical streams of Puerto Rico. The decapod communities were less diverse and less abundant in HUW than in the MUW and LUW. This difference suggests that watersheds with high percentage of forested land-use are important to sustain the freshwater decapod diversity. These observations agree with previous patterns associated with the “Urban Stream Syndrome” where streams are degraded by complex and multiple physico-chemical and ecological stressors (Meyer et al. 2005; Walsh et al. 2005; Wenger et al. 2009). The effects of urbanization on rivers can decrease ecological integrity and associated ecosystem services (Walsh et al. 2005; Wallace and Eggert 2009). Nonetheless, the HUW retained 4 of the 13 total species observed in the LUW. Although the number of species is relatively low in the urbanized river, these organisms, especially *Xiphocaris*, can still function as shredders in the ecosystem.
The diversity and abundance of freshwater decapods among watersheds were best explained by an increase in water discharge in the HUW relative to the MUW and LUW. A disproportionate increase in water discharge in the HUW in comparison with the LUW and MUW, as result from changes in the land use patterns among these watersheds, appeared to determine a reduction in the number of decapods in each stream. Even though the HUW had fewer species than the LUW, this urbanized watershed had a higher diversity of decapod species than expected. The presence of some species of palaemonids, xiphocarids and the endemic crab *Epilobocera sinuatifrons* in the HUW demonstrates that these ecosystems can support species that are critical for sustaining ecological processes such as shredding of leaf litter. Most of the shrimp apparently benefited from high discharge during their spawning by having rapid downstream transport of their larvae to the estuary as part of their amphidromous life cycle (Bauer 2011a; 2011b; 2013). However, extremely high discharge events can wash out some macroinvertebrates, organic matter and cause changes in the morphology of the pools in headwater streams (Covich et al. 1991; 1996; 2006). In urban streams, high-discharge events have been associated with the reduction on diversity in the lower valleys of the watersheds (Urban et al. 2006). An increase in sedimentation, alteration of river banks, and changes in the physico-chemical environment of the stream can result in the reduction of the habitat heterogeneity and the loss of sensitive species.

The HUW has been developed over many years (Lugo et al. 2011) and has the largest percentage of impervious surfaces, pipes, and culverts that transport water (precipitation or wastewater overflow) to the stream (Potter et al. 2013). These effluents, the channelization of the main channel and some of the tributaries resulted in an increase of the river discharge in these reaches. Such modifications in the watersheds together with the reduction of the riparian forest can increase discharge that disrupts the natural conditions of pools, increase sedimentation, and decrease food quality. The HUW (Río Piedras) tends to be a “flashy” stream as result of frequent, brief rainfall events, and changes in land use. The geomorphology of the Río Piedras
Headwaters is steeply sloped along a gradient of elevation from 200 to 0 masl. The urban areas are located in the coastal valleys while the land uses on the steep slopes are suburban areas with secondary forests. Changes in discharge in the urban and suburban zones occur as a result of the combined effects of changes in land use, increases in impervious surface, rapid runoff, and overflows of the sewage systems. Headwaters in the HUW also exhibit flashiness as result of saturated soils and a network of natural drainage channels (Ramírez et al. 2009; 2012). The soils can retain water before the excess runoff flows to the stream in contrast to coastal and lower valleys where the rainwater rapidly runs off the impervious surfaces increasing the water discharge. Frequent and intense flashiness in these valleys exert a strong effect on the freshwater biota and in the quality and quantity of energy derived from the riparian organic matter (Paul and Meyer 2001; Walsh et al. 2005; Braud et al. 2013). Heavy rainstorms remove the small amount of organic matter deposited in the stream by the urban riparian vegetation as well the human derived-organic matter (fecal coliform and Streptococcus) and export it to the ocean (Larsen and Webb 2009; Bachoon et al. 2010).

Macrobrachium faustinum, Palaemon pandaliformis and Xiphocaris elongata were the only shrimp species collected in the HUW, suggesting that these species are highly tolerant to changes in water discharge, temperature and water chemistry. In the headwaters, P. pandaliformis was the dominant species and responded more positively to uniform conditions, a variety of habitats, and access to food resources. Paschoal et al. (2013) suggest that palaemonids seek locations with sufficient organic matter for food and as refuge to avoid fish predation. The high abundance of Palaemon in these headwater reaches is related to their detritivorous feeding (Campanelli et al. 2009), a role shared with Xiphocaris (Crowl et al. 2001). Xiphocaris elongata process leaves and produces fine, medium and coarse particulates that can be used by filter-feeding species (Crowl et al. 2001). Species like Macrobrachium faustinum are generally more abundant in the lower and shallow reaches with low-flow conditions (Hunte and Mahon 1983;
Thorpe and Lloyd (1999). These results are consistent with those of Nemeth and Platenberg (2007) who reported similar species richness and distribution in streams with different degrees of human impact in the St. Thomas U.S. Virgin Islands. They found *M. faustinum* and *X. elongata* in the low, moderate and highly impacted streams while *Atya* species were restricted to the low and moderate-impacted urban streams.

The lowest densities of *X. elongata* and *M. faustinum* in the headwaters might be the result of inter-specific competition with *P. pandaliformis*. These observations are consistent with the results of an exclusion experiment developed in artificial streams of Puerto Rico, where *P. pandaliformis* displaced individuals of *X. elongata* and *M. faustinum* when they were in the same cage; neither *Xiphocaris* nor *M. faustinum* exhibited this behavior when they were interacting in the same location. *Palaemon pandaliformis* is a shrimp species from lowlands and shallow aquatic systems that is tolerant of changes in salinity and water flows in estuaries (Campaneli et al. 2009).

The absence of filter feeder species of shrimp in the HUW may represent the result of direct or indirect disturbances in this stream as well the replacement of sensitive species by more tolerant species. The higher concentrations of oxygen and rocky substrate and submerged wood could be related to the presence of larger populations of these shrimp. Hobbs and Hart (1982) reported that the absence of atyids in certain streams in the Caribbean and Central America were the results of the absence of rocks, debris and macrophytes. Previous studies in the headwater tributaries of this watershed have reported the presence of some adults of *Atya lanipes* (A. Ramírez, personal communication). These findings could represent a previous population of this species in the stream that was temporarily able to remain in a particular location with adequate cover; watersheds with diverse habitats and relatively low normal flow conditions tend to have diverse population of atyids. Similar to *Palaemon pandaliformis*, *Atya lanipes* prefers pools with natural substrate, high concentration of organic matter and stable flow conditions.
Small numbers of *Epilobocera sinuatifrons*, the endemic freshwater crab of Puerto Rico, were observed in the headwater and suburban reaches of all the watersheds. Previous collections documented their presence in almost all types of freshwater bodies, from pristine montane streams to wetlands, karsts, and caves of the island (Pérez-Reyes et al. 2013). The amphibious movement of adults and their direct development makes *Epilobocera* relatively resistant to changes in discharge and land use but sensitive to water pollution. The presence of *E. sinuatifrons* in the forested headwaters of the HUW demonstrates the importance of these reaches as refuges for the conservation of sensitive species (Thorpe and Lloyd 1999; Yeo et al. 2008; Cumberlidge et al. 2009).

**Biota and water quality.** A decrease in water quality tends to relate land use with increases in temperature, pH, TDS, conductivity and salinity with increased urbanization. Higher water temperatures were observed in the MUW and HUW than in the LUW likely because of reduced riparian forest cover. Increased water temperatures in higher-latitude urban streams are often associated with the removal of riparian forest that reduces the shade in the streams (Meyer et al. 2005). In the HUW, more than 60% of the watershed is residential land while in the MUW nearly 30% of the watershed is urbanized. Concrete buildings, roads, culverts, and channels can store and transfer heat (during rainstorms) to warm the stream water and affect the stream biota (Somers et al. 2013). Higher water temperatures in the streams reduce the percentage of dissolved oxygen in the water, and accelerate decomposition rates, nutrition release, and animal metabolism. Palaemonids in the highly urban watershed tolerate high water temperatures, salinity, and changes in oxygen concentrations. Atyids are sensitive to warm temperatures and low dissolved oxygen (González-Ortega et al. 2012; 2013).

Reductions in oxygen concentrations at urban watersheds can result from the combined effects of organic pollution and changes in the land use in the watersheds. Meanders and channels in the coastal valleys of the high and moderately urban watersheds have been modified
to prevent flood and to transport stream water rapidly to the ocean. Replacing the natural, complex substrate with uniform concrete channels, increased channel width and channel straightening all combine to reduce the turbulence that in turn decreases the dissolved oxygen concentration (Miller 2013). Studies on macroinvertebrates have demonstrated that reduction in DO concentrations affect the emergence of insects and produce the mortality of sensitive groups (Connolly et al. 2004).

In natural streams, conductivity generally increases from headwater to downstream and is affected by geology, but in urban systems the highly variable discharges can rapidly change the conductivity. Leaks in the sewage system, run-off or soil erosion can raise the conductivity because of the increased input of chloride, phosphate, and nitrate (Paul and Meyer 2001). Conductivity was higher in the MUW and HUW than in the LUW. These watersheds have both point and non-point pollution from agriculture, septic tanks, and run-off due to the large amounts impervious surface.

Decapods in Impacted Streams. Urbanization is known to decrease the abundance and diversity of organisms living in streams, but it is not clear which forcing factors (e.g. changes in discharge, sediment, and pollutant concentrations), are most important for causing these reductions. Our results suggest a negative effect of the physico-chemical and environmental impacts on the diversity and abundance of freshwater decapods in the urban watersheds. Hydrologic changes, physico-chemical factors and land use appear to be the main stressors that influence the abundance and diversity of decapods in the streams. Higher stream discharge reduced the densities and diversity of macroinvertebrates regardless of whether they were in LRF and HRF periods, discharges representing press or pulse disturbances. Tropical streams with LRF and HRF periods are characterized by the relatively high frequency and intensity of storm-flow events.
Riparian vegetation had positive effect on species richness and abundance by providing food, shelter and substrate for aquatic organism as well by reducing the water temperature. The riparian vegetation in the headwater reaches in the highly urbanized watershed of Río Piedras is characterized by non-native trees that provide input of leaf litter to the detritivores. Also, these reaches have closed canopies, relatively slower flow conditions, lower water temperature, and a more diverse community of other macroinvertebrates (freshwater sponges, flatworms, snails, clams, and insects) than the urbanized sections of the stream. Increased urbanization, impervious surfaces, channelization, and forest clearing can reduce lateral subsidies of leaf litter that are needed to support the higher taxonomic richness and abundance. The loss of species richness and abundance during high discharge is consistent with other studies in temperate (Boulton et al. 1992; Bogan and Lytle 2007) and tropical (de Jesús and Ramírez 2011) streams, where high discharge removes the living and non-living biota from the stream reach. Ramírez et al. (2009) and de Jesús and Ramírez (2011) observed that diversities of Ephemeroptera and Trichoptera decreased from the forested to urban reaches, while the densities of Chironomidae increased because of a lack of hard substrata. The patterns of changes on diversity of decapods and insects were also observed in the fish communities in this stream. Engman and Ramírez (2012) demonstrated that natural and low impacted reaches have more native species of aquatic insects than reaches in highly urbanized reaches.

The HUW has all the 9 native species of fishes present on the island in addition to some exotic species. Native fish are sensitive to habitat alterations and studies in Puerto Rico (e.g., Engman and Ramírez 2012; Cooney and Kwak 2013), and Hawai’i (e.g., Brasher 2003; Keith (2003) have shown that Sicydium, Eleotris and Gobiomorus species prefer natural channels and spawn in streams with low amounts of silt substrate, larger coarse substrate, closed canopy, un-altered channels, and cool water temperatures.
The decapod community in the MUW contrasts with our observations in LUW. The decapod communities in the MUW resemble the communities observed in the LUW and many other streams in the island (Pérez-Reyes et al. 2013). Only 10 out the 18 decapods species present in the island were found in this stream. The differences in species richness and abundance among sites are likely affected by the presence of barriers caused by two dams (The San Juan and Cidra Lake Dam) that isolate the decapod communities in the headwater reaches from the communities in the urban and coastal reaches in this stream. Smaller densities of decapods (*Atya scabra*, *A. innocuous*, *Micratya poeyi*, and *Macrobrachium faustinum*) collected in the headwater reaches, located above the dams, contrast with the densities observed in the urban reaches where densities were higher. In tropical and temperate streams where freshwater fauna have life cycles dependent on the marine environment, dams have restricted the migration of fish and shrimp, and disrupted the longitudinal connectivity in the stream resulting in detrimental effects on the freshwater environment above and below the dam (Holmquist et al. 1998; Greathouse et al. 2006a; Cooney and Kwak 2013). However, the increase in shrimp density in these sites could represent the effect of the dam located upstream that prevents the migration of the faunal biota to the upper parts of the stream. Headwaters of the LUW had the higher densities of decapods among streams. That high density most likely represents the massive upstream migration of post-larvae (juveniles) shrimp from the estuary during the LRF period.

The LUW was the most diverse in freshwater fauna among the studied streams with 11 of the 18 species of freshwater decapods reported for the island. The abundance and species richness showed no variations between rain periods (LRF/HRF). Atyids and xiphocarids were the most abundant; palaemonids and pseudothelphusids were present but in lower densities. In this stream, in contrast to the others, all the shrimp families were represented in all the sampling reaches. Higher densities of decapods during the low rainfall period can be attributed to the
upstream migration of post-larval shrimp from the estuary. Amphidromous shrimp reproduce during the HRF period (June-November) that concurs with the hurricane season and the increased of the allochthonous input from the forest (Heartsill-Scalley et al. 2012). This input of litter increases food resources during the period when most reproduction occurred. Macroinvertebrate diversity and abundance were significantly lower in the HUW than at the LUW and MUW. This difference among the three rivers can probably be explained by limited food availability, habitat loss, and warmer water temperature in conjunction with the flashy discharge regimes; low invertebrate production can be a consequence of high water discharges (Heino et al. 2004; Girard et al. 2013).

**Shrimp fecundity in urban streams.** The drift of shrimp larvae was similar among watersheds in terms of the density of larvae drifted and the time of release. All the shrimp species exhibited positive relationship between size and egg number and no differences among watersheds were observed. Fecundity in decapods is determined primarily by body size and energy allocation. The larvae releases coincide with high-discharge events; shrimp release larvae after an increase in stream discharge. The larval drift started at 18:00 and drift densities peaked 2-h later, except for the low impacted watershed that had a prolonged larval drift 5 h later. The concentration of larvae released at this time can reach a maximum of 2500 larvae m$^{-3}$. This concentration is consistent with the breeding pattern that peaks during the warmest months with high-flow conditions, and warmer water temperatures (Heartsill-Scalley et al. 2012). In general, drift usually increases from sunset to darkness (March et al. 1998), continues at low densities after the initial peak throughout the night and ends with a reduction in drift densities at dawn (Ideguchi et al. 2007). Shrimp are active at night and avoid visual predators (Johnson and Covich 2000; Kikkert et al. 2009). The reproductive patterns in freshwater decapods are apparently synchronized by physical and environmental factors as water temperature, photoperiods, rainfall, nutrients availability, and phases of the moon. Tropical and subtropical shrimp can breed
throughout the year, but mostly during warm months and high-flows events which transport the larvae to the estuarine zone. After the larvae are released they spend 30-90 days (depend on the species) in estuarine or marine waters where after several molts they transform into post-larval shrimp that migrate to headwaters (Bauer 2011a; 2011b; 2013).

Conclusion

Anthropogenic stressors increase the environmental pressure on macroinvertebrate communities that can alter biotic distributions in tropical streams. Changes in the riparian vegetation can increase the erosion of the stream banks, sedimentation, and water flow that decreases the habitat heterogeneity and the abundance and diversity of decapods in the stream. Complete or partial removal of riparian forests greatly decreases the input of allochthonous material, a major source of energy for decapods and other macroinvertebrates. These removals also increase the water temperature that raise rates of animal metabolism and deplete oxygen concentrations. The relatively rich and unaltered environment, presence of organic matter, longitudinal connectivity and the physical-chemical variables can provide the conditions for which these streams are important areas for the conservation of these aquatic animals.

In general, urbanization in tropical regions decreases the species richness and abundance of decapod communities in highly urbanized watersheds when compared to watersheds with low or moderate urbanization. Previous studies of macroinvertebrates in temperate-zone streams (Paul and Meyer 2001; de Jesús and Ramírez 2011) have demonstrated that poor quality waters are often a result of urbanization that decreases the species richness and abundance. Urban streams reflect the impact of human activities in their hydrology, geomorphology, water quality and aquatic biota. The effect of a combination of all or some of these variables impacts on the species assemblages as well on the energy inputs in the stream. Our study suggests that the loss of species richness and abundance of freshwater decapods in tropical insular urban streams is the
result of a series of stressors that degrade decapod habitat. The alterations of the terrestrial environment as well the construction of barriers to migration change the local energy inputs as well the longitudinal connectivity among streams sections. These changes affect the organization and functions of the stream communities in the upper reaches of insular river drainages and are similar to effects initially outlined in the river continuum concept for larger watersheds (Vannote et al. 1980; Greathouse et al. 2006b; Tomanová et al. 2008; Gorbach et al. 2014).

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Table 3-1  Mean (± SE) of physicochemical and environmental parameters of the water in low, moderate and highly urban development watersheds in Puerto Rico. Measurements were made per sampling site (n=3) in each watershed (n=3) during 24 hours in 2010–2011.

<table>
<thead>
<tr>
<th>Watershed type</th>
<th>Water Temperature (°C)</th>
<th>% Dissolved Oxygen (mg L⁻¹)</th>
<th>pH</th>
<th>TDS (g L⁻¹)</th>
<th>Conductivity (µS cm⁻¹)</th>
<th>Salinity (ppt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low (Sabana)</td>
<td>26.1 ± 0.1</td>
<td>94.4 ± 0.5</td>
<td>7.3 ± 0.01</td>
<td>0.06 ± 0.003</td>
<td>114.5 ± 2</td>
<td>0.04 ± 0.001</td>
</tr>
<tr>
<td>Moderate (Bayamón)</td>
<td>28.3 ± 0.1</td>
<td>97 ± 1</td>
<td>8 ± 0.01</td>
<td>0.2 ± 0.003</td>
<td>361 ± 5</td>
<td>0.18 ± 0.003</td>
</tr>
<tr>
<td>High (Río Piedras)</td>
<td>27.5 ± 0.1</td>
<td>83.3 ± 0.5</td>
<td>7.7 ± 0.01</td>
<td>0.2 ± 0.003</td>
<td>357 ± 3</td>
<td>0.8 ± 0.002</td>
</tr>
<tr>
<td>ANOVA</td>
<td>***</td>
<td>***</td>
<td>***</td>
<td>***</td>
<td>***</td>
<td>***</td>
</tr>
</tbody>
</table>

NS- not significant at p = 0.05; * p < 0.05; ** p < 0.01; *** p < 0.001
Table 3-2  Mean decapod species density (± SE) in the different watersheds of the low, moderate and high urban watersheds during 2010-2011.

<table>
<thead>
<tr>
<th>Taxa</th>
<th>Low urban</th>
<th>Moderate urban</th>
<th>High urban</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>LRF</td>
<td>HRF</td>
<td>LRF</td>
</tr>
<tr>
<td><em>Palaemon pandaliformis</em></td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td><em>Macrobrachium faustinum</em></td>
<td>0.3±0.2</td>
<td>0.1±0.03</td>
<td>0.2±0.1</td>
</tr>
<tr>
<td><em>Xiphocaris elongata</em></td>
<td>0.8±0.1</td>
<td>0.6±0.3</td>
<td>0.3±0.2</td>
</tr>
<tr>
<td><em>Epilobocera sinuatifrons</em></td>
<td>0.0001±0.0001</td>
<td>0.01±0.01</td>
<td>0.001±0.001</td>
</tr>
<tr>
<td><em>Atya innocuous</em></td>
<td>0.2±0.1</td>
<td>0.2±0.1</td>
<td>0.3±0.2</td>
</tr>
<tr>
<td><em>Atya scabra</em></td>
<td>0.04±0.03</td>
<td>0.03±0.02</td>
<td>0.1±0.1</td>
</tr>
<tr>
<td><em>Micratya poeyi</em></td>
<td>0.7±0.2</td>
<td>0.7±0.3</td>
<td>0.001±0.001</td>
</tr>
<tr>
<td><em>Macrobrachium acanthurus</em></td>
<td>0.01±0.01</td>
<td>0.01±0.01</td>
<td>0.002±0.001</td>
</tr>
<tr>
<td><em>Atya lanipes</em></td>
<td>0.3±0.2</td>
<td>0.3±0.2</td>
<td>0</td>
</tr>
<tr>
<td><em>Potimirim mexicana</em></td>
<td>0.1±0.1</td>
<td>0.02±0.01</td>
<td>0</td>
</tr>
<tr>
<td><em>Sesarma roberti</em></td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td><em>Macrobrachium carcinus</em></td>
<td>0</td>
<td>0.003±0.003</td>
<td>0</td>
</tr>
<tr>
<td><em>Potimirim glabra</em></td>
<td>0.06±0.06</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
Table 3-3 Minimum, mean (± SE) and maximum number of embryos per female, regression equations showing relationship between female size (CL) and fecundity (FEC) for each land use section in the Low, Moderate, and High impact watersheds during the wet season.

<table>
<thead>
<tr>
<th>Watershed</th>
<th>Species</th>
<th>Fecundity</th>
<th>Regression Equation</th>
<th>R²</th>
<th>F</th>
<th>p</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Min</td>
<td>Mean (SE)</td>
<td>Max</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low</td>
<td><em>Atya innocuous</em></td>
<td>25</td>
<td>360 (40)</td>
<td>1256</td>
<td></td>
<td></td>
<td>43</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.8</td>
<td>197</td>
<td>***</td>
</tr>
<tr>
<td></td>
<td><em>Micratya poeyi</em></td>
<td>12</td>
<td>65.9 (3)</td>
<td>153</td>
<td></td>
<td>10.6</td>
<td>***</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.13</td>
<td>10.6</td>
<td>***</td>
</tr>
<tr>
<td></td>
<td><em>Xiphocaris elongata</em></td>
<td>55</td>
<td>228 (13)</td>
<td>446</td>
<td></td>
<td>42.2</td>
<td>***</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.5</td>
<td>42.2</td>
<td>***</td>
</tr>
<tr>
<td></td>
<td><em>Macrobrachium faustinum</em></td>
<td>16</td>
<td>179 (42)</td>
<td>827</td>
<td></td>
<td>19.4</td>
<td>***</td>
</tr>
<tr>
<td>Moderate</td>
<td><em>Atya innocuous</em></td>
<td>132</td>
<td>1321 (206)</td>
<td>6587</td>
<td></td>
<td>310</td>
<td>***</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.9</td>
<td>310</td>
<td>***</td>
</tr>
<tr>
<td></td>
<td><em>Micratya poeyi</em></td>
<td>32</td>
<td>70.6 (5.3)</td>
<td>154</td>
<td></td>
<td>6.1</td>
<td>*</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.2</td>
<td>6.1</td>
<td>25</td>
</tr>
<tr>
<td>Species</td>
<td>N</td>
<td>FEC [%]</td>
<td>CL [cm]</td>
<td>p-value</td>
<td>Significance</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-----------------------------</td>
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<td>---------</td>
<td>---------</td>
<td>--------------</td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>Xiphocaris elongata</em></td>
<td>54</td>
<td>147 (19)</td>
<td>413</td>
<td>0.5</td>
<td>*** 25</td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>Macrobrachium faustinum</em></td>
<td>47</td>
<td>98 (8)</td>
<td>258</td>
<td>0.2</td>
<td>** 34</td>
<td></td>
<td></td>
</tr>
<tr>
<td>High</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>Macrobrachium faustinum</em></td>
<td>96</td>
<td>302 (33)</td>
<td>601</td>
<td>0.5</td>
<td>*** 19</td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>Palaemon pandaliformis</em></td>
<td>12</td>
<td>49 (3)</td>
<td>91</td>
<td>0.6</td>
<td>*** 43</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

NS- not significant at $p = 0.05$; * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$
Fig. 3-1 Location of the Low (Río Sabana), Moderate (Río Bayamón), and Highly urban (Río Piedras) watersheds of the studied streams in the north coast of Puerto Rico. The gray area represents El Yunque National Forest; closed circles- the sampling sites (low, medium and high elevation), horizontal bar – large dam with a vertical wall, open left triangle- small dam with acute vertical wall, and the closed left triangle- small broken dam. CiL represents Cidra Lake and CuL- Las Curias Lake.
Fig. 3-2  Comparison of predominant land use/land cover groups among watersheds (Low, Moderate, and High urban development). Watersheds analyses include all the area from the headwaters to the mouth of the streams.
Fig. 3-3 Mean (± SE) species number (S) a), Shannon-Weiner Diversity Index (H’) b), Evenness (J) c), and Density d) of the freshwater decapod communities for each watershed (Low-Sabana, Moderate-Bayamón and High-Río Piedras urban categories) during the rainfall season (HRF-High Rainfall and LRF-Low Rainfall). Closed bar- HRF, open bar- LRF, Horizontal line over the bars represents the nested Anova test differences among streams/ urban intensity categories. *NS*not significant at p = 0.05; *p* < 0.05; **p** < 0.01; ***p** < 0
Fig. 3-4 Nonmetric multidimensional scaling (NMDS) results from ordination of decapod family densities. Stream habitat variables measured at the different sampling sites (LU-Low Urban-Sabana, MU-Moderate Urban-Bayamón and HU-High Urban- Río Piedras)(1-Headwater, 2-mid elevation, and 3- river mouth sampling sites) are plotted as vectors. Vector length and direction reflects strength and direction of relationship between the stream habitat variables (Disch- discharge, Omatter-Organic matter in the stream, %Pcov- %Pool cover, %Rcov- % Riparian cover, %SI- % Substrate Index, Mdepth- Maximum depth, Pvol- Pool volume,Parea- Pool area) and decapod family densities (Palaemonidae, Atyidae, Xiphocarididae, and Pseudothelphusidae). Stress value = 0.04; Axis 1 $R^2 = 0.79$ and Axis 2 $R^2 = 0.03$. 
Fig. 3-5  Multiple regressions showing the relation between female cephalothorax length (mm) and reproductive output. a) *Micratya poeyi*; b) *Atya innocuous*, c) *Xiphocaris elongata*, d) *Macrobrachium faustinum*, and e) *Palaemon pandaliformis* in the Low (closed circle), Moderate (open circle) and High (closed inverted triangle) urban watersheds. Regression lines: Straight line- Low Urban, Dashed line- Moderate Urban, and Dotted line- High Urban streams.
Fig. 3-6 Mean (± SE) larvae drift densities and discharge in 24-hour (H-hour, M-minutes, S-seconds) sampling period in the Low (Sabana) (a), Moderate (Bayamón) (b) and in the High (Rio Piedras) (c) urban watersheds. The larvae density and discharge were collected near the estuary in each stream. Solid lines represent the discharge and the closed circle, open circle and closed inverted triangle represent mean (±SE) larvae drift in the studied watersheds.
CHAPTER 4
COMPARISON OF TROPHIC RELATIONSHIPS IN CONTRASTING TROPICAL STREAMS
IN PUERTO RICO

Summary

1. In tropical islands, urbanization occupies a large percentage of land use along streams and rivers and strongly affects the biota and habitat in them.

2. Clearing of riparian vegetation, increased impervious surface, and channelization results in changes in water quality and quantity that affect the assemblage of the freshwater biota, and the health and services of the ecosystem.

3. Stomach analysis and natural abundances of the stable isotopes $\delta^{13}C$ and $\delta^{15}N$ of shrimp, fishes, snails, plants, and algae were used to determine the influence of anthropogenic nutrients on food web dynamics in forested and urban tropical streams in Puerto Rico.

4. Primary production (biofilm, algae and plant detritus of terrestrial origin) showed distinct $\delta^{13}C$ signatures, which provided a clear discrimination of carbon sources. The C-sources for the primary, secondary and tertiary consumers were similar among streams; enrichment with $^{15}N$ was observed in the urban streams. $\delta^{15}N$ values for all food web components varied significantly among streams.

5. These results demonstrate the importance of organic matter and the dependence of freshwater biota on terrestrial inputs.

Keywords Stomach content, Atya, Xiphocaris elongata, Macrobrachium, food web

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3 Coauthored by Omar Pérez-Reyes, Todd A. Crowl, and Alan P. Covich
Introduction

Streams in islands constitute one of the freshwater sources for the people living in these islands, in some cases the only source of freshwater. Similar to continental counterparts, streams in islands have been impacted by urbanization and the health of the ecosystem has been degraded. In these locations, the effects of urban development (Urban Stream Syndrome: Walsh et al., 2005) tend to impact the whole ecosystem due to the low order and small size streams. Islands have restricted options when developing their freshwater resources. Many islands are vulnerable to extreme climatological periods of heavy/low rains, contamination, saline intrusion, and soil erosion; but the freshwater biota in the islands consists of species adapted to exploit these hydrological and environmental conditions.

In tropical islands, urbanization occupies a large percentage of land use along streams and rivers and strongly affects the biota and habitat in them (e.g. urbanization in Puerto Rico represent 10% of the land use). Removal of the riparian vegetation, increased of impervious surface, channel destabilization and widening results in an increased in water pollution (changes in ionic concentrations, inputs of toxins, wastewater discharge, increase in water temperature, increase in sedimentation and suspended solids, and reduce of oxygen concentrations) which is recognized as the main problem in tropical streams (Ramírez et al., 2012). Density, diversity and assemblages of the freshwater biota change with an increase in water pollution in the streams. Studies in urban streams have demonstrated that some groups of macroinvertebrates are sensitive to pollution and had been replaced by tolerant taxa. The aquatic insect taxa (de Jesus-Crespo & Ramírez, 2011), ostracods (Hartland et al., 2011), annelids and flaworms (Pinilla 2010), and shrimp (personal observation) seem to be the most impacted by urbanization and water pollution in tropical urban streams.

Similar to other tropical countries, Puerto Rico went through an intensive agriculture that took place in the watersheds of all the streams. During the second half of the 20th century, the
economy of the island changed from agriculture to industrialize as result of the intervention of the local government. New urban settlements were developed near the main cities and the natural resources were endangered or extirpated. The infrastructure in the cities did not grow as the same rate of the houses and buildings then problems with water distribution, and wastewater are visible everywhere. Then fertilizers and sewage effluents, sources of nutrients and particulates of organic matter, invade the freshwater systems of the island with the results of a disruption in the natural nutrient balance and alteration the biota assemblages in the urban streams.

Four families of decapods (Atyidae, Palaemonidae, Pseudothelphusidae and Xiphocarididae), fish (Eleotridae, Gobiidae, Anguillidae, and Mugilidae), and snails (Neritidae) compose the freshwater endemic biota in the Caribbean (Covich & McDowell, 1999; Debrot, 2003; Coat et al., 2009). Most of the members in these families present an extended life cycle that included two aquatic environments, as adult, in the freshwater system and as larvae short time in the ocean. Shrimp, snails, and river gobies are diadromous species which reproduce in the headwaters where they release planktonic larvae that are transported by the water to the estuary where they go through a serial morphological changes in order to reach the metamorphosis stage, then a juvenile is formed and the upstream migrations began (Bell et al., 1995; Blanco & Scatena, 2005; Bauer, 2011 a; 2011 b; 2013). Big mouth and Cheek spiny sleepers, mountain mullets, and eels are catadromous. These migration patterns play an important role in the longitudinal distribution of the species as well in the use of different types of marine and freshwater resources (Coat et al., 2009; 2011). Similar to their counterpart in the continents (e.g. salmons), these migrations provide an exchange of nutrients between the stream and the ocean (Kohler et al., 2013; Reisinger et al., 2013). In the tropics, the lower valleys and sections near the river mouth received a direct impact from the marine environment and these areas are preferred by some representative species of shrimp (Macrobrachium acanthurus, Jonga serrei), crabs (Callinectes and Sesarma), and fish (Eleotris perniger and Gobiomorus maculatus). In
addition, these localities host juveniles of shrimp, fish, and snails in their travel to the upper parts of the stream. During the migrations these animals are exposed to different environmental conditions, and variable sources of nutrients (March and Pringle 2003; Coat et al., 2009; 2011). Migratory fauna has shown important roles in the food webs in the tropics as filter feeders, scrapers, shredders, and predators (Brasher et al., 1997; Covich & McDowell, 1996; McDowall, 2003; March & Pringle, 2003).

We studied the fish and decapod communities in three watersheds that represent a gradient of urbanization in Puerto Rico in order to propose and compare food webs, estimated the relative importance of the food sources supporting them, and determined the trophic positions of their dominant species. These comparisons are of great relevance and interest because urban streams are surrounded by an extensive gradient of urbanization in contrast to forested or low impacted streams, which are rarely exposed to urban stressors. We hypothesized that the effects of anthropogenic stressors on freshwater biota would be less dramatic in forested streams compared with urban ones. How the food web structures change with increased levels of disturbance?

**Methods**

*Site selection and classification.*

Three streams that represent different conditions of human impact in Puerto Rico were used to conduct this study. The Sabana, Bayamón and Rio Piedras watersheds were classified as low (LUW), moderate (MUW) and high (HUW) urban watersheds based on the percentage of land use. These classifications were based on the results obtained by the Puerto Rico Gap Project (Gould et al., 2008). On each stream, nine, 10 m reaches were selected to collect organisms and the physico-chemical data. The sampling reaches were distributed along a longitudinal gradient of elevation from the river mouth to the headwaters.
Río Sabana (low urban watershed- LUW) is located in the northeastern portion of the Luquillo Experimental Forest. In the headwaters, the annual mean precipitation can reach the 3250 mm year\(^{-1}\), whereas in the coast, the precipitation can range up to 2616 mm year\(^{-1}\) (Scatena, 1989; Zou & Gonzalez, 1997; Quiñones & Torres, 2005). This stream has a mean annual discharge of 13.1 m\(^3\) s\(^{-1}\) · km\(^2\), and an annual mean temperature of 25°C (Brown et al., 1983). The headwaters of this stream are protected by the National Forest Service of the U.S. Department of Agriculture (28,000 ha). The Puerto Rico government, through the Puerto Rico Environmental and Natural Resources Department, protect the mid-elevation and coastal valleys (approximately 1083 ha). The headwaters of the Sabana stream are dominated by primary forests of Tabonuco, Palo Colorado and Sierra Palm. Native trees and exotic grasses are the most common plants in the watershed.

Río Bayamón (moderate urban watershed- MUW) has a medium influenced basin due to human activities in its watershed and riparian zones. Estimates show that 22% of this basin had been affected by human activities (Ortíz-Zayas et al., 2004; 2006). This river is one of the largest rivers of the island and its watershed comprised by six municipalities (Toa Baja, Cataño, Bayamón, Guaynabo, Aguas Buenas, and Cidra) and several tributaries. The headwaters are located in the Cordillera Central at an elevation of 500 m above sea level (asl). The land cover for the Bayamón stream consisted of secondary forests and grasses those dominate sub-urban and urban land use reaches. The mean annual precipitation in the watershed ranges between 1854 to 1625 mm year\(^{-1}\) (Quiñones & Torres, 2005) and the mean annual discharge is 1.13 m\(^3\) s\(^{-1}\). The Río Bayamón has three dams (Los Filtros-Guaynabo, San Juan Dam-Aguas Buenas, and Cidra Reservoir Dam-Cidra) and a reservoir (Cidra Reservoir) that provides water to the metropolitan area (Ortíz-Zayas et al. 2004, 2006; Quiñones and Torres 2005). San Juan Dam a concrete gravity-arch structure with a vertical wall of 50 feet hight constitutes an impediment in the upstream migration.
The Río Piedras (high urban watershed- HUW) has several tributaries, and flows through San Juan City (with a population density of 3200 people km\(^{-2}\)). The watershed is located in the center of the metropolitan area and is the most urbanized watershed with more than a 60% of urban cover (Ortíz-Zayas et al., 2004; 2006; de Jesus & Ramírez, 2011). The headwaters are located in the southern part of the San Juan municipality at the elevation of 70 masl where Las Curias Reservoir is located. Río Piedras flows from Las Curias Reservoir through several residential areas, and ends into the marine zone of the San Juan Bay. The mean annual discharge for ver is 20.6 m\(^3\)s\(^{-1}\) with a mean annual precipitation that range between 1879 to 1651 mm year\(^{-1}\) in the headwater and coastal valleys respectively (Quiñones & Torres 2005). The riparian vegetation in this stream is characterized by native, exotic trees, and exotic grasses.

**Animal samples**

Adult individuals of shrimp, snails, and fish were collected for stomach and stable isotopes analyses in the streams where the studies were done; during the high rainfall period of 2009 (June - November). All organisms were collected using a backpack electro shocker (Model 12-B Battery Powered Backpack Electrofisher, Smith-Root, Vancouver, Washington, USA). The animal collections consisted of three upstream passes backpack electrofishing long pool that was bounded by 6.4 mm mesh net to limiting the emigration of decapods and fish during sampling. Hand nets were used to collect the organisms; macro-invertebrates and fish were transferred to labeled plastic bags, preserved in ice, and identified in the laboratory. The reach sampled included riffle, run, pool and the aquatic vegetation. Identifications were based Pérez-Reyes (2013) and Erdman (1981).

**Gut content analysis**

Individuals of shrimp and fishes from the studied streams were collected for gut analysis. The samples were preserved in 95% ethyl alcohol in the laboratory. Stomachs were dissected,
emptied in a Petri dish, diluted in 75% ethyl alcohol, and the content identified under a
stereoscope. The stomach content was separated and identified as: unicellular algae, filamentous
algae, coarse organic matter (> 1mm), seeds/spores, spicules, insects, spiders, shrimp/crabs, fish,
mollusk (snail), rotifers, and sand. Fine organic matter was present in all the stomach and was
removed from the analysis due to difficulties in the identification. Algae and animal parts were
identified to lowest taxonomic group using taxonomic keys available for each group.

Stable Isotopes samples

At the laboratory, shrimp were dissected and a section of the abdominal muscle (flexor
muscle) was removed, cleaned, preserved in ethyl alcohol (95%) and deposited in sterile
Eppendorf vials previously labeled. To collect tissue from the snail it was necessary to break the
shell and remove the foot. The epidermis and the operculum were removed from the foot before
preserving and placed in the labeled vial. The fish were dissected and a piece of the light muscle
tissue from the lateral side of the body was removed, cleaned and preserved. Approximately 2 g
of muscle tissue was removed from each organism and preserved prior to isotopic analysis.
Periphyton samples were collected from rocks in the streams; rock surface was scrapped using a
tooth brush and the sample collected with a dropper and deposited in Eppendorf vials. Leaves
and CPOM were collected directly from the stream, deposited in labeled sample plastic bags and
identified in the laboratory. We dried the samples at 60–75 °C for 24–48 h, ground them into a
fine powder with mortar and pestle, and packed them into acid-washed 5 mm × 8 mm tin capsules
for carbon and nitrogen isotope analysis.

The University of California Stable Isotope Facility performed all isotope analyses.
Carbon and N stable isotope ratios were determined on CO₂ and N₂ gases, produced by
combustion of samples in an elemental analyzer coupled to a continuous flow isotope ratio mass
spectrometer (ANCA-CFIRMS; Europa Scientific Crewe, England; ANCA combustion unit and
Stable isotope ratios are expressed in delta (δ) notation, defined as the parts per thousand (‰) deviations from a standard material: δ¹³C or δ¹⁵N = ([R_sample/R_standard − 1] − 1) × 1000 where \( R = ^{13}C/^{12}C \) or \( ^{15}N/^{14}N \). For C, the international standard is the Peedee Belemnite (PDM) limestone formation; N, the standard is atmospheric N (AIR). \( R_{\text{sample}} \) and \( R_{\text{standard}} \) are the fractions of heavy to light isotopes in the sample and standard, respectively.

We used δ¹³C and δ¹⁵N stable isotope data to determine the energy source and trophic position of shrimp relative to fish. Carbon and nitrogen stable isotope ratios (δ¹³C and δ¹⁵N) are tracers of energy flow in aquatic food webs (Peterson & Fry, 1987; Fry, 1988; Pinnegar & Polunin, 2000). There is typically a three- to four-fold increase in δ¹⁵N from prey to predator, such that δ¹⁵N can be used to estimate consumer trophic position.

**Estimation of trophic positions**

The δ¹⁵N values of primary producers are highly variable; δ¹⁵N values of primary consumers (shrimp, fish, and snails) were used as a baseline to estimate the trophic positions of other consumers. The formula adheres to that of Cabana and Rasmussen (1996): trophic position of consumers = [(higher level consumers δ¹⁵N − primary consumers δ¹⁵N)/3.4] + 2; where 3.4 represents an increment in δ¹⁵N per each increase in trophic position, and + 2 represents the trophic position of primary consumers that is one position higher than primary producers, a basal group counted as trophic position 1 (Vander Zanden & Rasmussen, 2001; Post, 2002; Leclerec et al., 2013).

We expected that the carbon signatures of consumer organisms would be closely aligned with their source of carbon. We do not present a mixing model applied to the data due to we were unable to sample the source of algae, organic matter, and all the exotic fish species present in the stream; these cases a mixing model would give anomalous results.
Statistical analyses

We compared the shrimp $\delta^{15}$N and $\delta^{13}$C values to the values of primary producers (leaves, CPOM, and periphyton) and primary consumers (shrimp, fish and snails), to estimates the food sources of shrimp, since isotopes values of primary producers indicate potential food sources and primary consumers provide an isotope baseline for the food web (Post, 2002).

Biplots of $\delta^{15}$N and $\delta^{13}$C values for each species were used to compare patterns of isotopic variation among streams. To view overlap of consumers, predators and prey in the bi-plot, we only plotted $\delta^{15}$N and $\delta^{13}$C values of the animal species; the $\delta^{15}$N and $\delta^{13}$C values of the CPOM, periphyton and plant species were removed from the comparison. One way ANOVAs were used to compare the means of $\delta^{13}$C and $\delta^{15}$N of primary producers and consumers among streams.

Isotopic metrics of $\delta^{13}$C and $\delta^{15}$N were and the corrected stable isotope data were then used to calculate the standard ellipse area (SEA) as measure of niche width for each species in each treatment using the SIAR package in the R computing program. SEA is a bivariate measure of the distribution of individuals in trophic space; each ellipse encloses 40% of the data and, therefore, represents the core dietary niche, indicating typical resource use within a species or population.

Results

Shrimp and fish stomach analyses. Moss, ferns, seeds/spores, wood, trichomes, roots and leaves, filamentous (Chaetophora, Spirogyra, Oedogonium) and unicellular algae (Navicula and other diatoms) constituted the main components in the shrimp stomachs. For the filter feeder shrimp (Atya innocuous, A. scabra, and Micratya poeyi) these components represented the main organic material in their stomach (Figs. 4-1a, b). Insect parts were identified in the guts of A. scabra and A. lanipes but these represented less than 3% of the total of the total stomachs analyzed. Palaemonids and xiphocarids showed more diverse stomach content than the atyids.
The organic material in their stomach were plant and algae (> 80%), and animal-derived matter (insects, spiders, snails, ostracods, freshwater sponges, rotifers, and fish) (< 12%) (Figs. 4-1a, b).

Insects were the main prey for Macrobrachium faustinum; legs, mouth parts and claws were found in the analyzed stomachs. Sand grains were found in stomachs of M. acanthurus, P. pandaliformis, and A. lanipes (Figs. 4-1a, b).

Fish stomachs were constituted mainly by algae, CPOM, snails, insects, crabs, shrimp and fish. Gobiomorus dormitor was the fish predator with a most rich diet. Sleepers feed on snails, [Tarebia (Thiara) granifera, Melanoides tuberculata, and Marisa cornuarietis] as well on Sesarma crab, M. faustinum, poecilids, Eleotris perniger and juveniles of their own species. Snails apparently constituted the most important source of nutrients for Agonostomus monticola, G. dormitor, E. perniger, and the exotic Lepomis auritus. Stomach analyses for the Agonostomus showed that this species had an omnivore diet that consisted on algae, snails, aquatic insects and small fish; no shrimp were found in their guts. American eels were present in the streams but the stomach analyses showed the presence of algae and plant organic matter.

**Stable isotopes analysis.** For all streams, shrimp and fish consumer taxa had δ^{13}C isotopes ratios heavier (higher δ^{13}C values) than the mean of basal sources samples. In the LUW, the δ^{13}C for the producers ranged from -29.82‰ (Syzygium jambos) to -27.69‰ (periphyton), ratios for primary consumer values ranged from -30.8‰ to -18.94‰ (X. elongata), and for secondary consumer were distributed from -30.13‰ (M. faustinum) to -18.29‰ (A. rostrata) (Fig. 4-2a; Table 4-1). The stable ellipsis analyses for the animal species in the LUW showed three main groups: herbivores, omnivores and carnivores. The herbivore ellipsis grouped the filter feeders (Atya) and the shredder (Xiphocaris elongata) but not the scrappers (Nereina and Sycidium plumieri). The omnivore group was composed by the Macrobrachium species. The predators group only included the sleepers (Eleotris and Gobiomorus).
In the MUW, primary producer showed a δ¹³C that ranged from -30.38 (Bambusa vulgaris) to -27.24‰ (periphyton). Primary and secondary consumers showed ratios of δ¹³C that ranged from -26.79‰ (A. scabra) to -19.23‰ (H. plecostomus) and -27.74‰ (G. dormitor) to -20.71‰ (G. dormitor) respectively (Fig. 4-2b; Table 4-1). The herbivore, omnivore and carnivore groups showed overlapped ellyssis; but only the filter feeders and the predator fish had a distinctive signature.

The HUW had δ¹³C mean values for producers that ranged between -31.33‰ (Bambusa vulgaris) to -23.41‰ (periphyton). The primary consumers had values from -29.52‰ (P. pandaliformis) to -17.37‰ (P. pandaliformis) and secondary consumers showed values between -32.60‰ (A. rostrata) to -17.37‰ (P. pandaliformis) (Fig. 4-2c; Table 4-1). The δ¹³C values for CPOM samples in the studied streams revealed heavier δ¹³C signatures in Sabana (-29.6‰) than Rio Piedras (-31.33‰) and Bayamón (-30.15‰). Periphyton samples from Rio Piedras showed heavier δ¹³C (-24.7‰ ± 0.5) in comparison with Sabana (-28.8‰ ± 0.6) and Bayamón (-30‰ ± 1.4). The herbivore, omnivore and carnivore groups showed overlapped ellyssis.

All the shrimp species and some fish were identified as grazers based on the isotopes analysis as well in the observations of vegetative organic matter in their stomachs. These grazers included Atya lanipes, A. innocous, A. scabra, Micratya poeyi, Xiphocaris elongata, Macrobrachium faustinum, M. acanthurus, Palaemon pandaliformis, Sicydium plumieri, and Awaous taijasica. Other species identified as grazers were the native snail Nereina punctulata (LUW = -22.4‰ ± 1.5) and the exotic catfish Hypostomos plecostomus (HUW = -28.26‰; MUW = -19.77‰ ± 0.27). No significant differences were observed in the δ¹³C signatures of the shrimp species among the streams. The one-way ANOVAs’ for comparison of δ¹³C signatures among streams were significant for Gobiomorus dormitor (F², 36 = 34.15, P < 0.0001) and Anguilla rostrata (F², 6 = 8.26, P = 0.04). Similar means in δ¹³C signature for Gobiomorus were
found in the LUW -21.7‰ ± 0.5 and the MUW -22.26‰ ± 0.6; the HUW had a δ\(^{13}\)C mean value of -27.46‰ ± 0.5.

Trophic positions (TP) for the primary consumers collected in the LUW revealed that the filter feeders (atyids), shredders and scrappers (snails and river gobies) had lower values (ranged between 1-Nereina punctulata to 1.99- S. plumieri). Secondary consumers in these streams were represented by M. acanthurus (TP- 2.9), M. faustinum (TP- 2.5), and A. rostrata (TP-2.9). The tertiary consumers were represented by Gobiomorus dormitor (TP-3) and Eleotris perniger (TP-3), and Anguilla rostrata (TP- 3). Organisms with heavier isotopes (δ\(^{15}\)N) in this stream were E. perniger (δ\(^{15}\)N- 12.3), G. dormitor (δ\(^{15}\)N- 11.4), A. rostrata (δ\(^{15}\)N- 10.7), and M. acanthurus (δ\(^{15}\)N- 10.7). Primary consumer species in the MUW had higher values in the TP in comparison with the LUW; A. innocuous (TP- 2.8), A. scabra (2.7), A. tajasica (3.7), H. plecostomus (2.7), S. plumieri (3.9), and X. elongata (3.0). Secondary and tertiary consumers showed TP that ranged between 1.6 (M. acanthurus) to 4.2 (E. perniger). The primary consumers at the HUW showed TP that ranged between 2 (A. tajasica) to 4.4 (H. plecostomus) and the secondary and tertiary consumers trophic positions were A. rostrata (TP - 2.3), G. dormitor (2.6), M. faustinum (2.9), A. monticola (3), and E. perniger (3.3).

For the MUW and HUW the δ\(^{15}\)N values were higher than the values obtained from the reference stream. These values likely capture enrichment with nitrogen. Comparison of the δ\(^{15}\)N enrichments between the LUW and the MUW and HUW showed that the organisms from MUW had higher levels of δ\(^{15}\)N than HUW. Atya innocuous (increment of 5.5), A. scabra (5.13), Xiphocaris elongata (5.3), and S. plumieri (12.44) showed increments in δ\(^{15}\)N levels when were compared with LUW. The secondary and tertiary consumers also had increments in δ\(^{15}\)N levels (M. faustinum- 3.32, M. acanthurus- 0.91, A. rostrata- 3.5, and G. dormitor- 2.8). Organisms in the HUW showed increments in the δ\(^{15}\)N levels in relation to LUW. Gobiomorus dormitor (0.19), M. faustinum (1.9), X. elongata (0.4), and S. plumieri (9.0) had higher δ\(^{15}\)N levels in
comparison with the LUW but were lower than MUW. Significant differences in δ¹⁵N signatures among streams were found in *Macrobrachium faustinum* (F₂,₄₉ = 23.02; P < 0.001), *Xiphocaris elongata* (F₂,₃₉ = 16.14; P < 0.001), *Atya scabra* (F₁,₂₆ = 132.47; P < 0.001), and *Atya innocuous* (F₁,₂₇ = 227.9; P < 0.001). Urban streams showed higher values in δ¹⁵N than the reference stream. Significant differences in δ¹⁵N signatures among streams were observed in *Gobiomorus dormitor* (F₂,₃₆ = 9.27; F < 0.001) and *Anguilla rostrata* (F₂,₆ = 11.65; P = 0.021).

**Discussion**

Our results showed that δ¹⁵N values in the tissues of the freshwater shrimp and fish varied remarkably among streams. Based in the position of the consumers relative to producers, periphyton, CPOM, and allochthonous matter can be important sources of carbon to many freshwater invertebrates and fish in the tropical streams. The stomach analyses observed in shrimp suggested that the diets of these organisms are mainly composed of aquatic primary producers (> 80%) (filamentous and unicellular algae) and allochthonous organic matter (CPOM, seeds, spores); however regardless of the food item each group used and exploited the available sources of nutrients in different ways.

This study suggests that filter feeders (*Atya lanipes, A. scabra, A. innocous*, and *Micratya poeyi*) shared the same autochthonous carbon sources (*Navicula, Oedogonium, Pinnularia, Closterium, and Spirogyra*) and allochthonous material (pollen, roots, trichomes, etc.). There were no clear distinctions in δ¹³C values of *Atya* from Sabana and Bayamón streams. Atyids have modified chelipeds with a brush of bristles that use to filter the water column or scrape the surface of the substrate in order to obtained organic matter. The bristles are armed with denticles that facilitate the sweeping, scrapping, plucking, and capture the food from the substrate surface. The stomachs of the atyids are adapted for the movements of fine particles into the gut than for crushing or grinding (e.g. *Macrobrachium*) (Fryer, 1977; Felgenhauer & Abele, 1983; Bailey-
Brock & Brock, 1993). Hobbs and Hart (1982) and Fryer (1977) considered *Atya lanipes* as the most ancestral shrimp among *Atya* (exploit the resources in two ways filter feeding and scapping) while *A. scabra* and *A. innocous* were considered the most specialized and ecologically restricted species (Girard *et al.*, 2013) due to their filter feeding habits. These types of feeding can result in the consumption of large amounts of FPOM, filamentous, and unicellular algae. These organisms change their feeding behavior from filter feeding to scapping; this permits the capture and incorporation of large amounts of CPOM in their diets.

The presence of insect parts in the stomach *Atya* suggests that these animals are not selective in their food consumption. Previous studies (Pringle *et al.*, 1993; March & Pringle, 2003) have shown that insects did not constitute an important aspect of the diet of *Atya* and only represent less than 1% of the total stomach content. Apparently insects are captured by the bristle in the periopods and incorporated as part of the food mass when the shrimp scrape a rock or plant matter in the stream. The absence of larger amounts of CPOM and animal parts in the stomach of *Micratya poeyi* was due to the size of shrimp. *Micratya poeyi* represents one of the smaller members in the Atyidae family. This species reach a maximum body size of 3 centimeters and their feeding consist in filtering the water column in the riffle to collect micro-organic particles. Atyids constitute a carbon sources for palaemonids, crabs, eels, and sleepers (Chace & Hobbs, 1969; Covich & McDowell, 1996).

The shredder shrimp (*Xiphocaris elongate*) was reported in the three streams with mean $\delta^{13}$C values of $-24.31\% + 0.57$ (LUW), $-21.76\% + 0.50$ (MUW), and $-22.58\% + 1.23$ (HUW). *Xiphocaris* is likely a keystone species in Caribbean streams due to its role in the recycling and decomposition of the organic matter. This species inhabits calm habitats close to the river banks where detritus is abundant (March *et al.*, 2001; March & Pringle, 2003; Coat *et al.*, 2009). *Xiphocaris* has tiny pincers that allow him to break down leaves in fine particulate organic matter and capture small macro-invertebrates. These shrimp showed a diverse stomach content that
included unicellular and filamentous algae, fine and coarse organic matter (leaves, moss, wood, trichomes) (Fryer, 1977; Covich & McDowell, 1996; Crowl et al., 2001), amoebas, insect parts (March & Pringle, 2003), and micro-crustacea (ostracods). The fine particulate organic matter produced as a result of the feeding of Xiphocaris became available to other consumers such as filter feeding shrimp, snails, clams, fish and insects (Crowl et al., 2001; 2006). In addition, Xiphocaris constitutes the source of carbon for other decapods (e.g. Macrobrachium and Epilobocera) and native fish (e.g. Eleotris and Gobiomorus). Our study suggests no change in food preferences and trophic position of Xiphocaris between reference and urban streams. This corroborates the idea presented by Crowl et al. (2006) that suggested that Xiphocaris is highly dependent on terrestrial carbon resources, especially native tree species as Cecropia, Dacryodes and Manilkara.

Palaemonids are omnivores, and the isotopic signatures $\delta^{15}$N positioned Macrobrachium faustinum and M. acanthurus in the secondary or tertiary trophic levels. In tropical studies they are classified as primary consumer in early stages and secondary or tertiary consumers when adults (Covich & McDowell, 1996; March & Pringle 2003; Coat et al., 2009). Macrobrachium faustinum, the most common and eurytopic freshwater shrimp, inhabits slow flowing rivers at low elevation sites and fast flowing streams in mountain area (Girard et al., 2013). It has a diverse diet compose of shrimp, snails, insects, spiders, crabs, fish, filamentous algae and detritus. Macrobrachium acanthurus presents a limited distribution restricted to the lower valleys and elevations near the estuaries. The stomach content of M. acanthurus consists of grass, seeds, filamentous algae and insects; plants and organisms accessible in the urban reaches. Macrobrachium spp. ingests larger pieces of organic material and some animal parts compared to the finer particles in the guts of the atyids. They exploit a wide and diverse range of food items in the streams. Palaemonids have very strong pincers that use to break and crunch the chitinous exoskeleton of insects (Carvalho et al., 2011), crustaceans, and the shell of snails (Mantel et al.,
2004; Blanco & Arroyave, 2009) or fruits. Palaemonids constitute an important component in the diet of other shrimp, crabs, fishes, birds, and snakes.

The coupled analyses of gut content and stable isotopes demonstrated different feeding strategies in the fish communities among the LUW, MUW, and HUW. The δ\textsuperscript{13}C values for the algaevores and detritivores *Sycidium plumieri* ranged between -22.6 to -26 ‰, compared to other fish species. In LUW the δ\textsuperscript{13}C value for *Sycidium* was -22.6‰ closer to the scraper snail *Nereina*. These species feed on similar resources. The carbon signatures for this species from the urban streams (MUW and HUW) relate it with the omnivorous and carnivorous fishes (*Oreochromis*, *Lepomis* and *Gobiomorus*). *Sycidium* derived their carbon nutrients from the algae and desmids scraped from the substrate surface (Gillet, 1983). Its mouth parts are adapted to grazing slime algae (desmids) that grow on the surface of rocks and stones in the fast-moving water. The jaw of this fish has a ridge-like structure in the front which probably aids in scraping algae off the rock surfaces, teeth will regularly be replaced so as to allow grazing and the intestines are long and coiled to digest the vegetative organic matter (Erdman, 1961; 1986; Keith, 2003; Maie *et al.*, 2008). Similar results were observed in *S. punctatum* by Gillet (1983), but differ from the observations done by Maciolek (1977) in the sibling species *Lentipes concolor*. *Lentipes* can change its diet from herbivore to carnivore when the goby increase in size. *Awaous tajasica* and *Agnostomus monticola* were classified as omnivores. Isotopic similarities between consumers with different feeding strategies suggest similar food sources. Studies with sibling species of *Awaous* showed that the diet of these gobies consisted on filamentous algae, diatoms, and insects (Ego, 1956; Sabino & Correa, 1990; Kido *et al.*, 1993; Watson, 1996; Kido, 1997; Debrot, 2003). Isotopic signatures and gut analysis of *Agonostomus monticola* identified this fish as an omnivorous. In our study the isotopic values δ\textsuperscript{13}C placed this planktonic fish with the benthic species *G. dormitor* and *H. plecostomus*; this supports the idea of a mixed diet. Studies from Costa Rica (Winemiller, 1983), Honduras (Cruz, 1987; Matamoros, personal...
communication), Jamaica (Aiken, 1998), Mexico (Torres-Navarro & Lyons, 1999), Trinidad (Phillip, 1993), Puerto Rico (Ramírez, personal communication), and the United States (Loftus et al., 1984) characterized *Agonostomus monticola* as omnivore fish. Aiken (1998) and Cotta-Ribeiro and Molina-Ureña (2009) supported the idea of omnivory because the mountain mullet changes its diet from insectivorous (juveniles stage) to herbivores when adult (leaves and filamentous algae). Also with the change in diet an increase in the length of the intestine has been observed.

The carnivorous guild was represented by benthic consumers. *Eleotris, Gobiomorus*, and *Anguilla* constitute the top freshwater predators in these streams. The feeding behaviors, stomach content analyses, and the δ¹³C signatures for these species reveal diets that consist primarily on snails, shrimp, fish, insects, and some plant detritus. *Eleotris, Gobiomorus* and *Anguilla* are benthic fishes with a sit-and-wait behavior to capture their slow moving prey (shrimp, small sleepers, and snails). Variation in the isotopic signal can be the result of a mixed diet or an ontogenic shift in prey utilization. Bacheler *et al.* (2002; 2004) reported changes in diet between juveniles and adult sleepers. Small individuals (< 100 mm) prefer insects, plankton, and ostracods while larger bigmouth sleepers (> 200 mm) feed on fish and crabs. These studies differed markedly with the results from Nordlie (1981) and Winemiller and Ponwith (1998) that reported a diet based mainly on shrimp. Our results support the idea of a mixed diet in bigmouth sleepers. *Eleotris perniger* feed on *Tarebia (Thiara) granifera* and *Marisa cornuarietis* snails (shell lengths > 10 mm), which in some occasions seemed disproportionate in size for ingestion and by the number of snails in the gut. These observations in *Eleotris* spp. agree with the reports from Brazil (Teixeira, 1994), Costa Rica (Nordlie, 1979; 1981; Winemiller & Ponwith, 1998), and Japan (Suzuki & Senou, 1981; 1982; Maeda & Tachihara 2004). The stomach analyses for *Eleotris* showed that the introduced melanoid snails constitute the first source of nutrients for this fish. There no clear idea about how *Eleotris* got the nutrients from the snails due to all the snails...
in the stomach and gut had unbroken shells, operculum closed and the internal body been complete. This might suggest that the spiny sleeper ingests snails but derive the nutrients from the algae that grow in the external surface of the shell. The stomach contents of *Anguilla rostrata* observed in this study were congruent with previos analyses done by Ogden (1970), Wenner & Musick (1975), Waldt *et al.* (2012). These studies showed that *Anguilla* has a diet based in bottom organisms and its change as the animal grows. In juvenile stages, the stomachs reflect the presence of insects while adults consumed mostly crustaceans and fishes.

The description of the overall feeding relationships of the dominant species in the reference and urban streams in Puerto Rico were developed by integrating the stomach content data and the isotope data described in this study. The food web described for the LUW contains four trophic positions moving carbon from the primary producer (periphyton, CPOM, vegetative matter) through three or four trophic levels occupied by omnivorous and carnivorous fishes. In this food web algaevores fish (*S. plumieri*), freshwater snail (*N. punctulata*), filter feeder atyids (*Atya* and *Micratya*) and the shredder shrimp (*X. elongata*) consume CPOM, debris, and leaves at the TP 2 or close to 2 (herbivores). Vegetative organic matter is incorporated by adults of *M. faustinum*, which are consumed by larger palaemonids (*M. acanthurus*), and the American eel (*A. rostrata*) (omnivores). Macroinvertebrates and some juvenile fishes are consumed by predatory fishes (*E. perniger* and *G. dormitor*) in TP 4 (carnivores). The primary and secondary omnivore consumers obtain their carbon directly from the periphyton, CPOM and allochthonous sources. Then the carbon is transported from macroinvertebrates (juvenile shrimp and crabs, and snails) to macroinvertebrates (adult shrimp and crabs) and fishes, which in turn are eaten by top consumers (predatory fishes).

In the urban streams the absence of important components of the food web (i.e. filter feeders) and the addition of new predators resulted in changes in the trophic levels and guilds. In the medium impact stream of Bayamón the number of animal species and the carbon sources
available were similar to the reference stream. The shrimp community in the highly impacted stream decreased (from 12 species to 4) in comparison with the middle and reference streams. The variation in δ\(^{13}\)C for *Gobiomorus dormitor* and *Anguilla rostrata* can be related with the carbon sources available in each stream and the ontogenic shift of the species (Waldt *et al.*, 2013). The animal communities in the LUW and MUW were similar in contrast to HUW. In the highly impacted watershed the absence of filter feeder shrimp and the lower number of palaemonids and xiphocarids suggest an increase of inter and intra specific predation in the fish community. This behavior was observed in the stomachs analyses of *Gobiomorus* and *Anguilla* where larger individuals fed on smaller. The nonexistence of filter feeder shrimp in the HUW redounded in the accumulations of FPOM and sedimentation. The accumulation of fine particulate and the incorporation of human derived organic matter reduce the surface available for insects, algae, plants and other organisms that use substrates for attachments. In this stream, the absence of atyids represented the change in diets for *Xiphocaris elongata* and *Macrobrachium faustinum*. *Xiphocaris elongata* changed the preferred carbon sources CPOM and filamentous algae to unicellular and filamentous algae. *Macrobrachium faustinum* also diversified their diets. In the reference stream it was based on CPOM, unicellular and filamentous algae, but in the highly urban stream incorporated animal-derived material (spiders, sponges, insects, seeds, and micro-crustaceans).

The presence of exotic fish species (e.g. *Cichla ocellaris, Lepomis auritus, Oreochromis mossambicus, Micropterus salmoides*) may result in alterations on the food web. These species were introduced by the government as game fishes and biological control of invasive snails, parasites and insects. The incorporation of piscivores and omnivores fishes to the freshwater ecosystem represents an alteration of a balanced food web due to an overlap with the diet of the native *G. dormitor* (Bacheler *et al.*, 2004).
Animals in the medium and highly impacted streams had higher $\delta^{15}\text{N}$ values than the reported in the reference stream. An increase in $\delta^{15}\text{N}$ stable isotope ratios in primary producers in the urban streams suggests the influence of wastewater or fertilizers into the stream water that might be related with changes in land use in the watersheds (Potter et al., 2013). The increase in $\delta^{15}\text{N}$ of the primary producers is passed on to consumers in the food webs of these streams. Consumers from MUW and HUW had higher $\delta^{15}\text{N}$ signatures than their counterparts in the reference stream of LUW. There are no discernible correlations between feeding mode and the magnitude of difference in $\delta^{15}\text{N}$ signatures between streams. Previous studies (Chang et al., 2002; Houhou et al., 2010; Bucci et al., 2011; Winemiller et al., 2011) reported that higher levels in $\delta^{15}\text{N}$ have been associated to inputs of fertilizers and sewer waste in the rivers, mangrove, and coastal zones. The land use in MUW is mostly private (99.9%) and only 0.1 % is on government hands (Gould et al., 2008). The urban and sub-urban developments constitute 30% of the land use and the remaining are forest, grasslands, wetlands, and agriculture lands. Municipalities those share the watershed of this stream used more than 40% of their lands as croplands and livestock lands which represent an increase in fertilizers and manure that reach the stream (Census of Agriculture, 2007). Ramos-Gines (1997) estimated that the amount of nitrogen that enter and leave the Rio Bayamón Reservoir was 18,863 kg/year and 8,600 kg/year respectively; most of the nitrogen inputs came from surface-water runoff (agricultural area- 9,780 kg/yr, forested area- 1900 kg/yr) and urban areas (sewered- 591 kg/yr; unsewered 2,280 kg/yr).

The HUW has a smaller watershed area than MUW, but a larger proportion of the watershed is urbanized. The water quality varies by location and season, and receives both point and nonpoint sources of pollution that occurs upstream. This pollution contributes excessive nutrient and contaminants in the lower valleys and the estuary resulting in eutrophication and biomagnifications problem in animals (crabs, mussels, fishes) (Webb & Gómez-Gómez, 1998; Delgado-Morales et al., 1999). Point and nonpoint pollution in combination with other effects of
urban land use have a direct impact on sensitive aquatic biota resulting in changes in the food web (Walsh et al. 2005; Wenger et al. 2009; Kininkova 2012).

Urban streams located in cities near the metropolitan areas tend to be impacted directly or indirectly by human activities. Higher enrichment of $\delta^{15}$N may occur with high Nitrogen loading in streams from human activities and illegal wastewater discharge. The species present in the urban streams showed higher levels of $\delta^{15}$N in their tissues than records that have been reported for pristine streams. Previous studies that have examined the influence of wastewater inputs to rivers, reservoirs and estuaries have also reported enriched $\delta^{15}$N in primary producers, macroinvertebrates and fish (McClelland et al., 1997; 1998; Piola et al., 2006; Eitzman & Paukert, 2009; Xu & Zhang, 2012). In this study $\delta^{15}$N enrichments were evident in the primary ($\textit{Xiphocaris elongata}$ and $\textit{Sycidium plumieri}$), secondary ($\textit{Macrobrachium faustinum}$), and tertiary consumers ($\textit{Gobiomorus dormitor}$) of MUW and HUW. Also the periphyton and CPOM were enriched with $\delta^{15}$N. The primary consumers had the largest enrichments of $\delta^{15}$N in their tissues. The MUW and HUWs streams had the greatest input of anthropogenic $\delta^{15}$N derived from sewer and septic leakages (Quinones & Torres, 2005; Potter et al., 2010; 2013 de Jesus-Crespo & Ramírez, 2011; Personal observation) which discharge solid matter into the stream that can be incorporated as source of nitrogen by the organism in the stream. Studies on $\delta^{15}$N signatures of the major sources of nitrogen (fertilizers and sewage) have shown that the nitrogen derived from human activities (sewage) have a distinctive value $\delta^{15}$N (range between 10 - 25‰) than other sources which have values that are relatively low (-5 to 5‰). Previous studies also concluded that the higher values in $\delta^{15}$N can be attributed to the fractionation process during the ammonification and subsequent volatilization of nitrogenous waste products (Cabana & Rasmussen, 1996). Nitrogen or related compounds can enter the stream water and being assimilated by the phytoplankton and subsequently consumed and incorporated by macroinvertebrates. Other studies correlate the amounts of $\delta^{15}$N in the stream water with the land
use in the watershed and have shown a difference in $\delta^{15}$N between forested and non-forested streams. There do not appear to be differences between agricultural and urban catchments however (Peipoch et al., 2012).

Based on our results, we concluded that there is significant variation in the food webs among low, medium and highly impacted streams in Puerto Rico. The variations consisted mainly in the amount of $\delta^{15}$N. Carbon source for the primary, secondary and tertiary consumers showed no differences. This demonstrates the importance of the organic matter in the ecosystem and the dependence of the freshwater biota on the terrestrial inputs. Independent of human inputs of Nitrogen, the aquatic organisms show the same dependence on carbon from allochthonous inputs. Autochthonous and allochthonous inputs subside in the primary, secondary and tertiary consumer directly or indirectly. Grazers and carnivorous use, or used these resources in different ways throughout their life cycle. The urban food webs presented in this study represent a generalized food web for urban streams in the tropics where the water pollution has an effect in the freshwater biota. This research provides further evidence for the importance of anthropogenic inputs on the organization of aquatic food webs. Excess in $\delta^{15}$N results in significant differences in trophic levels of the food webs from urban streams in comparison with the reference stream where the anthropogenic inputs are minimal. The enrichment in $\delta^{15}$N had an impact in all the tropic levels by increasing the trophic position of all consumers and decreasing the differences among feeding groups in terms of trophic level (Fig. 4-2). The urban rivers of Bayamón and Rio Piedras have similar fish communities, riparian vegetation and have polluted waters (fertilizer and wastewater). The amounts of $\delta^{15}$N were higher than normal and in some occasions were three times the values observed in the reference stream. This research further confirms the significant impacts of human activities on stream and watershed health and services of the ecosystem. In addition, we suggest that local authorities and researchers focus more on the management and
restoration highly impaired watersheds and make informed decisions about the wastewater treatment.

Acknowledgments

We thank the people who joined us in the field for deployment, with special appreciation to the fieldwork done by Francisco J. Pérez and José A. Rivera. This research was supported by grants BSR-8811902, DEB 9411973, DEB 0080538, DEB 0218039, and DEB 0620910 from National Science Foundation (NSF) to the Institute for Tropical Ecosystem Studies, University of Puerto Rico, and to the International Institute of Tropical Forestry, United States Department of Agriculture (USDA) Forest Service, as part of the Long-Term Ecological Research Program in the Luquillo Experimental Forest. Also was supported by the San Juan-ULTRA Project (NSF Grant 0948507). The USDA Forest Service and the University of Puerto Rico gave additional support.
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Ego K. (1956) Life history of freshwater gobies. Freshwater game fish management research. Department of Land and Natural Resources. Territory of Hawai‘i, Honolulu. Project No F-4-R.


Table 4-1  Feeding habits of the studied species based, the $\delta^{13}$C and $\delta^{15}$N values (mean ± SE) and the sample size of the macroinvertebrates and fish communities from the LUW, MUW, and HUW (Sabana, Bayamón, and Rio Piedras).

<table>
<thead>
<tr>
<th>Watershed</th>
<th>Species</th>
<th>Code</th>
<th>Description</th>
<th>Mean $\delta^{13}$C</th>
<th>N</th>
<th>Mean $\delta^{15}$N</th>
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<td>LUW (Sabana)</td>
<td>Atya innocuous</td>
<td>Ai</td>
<td>Herbivore</td>
<td>-24.79 ± 0.11</td>
<td>20</td>
<td>6.31 ± 0.19</td>
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<td></td>
<td>Atya lanipes</td>
<td>Al</td>
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<td>-24.89 ± 0.17</td>
<td>20</td>
<td>6.44 ± 0.26</td>
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<td></td>
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<td>As</td>
<td></td>
<td>-24.68 ± 0.06</td>
<td>20</td>
<td>6.36 ± 0.24</td>
<td>20</td>
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<td></td>
<td>Micratya poeyi</td>
<td>Mp</td>
<td></td>
<td>-24.31 ± 0.09</td>
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<td>7.28 ± 0.25</td>
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<td>9.43 ± 0.41</td>
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<td>Herbivore</td>
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<td>31</td>
<td>7.57 ± 0.31</td>
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<td>Ar</td>
<td>Carnivorous</td>
<td>-18.97 ± 0.35</td>
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<td>10.69 ± 0.32</td>
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<td>Ep</td>
<td></td>
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<td>2</td>
<td>12.28 ± 0.48</td>
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<td>Gobiomorus dormitor</td>
<td>Gd</td>
<td>Carnivorous</td>
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<td>Muw (Bayamón)</td>
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<tr>
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<td>21</td>
<td>9.56 ± 0.56</td>
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<tr>
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<td>10.54 ± 0.97</td>
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<td>12.01 ± 0.7</td>
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<td>Energetic Efficiency</td>
<td>Number of Observations</td>
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<td>-27.46 ± 0.49</td>
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<td><em>Anguilla rostrata</em></td>
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<td>-28.85 ± 3.75</td>
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<tr>
<td><em>Eleotris perniger</em></td>
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<td>Carnivorous</td>
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<td>Periphyton</td>
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<td>Carnivorous</td>
<td>-31.33</td>
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Fig. 4-1 Proportions of food items in stomachs of *Atya innocuous* (*Ai*), *A.lanipes* (*Al*), *A.scabra* (*As*), *Micratya poeyi* (*Mp*), *Macrobrachium acanthurus* (*Ma*), *M.faustinum* (*Mf*), *Xiphocaris elongata* (*Xe*), and *Palaemon pandaliformis* (*Pp*) shrimp from the LUW (Sabana) (a), MUW (Bayamón) (b) and HUW (Rio Piedras) (c) rivers.
Fig. 4-2  δ¹³C and δ¹⁵N stable isotope biplots for primary, secondary and tertiary consumers collected from LUW (a), MUW (b) and HUW (c). Shrimp filter feeders closed circle, shrimp omnivores as closed circle, herbivore fish as closed diamond, predator fish as open diamond, and snail as coled triangle. Continuous line represents herbivore, dotted line as omnivores, and long dashed line as predators. Values are mean ± Standard Error (SE).
CHAPTER 5
EFFECTS OF FOOD SUPPLIES AND WATER TEMPERATURE ON GROWTH RATES OF TWO SPECIES OF FRESHWATER TROPICAL SHRIMPS

Summary

1. Growth rates of individual freshwater shrimp of the species *Atya lanipes* and *Xiphocaris elongata* were measured in a second-order stream in the Luquillo Experimental Forest in Puerto Rico over 10 years (1997-2007). Shrimp living at lower altitudes in warmer water and wider stream channels with more algal and detrital foods were predicted to grow and reproduce more rapidly.

2. Shrimp were marked and re-captured periodically in pools located at three altitudes to determine if temperature affected growth rates among individual *A. lanipes* and *X. elongata*.

3. Mean annual water temperatures ranged from 20 to 24°C with the uppermost pool being cooler than the lower pools. Mean annual growth rates for *Atya* and *Xiphocaris* were 0.27 and 0.1 mm carapace length, respectively for all three populations.

4. Differences in growth were partially influenced by how each species obtains its food. *Atya* is a filter-feeder and scraper and has continuous access to suspended organic particles and biofilms. The slower growth rate for *Xiphocaris elongata* is most likely a result of the wider range in quality and accessibility of food resources.

5. Differences in pool morphology and depths probably affected differences in food availability. Increased leaf litter retention in the deeper upper and lower pools probably increased shrimp growth rates while washout of leaf litter from the relatively shallow, elongate mid-altitude pool decreased *Atya lanipes* growth rates.

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*Coauthored by Omar Pérez-Reyes, Todd A. Crowl, and Alan P. Covich*
6. These long-lived, slow-growing shrimp species transform a wide range of organic materials into their biomass. Because of the slow growth rates of these detritivores shrimp, tropical storms, hurricanes, droughts or other disturbances could have persistent, long-term impacts on detrital processing and on the populations of their predators.

**Keywords.** amphidromous, *Atya lanipes*, environmental factors, reproduction, *Xiphocaris elongata*

**Introduction**

Progress with identification of the decapod species diversity in Caribbean fresh waters (e.g. Karge *et al.*, 2013; Pérez-Reyes *et al.*, 2013) has stimulated more ecological research now that investigators can study the dispersal (Kikkert *et al.*, 2008) and evolution of co-occurring species (Page *et al.*, 2008; Bauer, 2013). Understanding of the primary controls on growth rates (Bright, 1982; Yam & Dudgeon, 2006; Vogt, 2012) and predator-prey dynamics (e.g. Crowl & Covich, 1994; Hein *et al.*, 2010; Ocasio-Torres *et al.*, 2014) is accelerating. Recent studies of growth (Cross *et al.*, 2008), dispersal (Kikkert *et al.*, 2008; Covich *et al.*, 2009), feeding (Covich, 1988a; 1988b; Pringle, 2003; Crowl *et al.*, 2001; 2006) and nutrient cycling (Benstead *et al.*, 2010) by decapods in Puerto Rican streams provide additional information on the life histories and ecological dynamics of these taxa (*Atya* and *Xiphocaris*) and their decapod predators (*Macrobrachium* and *Epilobocera*) in Neotropical insular rivers and coastal headwaters.

Decapod growth and reproduction can occur year round due to the rather uniform temperatures of warm tropical streams. Water temperature (Mantelatto & Barbosa, 2005; Chun *et al.*, 2008), food resource availability (Cross *et al.*, 2008) and possibly population density (Araneda *et al.*, 2008) are considered the major factors that influence the growth rates of freshwater decapods (Collins & Petriella, 1999). The growth of decapods is complicated due to
variations in the number and timing of molts, differences in size increment between molt events, differential growth among different ages and sexes, reproductive effort, and variations in susceptibility to predation (Hartnoll, 1983; 2001; Crowl & Covich, 1994; Cross et al., 2008; Chang et al., 2012).

Here we report growth rates of marked individuals of the two most abundant shrimp species (Xiphocaris elongata and Atya lanipes) in the headwaters of the Luquillo Mountains to compare changes in growth under natural conditions over 10 years and in response to storm-driven disturbances. In addition to temperature, the relatively continuous inputs of leaf litter (main source of detrital energy in these forested headwaters), are considered important drivers of shrimp growth (Crowl et al., 2012). The large pulse of leaf-litter input resulting from high winds and the high discharge that washed leaf-litter downstream during Hurricane Georges (September 1998) provided an opportunity to determine if this altered food availability affected individual growth rates of shrimp in different pools along an altitudinal gradient (Luq-LTER Algae data) (Crowl et al., 2012). Previously, we established that these freshwater shrimp species can respond relatively quickly to large-scale disturbances such as Hurricane Hugo in September 1989 (Covich et al., 1991), change their timing of reproduction at different altitudes (Johnson et al., 1998), have relatively long life spans, and have growth rates possibly influenced by inter- and intra-specific densities in headwater pools (Cross et al., 2008). Using data from this long-term study we here evaluate two hypotheses: 1) warmer water in downstream pools increases shrimp growth rates in a montane drainage network; and 2) access to higher quantity and quality of food in downstream pools (where channel widths are greater, increased light levels enhance algal growth, and leaf litter retention is longer) increases shrimp growth rates.
Material and Methods

Study site

The study took place in Quebrada Prieta, a second-order stream located in the Luquillo Experimental Forest (also known as the El Yunque National Forest) in the Luquillo Mountains (LM) of Puerto Rico (latitude 18°18’ N, longitude 65°47’ W). The headwaters of Quebrada Prieta are located at 550 m above the sea level and flow into Quebrada Sonadora at approximately 300 m altitude. The riparian forest has a closed canopy dominated by yagrumo (*Cecropia schreberiana*), tabonuco (*Dacryodes excelsa*) and the sierra palm (*Prestoea montana*) (Laurence, 1996; Crowl *et al.*, 2012; McDowell *et al.*, 2012). Although these dominant rainforest trees provide a relatively continuous input of organic matter (leaf litter, twigs, flowers, stems and fruits) to the stream, this input increases during high-rainfall periods from May to June and from September to November (Crowl *et al.*, 2001; Heartsill-Scalley *et al.*, 2012; McDowell *et al.*, 2012). The steeply sloped stream channel is lined with cobbles and boulders with variable amounts of sediments from bank erosion and landslides. Pools tend to have finer substrata of sand and silt. The mean annual water temperature is 22 °C and the mean annual precipitation is 3,600 mm. Stream water temperature is affected by season and rainfall; temperature is lower from November to March and briefly after large rainfall events. Rainfall is generally lower from December to May (Low Rainfall- LRF). The wettest months coincide with the hurricane season in the Atlantic that starts in June and ends in November (High Rainfall- HRF) with a peak storm activity from mid-August to late October (Ewel & Whitmore, 1973; Helmer *et al.*, 2002; Gould *et al.*, 2008; McDowell *et al.*, 2012).

The decapod community is dominated by a filter-feeder/scaper, *Atya lanipes* Holthuis 1963, and a shredder/grazer, *Xiphocaris elongata* (Guérin-Méneville 1856). Other decapod species such as *A. scabra* (Leach 1815), *A. innocous* (Herbst 1792), *Macrobrachium carcinus* (Linnaeus 1758), *M. faustinum* (de Saussure 1857), *M. crenulatum* (Holthuis 1950), *M.*
heterochirus (Wiegmann 1836) and Epilobocera sinuatifrons (A. Milne-Edwards 1866) were occasionally collected at low numbers.

**Sampling and growth measurements**

Surveys of decapod species distributions in Quebrada Prieta have been carried out since 1988 as part of the Luquillo Long Term Experimental Research (LUQ-LTER) Program. Distribution, abundance and reproductive status of freshwater decapods in six pools along a 1200 m stretch of stream channel were sampled at least bi-annually. Three pools distributed along an altitudinal gradient (305 m, 360 m, and 433 m) were selected for our current studies on growth rates and were during 1997-2007.

Gee’s Minnow traps were baited and left overnight in each pool as in previous long-term studies (Covich et al., 1996; Covich et al., 2009). The overnight period was necessary to capture the largest number of shrimp due to the nocturnal activity of these species (Johnson & Covich, 2000). The number of traps per pool was based on the superficial area of the pool (0.5 traps . m$^2$).

Growth rates of Xiphocaris elongata (N = 209) and Atya lanipes (N = 437) shrimp in Quebrada Prieta were determined using mark-recapture. Visible Elastomeric Implant Tags (Northwest Marine Technologies, Tumwater, WA, U.S.A.) were inserted laterally below the integument of the fifth and sixth abdominal segment of the measured shrimp. This numeric tag allowed for individual identification. These tags generally have over 88% retention over several years and have no significant effect on growth or mortality (Isely & Stockett, 2001; Buňič et al., 2008; Dinh et al., 2011). The initial size of the tagged shrimp ranged between 10.6-14.5 mm. Batch markings were also employed using different colours for shrimp in each of the three pools. These individuals ranged between 9.9-10.5 mm CL. Different elastomeric tag colours were assigned to each pool: low (green), mid (red), and high (yellow) altitude. Shrimps were marked in July (high rainfall period) of 1997.
During bi-annual sampling, shrimp were identified by species, counted and their reproductive status recorded (gravid or/and mature, non-gravid). Carapace length (CL) and presence of coloured tags were also recorded on site. Shrimp were measured from the tip of the rostrum to the post-median edge of the cephalothorax to the nearest 0.01 mm with a dial caliper. The CL measurements were used instead of the post-orbital length due to the absence from the stream of fish that induce variable enlargement of the rostrum in the shrimp (Covich et al., 2009; Ocasio-Torres et al., 2014; 2015). All shrimp were returned to their respective pool. Identifications were based on Chace & Hobbs (1969). If storm flows occurred during the sampling, traps were removed, shrimp released and the sampling re-scheduled for the next day that had base-flow conditions. Physical parameters measured for the pools included three width measurements, five random depths, maximum water depth, and pool length. Pool area and volume were derived from these data. Shrimp densities (shrimp. m$^{-2}$) were determined from each pool during sampling. Values for precipitation, together with air and water temperature, were obtained from the long-term data sets of the LUQ-LTER. We calculated growth rate (GR) as:
\[
\text{Growth Rate (mm} \cdot \text{year}^{-1}) = (\text{final length} - \text{initial length}) \ast (\text{time})^{-1}.
\]
All calculations of length were based on CL.

**Statistical analysis**

Long-term data from the LUQ-LTER that comprise the years 1997-2007 were used to estimate the bi-annual density of marked and unmarked shrimp in each pool. To determine variations in population density, Two-Way ANOVAs were performed for each pool using the low rainfall (LRF) and high rainfall (HRF) periods and the time (years 1997-2007) as factors. Prior to the analysis all the density data were tested for their fit to normal distribution and for homogeneity of variance, and were transformed using the natural log transformation for population data [Ln (X + 1)]. Adult shrimp were sorted into size classes based on carapace
length; *Atya lanipes* in five 5.0 mm size classes and *Xiphocaris elongata* in six 3.0 mm size classes. Percentages of breeding (gravid) females of both species in the LRF and HRF months were plotted as annual histograms per pool during the 10 year period. Two-Way ANOVAs were performed to determine if there were significant differences in the mean cephalothorax length for each species per pool (lower, middle and upper altitudes) and year (1997-2007), and to determine variation in shrimp densities across time and rainfall periods (Low Rainfall- LRF and High Rainfall- HRF) per pool. Linear regressions (Mean CL versus Time) for each species were performed to compare the growth rates of the shrimp among pools; the slopes were compared using analyses of covariance (ANCOVA).

**Results**

*Environmental factors*

The mean annual water temperature ranged between 20 and 24 °C among the three pools. The coldest temperatures were recorded during the months of November to March in the uppermost pool, while the warmest were recorded from July to September in the lowermost pool. Differences among the monthly mean temperatures (F$_{11,505} = 70.99$; $P < 0.00001$) and throughout the years (F$_{10,505} = 8.38$; $P < 0.0001$) were both significant. The lowest temperature was recorded in January 2005 (19.6 °C) and the lowest monthly mean water temperature was for January (21 °C ± 0.07 standard error). The warmest water temperature was recorded in September of 1997 (24 °C), while the highest mean monthly temperature was for September (23 °C ± 0.05). Monthly total rainfall ranged from 9.4 mm . month$^{-1}$ (March 2005) to 1076 mm . month$^{-1}$ (May 2004); the lowest monthly mean was for March (166.5 ± 42.9 mm) and the highest (453.2 ± 64.0 mm) during Hurricane Georges in 1998. Precipitation differences were significant on a monthly basis (F$_{11,110} = 2.22$; $P < 0.018$), but these differences were not significant across years (F$_{10, 110} = 1.78$; $P > 0.07$).
All of the three pools had low concentrations of dissolved nutrients (DOC 1.5 ± 0.83 mg L\(^{-1}\); DON 0.06 ± 0.04 mg L\(^{-1}\); TDN 0.15 ± 0.11 mg L\(^{-1}\)) and low conductivity (75.2 ± 13.3 micromhos cm\(^{-1}\)) with moderate hardness and a range of pH 6.2 to 8.0 (Table 5-1). The nitrogen and phosphorus concentrations were also low and typical of other Luquillo streams (McDowell et al., 2012).

**Shrimp abundance and growth**

A total of 42,563 shrimp was captured from the three pools in Quebrada Prieta from 1997 to 2007. The percentage of tagged shrimp recaptured annually from 1997 to 2007 ranged between 0.02 (2006) to 20.0 % (1999). No significant differences in the *Atya* densities across time and rainfall periods were observed in any of the pools. Densities of *X. elongata* varied significantly across time (F\(_{10,10}\) = 12.33; \(P < 0.0001\)) and rainfall periods (F\(_{1,10}\) = 24.63; \(P = 0.001\)) in the mid-altitude pool, and no significant variations were observed in the upper and lower pools. Inter-site differences in *A. lanipes* abundance showed higher densities of shrimp in the highest pool than in the middle and lower pools (F\(_{f,65}\) = 4.00; \(P = 0.028\)), but no significant differences were observed across time. Significant differences were observed in the *Xiphocaris elongata* densities across pools (F\(_{2,65}\) = 9.92; \(P < 0.0001\)) and time (F\(_{10,65}\) = 2.33; \(P = 0.033\)).

Breeding females of *Xiphocaris elongata* were more frequently observed during the HRF periods than the LRF, whereas *Atya lanipes* showed no preference between the LRF and HRF periods for reproduction. Only individuals in the lower pool showed a similar percentage in gravid females across time (Fig. 5-1).

The annual mean CL of *A. lanipes* showed significant differences among pools (F\(_{2,32}\) = 15.03; \(P \leq 0.0001\)) and across years (F\(_{10,32}\) = 3.11; \(P = 0.015\)) (Fig. 5-2a). The largest mean CL (17.2 ± 0.27 mm) was observed in the lower pool during 1997, while the smallest mean was 12.9 ± 0.16 mm from middle pool in 2007. After Hurricane Georges in September 1998, large
reductions in mean CL of *Atya lanipes* were observed in all the pools during 2000. The shrimp in the lower and upper pools increased their mean CL after the decrease in 2000, but the mean size of the organisms in the middle pool continued to decrease until 2007. Significant differences in mean CL of *Xiphocaris elongata* were observed across time ($F_{10,32} = 3.99; P = 0.004$), but not among pools. Mean CL of *X. elongata* ranged between $13.1 \pm 0.15$ mm (lower pool during 2000) to $15.1 \pm 0.27$ mm (upper elevation pool during 1997) (Fig. 5-2b).

A total of 329 shrimp (203 *A. lanipes* and 126 *X. elongata*) was measured, captured, marked and released in the three pools in 1997. The mean CL of the re-captured *A. lanipes* in 10 years ranged between $11.91 \pm 0.92$ and $15.56 \pm 0.72$ mm, while for *X. elongata* the mean CL ranged between $12.1 \pm 0.07$ and $14.23 \pm 0.62$ mm. Different growth between the two species revealed that individuals of *Atya lanipes* grew more than *Xiphocaris elongata* (Fig. 5-3). The filter feeder, *A. lanipes*, had a mean growth rate of 0.27 mm year$^{-1}$ ($CL = 0.2726^{*}Time - 532.75; r^2 = 0.687; P < 0.003$), while the shredder/grazer, *X. elongata*, had an overall mean growth rate of 0.1 mm year$^{-1}$ ($CL = 0.0843^{*}Time - 155.88; r^2 = 0.2105; P = 0.156$). The comparison of the slopes shows significant differences in CL across time ($F_{1,18} = 13.31; P < 0.002$) but not between species ($F_{1,18} = 0.06; P = 0.807$).

**Discussion**

Populations of *Atya lanipes* and *Xiphocaris elongata* in the Quebrada Prieta are widely distributed among headwater pools (Covich *et al.*, 1996; Crowl *et al.*, 2001). Comparison of the mean growth of both species among pools revealed faster growth of *A. lanipes*, a filter feeder and scraper, while the mean growth of *X. elongata*, a shredder and grazer, was similar among pools and across time. As expected, shrimp in warmer waters grew faster than those in cooler waters. These observations are the first to document a significantly higher growth rate for *A. lanipes* than *X. elongata* over a range of temperatures, pools, densities and time.
The size distributions in the populations of *Atya lanipes* and *Xiphocaris elongata* followed the distribution observed in previous studies in Puerto Rico (Covich *et al.*, 2003, Cross *et al.*, 2008) where more than 60% of the shrimp in these populations have a CL between 12-17 mm. The *Atya lanipes* populations in these locations can be divided into three main cohorts: *cohort 1* (< 11 mm CL) comprised new recruitments with active growth but not mature enough to be reproductive adults; *cohort 2* (12-17 mm CL) comprised adults with high reproductive outputs and active growth; and *cohort 3* (> 18 mm CL) comprised mature and older adult shrimp with low reproductive output, slow growth rate, and which tended to be permanent residents of the pools. These size distributions and population structures are similar to those reported for *A. scabra* in Brazil (Oliveira-Almeida *et al.*, 2010; Herrera-Correa *et al.*, 2013). Like the *A. lanipes* populations in Puerto Rico, the middle class size of *A. scabra* in Brazil contained the most gravid individuals. Appreciable differences in size between gravid females and larger adults were observed in the Luquillo populations of *A. lanipes*. Individuals with a CL larger than 19 mm were males and most of the gravid females had a CL between 5-18 mm. In this study, no females or gravid females with a CL larger than 19 mm were observed; it appears that *Atya lanipes* has a marked sexual dimorphism (Martínez-Mayen *et al.*, 2000; Sanchez *et al.*, 2008).

The filter-feeding planktonic larvae of shrimp spend 60 to 90 days (depending on the species) in estuaries. After their metamorphosis in the estuary, the post-larvae begin an upstream migration until they reach headwater pools. During the migration the post-larvae mature into juveniles and reach reproductive status in the upstream adult habitat (Bauer, 2011a; 2011b; 2013). Generally, most individuals reach lower and mid-altitude pools when they are still small juveniles and sub-adults. These shrimp appear to synchronize their complex life cycle with the changes in temperature, precipitation and nutrient availability. Adult shrimp can breed throughout the year, but most of the reproduction occurs during the HRF period. This timing increases the chances for the rapid downstream transport of the first-stage larvae to an estuary during periods of high-water
discharge (Hoffmann & Negreiros-Fransozo, 2010; Heartsill-Scalley et al., 2012). Initiation of reproduction in the drier months may increase access to large amounts of available food resources (leaves, fruits, detritus and fungi) for the breeding females, because washout of litter is less during periods of low flows (Johnson et al., 1998; Covich & McDowell, 1996; Hoffmann & Negreiros-Fransozo, 2010). These results reinforce earlier observations that *Xiphocaris elongata* tends to be relatively seasonal in its reproduction when sufficient food is accessible (Johnson et al., 1998). Reproductive seasonality is apparently associated with the amount of food available for shredding by *Xiphocaris elongata*. Inputs of coarse particulate organic matter (CPOM) increase from March to August with an extended period until November (hurricane season) (Heartsill-Scalley et al., 2012). These inputs coincide with the reproductive timing of *Xiphocaris elongata*. *Atya lanipes*, primarily a filter feeder, uses different resources than *Xiphocaris*. During base flows, *Atya* is effective in filtering suspended FPOM derived from the decomposition of CPOM (Crowl et al., 2001; 2012). Suspended FPOM varies in concentration over time and space, but some food resources are always available for biofiltration in these streams during base flows. In contrast, *Xiphocaris* is an active swimmer and shredder that can use resources not available to *Atya*.

During 2000 *Atya lanipes* and *Xiphocaris elongata* increased in frequency in the size classes of 6-11 and 8-11 mm CL respectively. This increase in size during 2000 suggests that these individuals represent the new cohort of shrimp after the washout of Hurricane Georges. Moreover, the number of gravid females also showed an increase in the years after the hurricane. Similar changes in shrimp densities were observed after Hurricane Hugo in 1989. The shrimp densities decreased soon after Hurricane Hugo, but months later the shrimp densities reached maximum densities that were greater than previously recorded, apparently as a result of the large pulse of wind-transported leaf litter that was available along with more algal production as a short-term result of canopy loss in Quebrada Prieta (Covich et al., 1991).
In the last decades, the number and intensity of tropical storms and hurricanes that pass through the Caribbean have increased. In 1998, Hurricane Georges made landfall in Puerto Rico as a category 3-hurricane with sustained winds of 115 mph (Ostertag et al., 2003). During Hurricane Georges, LM had rainfalls of 75.4 mm and a peak discharge in the Rio Espiritu Santo of 64.9 m³. seconds⁻¹ (USGS-Rio Grande Gauge Station- 50063800). As a consequence of the intense winds, precipitation, and floods during the hurricane, the riparian forest was defoliated and stream discharge transported some shrimp and leaf litter from the headwaters to the downstream pools. The winds increased input of leaf litter in one day that represented approximately 0.9 times the annual rates reported in pre-hurricane standings (Ostertag et al., 2003). Defoliation of the riparian forest increased sunlight to the stream resulting in an increase in sunlight and water temperature. The increased light probably increased algal production that contributed to higher growth of periphyton and biofilm that were available to filter-feeding Atya (Crowl et al. 2012); Lefrancois et al. (2011) demonstrated that biofilm (aggregates of microorganisms) can be an important source of nutrients for atyids and xiphocarids in the Caribbean. In streams with wider channels, the light conditions increase algal production, resulting in higher numbers of shredders, grazers and scrapers (P Torres, unpublished data).

An increase in water temperature was expected to increase growth rates. This effect was evident in the size increase observed in Atya lanipes during 1999. A similar increased size was observed from 2004 to 2007 when the individuals in the upper and lower pools increased in CL as the water temperature increased. The highest water temperatures observed in Quebrada Prieta occurred during May to September, which coincide with the HRF and the hurricane season in the Caribbean. Studies on crayfish (Geddes et al., 1988; Verhoef & Austin, 1999; Tropea et al., 2010; Paglianti & Gherardi, 2004) and freshwater shrimp (Stephenson & Knight, 1980; Chen & Kou, 1996; Niu et al., 2006; Yam & Dudgeon, 2006) have shown a direct relation between the increase in size and increase in temperature. In general, growth rate is observed to increase as the
water temperature increases until the maximum growth rate is reached, after which the growth rate declines at higher water temperatures beyond a threshold (Hart, 1980).

During the LRF period, previous Hurricane Georges (1998) densities of Atya in the upper, middle and lower pools were 52.0, 10.1 and 26.1 shrimp. m\(^{-2}\) respectively; months later the densities decreased to 24.3, 10.8 and 8.5 shrimp . m\(^{-2}\). The decline in shrimp densities after the hurricane in the upper and lower pools most likely resulted from the washout during high flows during Hurricane Georges. Shrimp densities in the mid-altitude pool were not affected by the high discharge because this elongate pool (length > 15 m) was less subject to washout. Xiphocaris, in contrast to Atya, is an active swimmer that can be removed easily from the pool with a high discharge event.

The variations in densities of Xiphocaris elongata in the upper and lower pools reflect the variability in environmental conditions. Pools at higher altitude generally have confined reaches, smaller size and shallow depths. Lower pools generally are larger and deeper but also have confined reaches. The uppermost, shallow pools are affected more than deeper pools by droughts, extreme discharges and high inputs of organic matter. Extensive removal of leaf litter occurs during storm flows (Covich et al., 2003) Extreme environmental conditions can decrease or increase the shrimp densities (i.e. concentrate individuals by inwash during storm flows or reduce pool volume during dry periods). These effects were observed in the lowest and highest pools in this study.

The mean annual growth rate of Atya lanipes was moderate in the mid-altitude pool, apparently as a result of less variable shrimp densities and lower retention of leaf litter. The data on growth rates and densities suggest that pools with variable densities, like the higher and lower pools in Quebrada Prieta, promote growth in Atya lanipes in contrast to pools with stable densities. This discrepancy among growth rates is possibly explained by the amount and type of
available food resources (FPOM and CPOM) in each pool as well the differences in water temperature.

Due to differences in pool sizes and locations, shrimp in the uppermost pool are exposed to more variability in pool volume. The uppermost pool was located in a reach where the riparian forest produced a large, continuous input of *Cecropia* leaf litter which represented the main source of energy for these shrimps (Crowl *et al.*, 2001; Wright & Covich, 2005a; 2005b). The shallow mid-altitude pool was located in a *Prestoea montana* (Sierra Palm) forest. Palm fronds are generally not high-quality sources of food for *Atya* because most of the litter decomposition occurs while the fronds remain attached to the tree and relatively little leaf litter enters the stream food web (Zimmerman & Covich, 2007). Atyids and xiphocarids in deeper pools can use available food resources over a longer period before the storm-flows remove the microbially processed litter from the pool. A relatively continuous input of *Dacryodes* leaf litter assured some level of food resources for the upstream migrants in all pools. Wright & Covich (2005a) showed that *Xiphocaris* preferred to feed on microbially conditioned *Dacryodes* over *Cecropia* leaves. This food preference among shrimp can result from the different conditioning processes by dominant micro-organisms (fungi and bacteria) and the relative greater toughness of the *Cecropia* leaves (Wright & Covich, 2005b).

Shrimp in the uppermost pool tended to be mature adults near to the maximum CL size (*cohort 3*) where the growth rate and reproduction output generally decline. Cross *et al.* (2008) described the growth pattern for *Atya* in this stream and suggested that *Atya* has an active growth phase from 5 mm CL until it reaches the maximum size of 20 mm CL 7 years later. After this period, the growth rate is reduced dramatically and the shrimp function as mature, reproductive adults. This shift coincides with the range of growth rate observed in decapods, when they exhibit an active growth rate during their first years of life. When the adult stage is reached, the
growth rate and moulting process are typically reduced to a minimum of 2 or 3 moults per year (personal observation, OPR).

Shrimp in the lower pool were part of the new cohort (cohort 1) of post-larvae and juveniles that were in the process of migrating to the upper pools as part of their amphidromous life cycle. These shrimp were in their active growing phases. In this stage of development the shrimp appendages were not sufficiently sclerotized (Fryer, 1977) to readily breakdown the more lignified Cecropia leaves and the juvenile shrimp preferred softer, microbe-enriched leaves (Wright & Covich, 2005b). In contrast, adult shrimp in the uppermost pools (cohort 3) generally had an excess of Cecropia leaf litter available that was readily decomposed, and fewer post-larvae reached these upper pools (Kikkert et al., 2009).

The average annual growth rates for Atya lanipes and Xiphocaris elongata during the 10 years of the study were 0.28 and 0.1 mm . year⁻¹ respectively. The mean growth for these shrimp in the current field experiment is consistent with current models for these species, (Cross et al., 2008). The model predicted that Atya continue to grow until they reach the maximum size of 20 mm CL, when the growth rate declines. For Xiphocaris, the model predicted a rapid growth rate between the 5-11 mm CL with the growth rate declining after that threshold until it reaches the maximum CL of 17 mm is reached, after which the growth rate is further reduced.

As expected, the growth rates of Atya lanipes and Xiphocaris elongata were positive and associated with differences in water temperature and food supplies in different pools in Quebrada Prieta; effects of a hurricane increased leaf-litter input that also affected growth rates. Additional manipulative experiments in the field and laboratory are needed to increase knowledge of the growth rates among individual shrimp in the early and late stages in their life history. The important roles that these long-lived, slow-growing species play in headwater stream food webs also need to be considered when managing watersheds to sustain the ecosystem functions and services that these key species provide.
Acknowledgments

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References


Table 5-1  Range, mean and standard deviation of chemical variables of the stream water in Quebrada Prieta. Long-term chemical data from Luq-LTER (1999-2007)

<table>
<thead>
<tr>
<th>Chemical variables</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Mean</th>
<th>Std. Dev.</th>
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</thead>
<tbody>
<tr>
<td>pH (pH units)</td>
<td>4.1</td>
<td>7.9</td>
<td>7.1</td>
<td>0.32</td>
</tr>
<tr>
<td>Conductivity (micromho . cm(^{-1}))</td>
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<td>127.4</td>
<td>75.2</td>
<td>13.3</td>
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<tr>
<td>Chloride (Cl) (mg . L(^{-1}))</td>
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<td>Nitrate (NO(_3)-N) (mg N . L(^{-1}))</td>
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<td>68.5</td>
<td>50.1</td>
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<td>Sodium (Na) (mg . L(^{-1}))</td>
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<td>10.8</td>
<td>6.3</td>
<td>1.13</td>
</tr>
<tr>
<td>Potassium (K) (mg . L(^{-1}))</td>
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<tr>
<td>Magnesium (Mg) (mg . L(^{-1}))</td>
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<td>Calcium (Ca) (mg . L(^{-1}))</td>
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<td>Ammonium (NH(_4)-N) (mg N . L(^{-1}))</td>
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<td>6.4</td>
<td>9.6</td>
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<td>Phosphate (PO(_4)-P) (mg P . L(^{-1}))</td>
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<td>Sulphate (SO(_4)-S) (mg S . L(^{-1}))</td>
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<td>Dissolved Organic Carbon (DOC) (mg . L(^{-1}))</td>
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<td>1.5</td>
<td>0.8</td>
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<td>Total Dissolved Nitrogen (TDN) (mg . L(^{-1}))</td>
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<td>Dissolved Organic Nitrogen (DON) (mg . L(^{-1}))</td>
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<td>0.3</td>
<td>0.06</td>
<td>0.04</td>
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Fig. 5-1 Percentage of gravid females of *Atya lanipes* and *Xiphocaris elongata* across time (1997-2007), rainfall periods (HRF and LRF), and pools (Upper, Middle and, Low altitude) in Quebrada Prieta. Vertical line during 1998 represents the impact of Hurricane Georges. a) *Atya lanipes* upper pool; b) *Xiphocaris elongata* upper pool; c) *Atya lanipes* middle pool; d)
*Xiphocaris elongata* middle pool; c) *Atya lanipes* lower pool, and f) *Xiphocaris elongata* lower pool.
Fig. 5-2 Annual frequencies of size classes in populations of a) *Atya lanipes* and b) *Xiphocaris elongata* during 1997 to 2007. Bars represent frequency of shrimp per year and line represents
total frequency of shrimp during 10 years of sampling.
Fig. 5-3  Relationship between average growth (± SE) of the shrimp *Atya lanipes* (n = 10) and *Xiphocaris elongata* (n = 12) and the years of the experimental period in Quebrada Prieta. Vertical line represents the impact of Hurricane Georges. Solid (*Atya lanipes*) and dotted (*Xiphocaris elongata*) lines represent linear regressions (cephalothorax- CL). *Atya lanipes*, CL = 0.2756*Time* - 532.75; $r^2 = 0.69$, $P < 0.003$; *Xiphocaris elongata*, CL = 0.0843*Time* - 155.88, $P$ = 0.156; $r^2 = 0.21$. 
CHAPTER 6
EVALUATION OF A WEB-BASED EDUCATION PROGRAM: COMMUNICATING ECOLOGICAL KNOWLEDGE TO THE PUBLIC ABOUT THE LUQUILLO EXPERIMENTAL FOREST

Abstract

Increasing local knowledge about freshwater biota and enhancing communication between the scientific community and local populations were the main objectives for developing an educational program about the ecology of rivers in Puerto Rico. Two websites (River Education Program and Programa Educativo sobre Rios) with posters, fact sheets, taxonomic keys, scientific articles, plots, and pictures were developed to present ecological information regarding the Luquillo mountain streams to Spanish and English-speaking audiences. This study reports visitors’ behavior over 24 months after the release of the two websites. In total there were 12,343 sessions were reported for the websites. Both websites were used by Spanish and English speakers from diverse local, national and international locations. Most of the connections were from locations in Puerto Rico with universities and/or research centers with active research on the island. Keyword searches were the most common method to reach the websites; ‘Abiotic and Biotic Factors’, ‘Taxonomic Key’, and ‘El Yunque Rainforest’ were the pages with the most sessions and pageviews. This educational program provided the opportunity to develop a complete and integrative educational program that presents new scientific findings in the Luquillo Mountains in order to increase knowledge about the freshwater biota. This information pathway can help in highlighting the value of conserving these resources.

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Keywords. biodiversity, decapods, El Yunque National Forest, Puerto Rico, river education, tropical streams, website

Introduction

The Internet reaches increasingly large numbers of people in many countries and provides up-to-date information in a wide range of formats. The combination of text, multimedia, and user-interactive technology makes the Internet extremely effective for the dissemination and acquisition of knowledge (Flanaging and Metzger 2001; Morris and Ogan 1996; Dworak et al. 2014). The results of peer-reviewed field and experimental studies can have a profound impact in the lives of citizens given the increased accessibility and relatively low cost. The use of the Internet to support scientific communication is one of the major developments in the practice of ecology (Hurd 2000; van Raan 2001).

The public today is more aware of the many ecological and environmental issues that impact everyday life than ever before. A main barrier in the acquisition of this new knowledge remains a lack of sufficient scientific literacy (Rickinson 2001; Bickford et al. 2012). People obtain limited or oversimplified information about environmental and conservation issues from sources that are sometime biased, leading to misconceptions and wrong or incomplete interpretations of the ecological and environmental problems (Coyle 2005; Ladle et al. 2005). Communicating ecological science to non-scientists is one of the most important challenges (Sunderland et al. 2009).

Puerto Rico’s population has increased at a high rate with most of the growth in the major metropolitan areas (Ramirez et al. 2012; Gould et al. 2012). This growth results in a significant increase in both residential and industrial development and a corresponding decrease in habitat for fish and wildlife (Gould et al. 2012). One of the significant habitat alterations has been to wetlands and watersheds. Puerto Rico has lost and continues to lose wetlands at an alarming rate
Riparian forests and wetlands are especially important as they provide habitats for freshwater shrimp (Pérez-Reyes 2014), fishes, and wildlife (Ramos-Scharron et al. 2015). These ecosystems also produce important services such as flood control, groundwater recharge, filtration of organic materials, storage and recycling of nutrients, control of erosion as well as reduced transport of sediment and pollutants. It is especially important for the public and policy makers to protect the island's remaining wetlands and riparian forests. These habitats used by diverse species help provide clean water that is essential to maintaining recreational fisheries and other freshwater benefits (Lugo et al. 2011).

In Puerto Rico, the El Yunque National Forest in the Luquillo Mountains (also known as the Luquillo Experimental Forest –LEF) represents a location where scientists, technical experts, and the general public converge daily. The LEF serves as a site for research by scientists from the United States, especially Puerto Rico, and many other countries around the world. The LEF is uniquely suited for research in tropical rainforests because the ecological life zones are representative of the many other tropical forests. The LEF has served as a living laboratory since 1942 when the land was recognized as important for watershed protection and later for experimentation about forest productivity following disturbances (Odum and Pigeon 1970), effects of hurricanes on the biota (Covich et al. 1991), nutrient cycling in the ecosystem (Heartsill-Scalley et al., 2012), effects of urbanization (Ramírez et al. 2009; 2012; Thomlinson and Rivera 2000), hydrological cycles and water budgets (Scatena 1989; Covich et al., 2003), meteorology (Jennings et al. 2013; 2014), recreational use of the forest (Kartchner 2002; Santiago and Loomis 2009), and many other initiatives funded by governmental agencies and universities. The data and results of this research are in academic and research libraries that are largely inaccessible to the general public or the local inhabitants. Moreover, the lack of communication between scientists and the general public, frequent misconceptions, and absence of general
information about environmental and ecological issues have often resulted in degradation of the natural resources of the island.

Our experiences with the island’s community, general public, graduate and undergraduate students led us to develop an outreach program that includes two educational websites: River Education Program and Programa Educativo sobre Ríos. This study investigates the use of these websites to answer the following research questions: 1) How often do visitors use the websites, from which countries, number of page views and how much time spend on each one?, and 2) Does language represent a problem for users of the websites?

**Methods**

The River Education Program (REP) has a version in English as well as one in Spanish named Programa Educativo sobre Ríos (PER). These websites present a synthesis of information from field observations and laboratory experimental results based on the scientific literature in colloquial language so that the scientific and non-scientific public can find the answers to most common issues related to freshwater ecosystems in Puerto Rico. The REP and PER were designed as web-based learning environments with an interactive learning interface (Khalifa and Lam 2002) where the learner can interact and explore informational materials based on the many ecological findings in the Luquillo Experimental Forest. The material is organized into 13 sections (main menu) such as Archeology, Biological Resources, Ecosystems and Landscapes, Education, El Yunque Tropical Rainforest, Literature, Luquillo-Long Term Educational Research (Luq-LTER), Physical Resources, Researchers, River and Stream Terminology, River and Streams, Species List, and Taxonomic Key. Each section is accompanied by a brief description of the main topic with a series of pictures, hyperlinks, and educational materials that can be downloaded and printed. The materials in the REP/PER have explanations of ecological processes (e.g. amphidromous migration of shrimp and fishes),
descriptions of native and exotic species (e.g. plants, invertebrates, vertebrates, and fungi),
diagrams of the forest (forest vegetation types), streams (anatomy and morphology of the stream),
and descriptions of the interactions between the organisms in the food webs (food web of a
tropical rain forest). The pictures in each section show a descriptive representation of the
organisms and their interactions with other organisms. These pictures were selected to represent
the uniqueness of the Puerto Rican biota. Hyperlinks on the web pages are linked to websites of
different universities, local and federal agencies, and those individuals who collaborate with the
researchers at the LEF. In addition some hyperlinks connect to other relevant sections within the
website.

Data Collection

To assess usage of the websites we used Google Analytics (GA), a web analytic tool that
provides data summaries and visualizations about visitors and users to facilitate evaluation of
website performance (Clifton 2012).

Data on website sessions were collected during two years (2012 and 2013) after the
release of the sites. The period of 24 months was selected to ensure enough data and time to
identify trends in the site usage. To analyze the usage of the websites the number of sessions,
pageviews, users, and bounce rate were measured (Burby and Brown 2007; Booth and Jansen
2009). For the analyses, “sessions” were defined as the number of individual sessions initiated by
the visitors to the site. “Users” were those visitors who viewed or interacted with the content
within a specific date range. “Pageviews” were the visitors who viewed a page on the site and
tracked from the beginning to end of their visit. “Bounce rate” was defined by the percentage of
visitors who enter the website and leave the site (single page sessions). All the data were
generated using GA.
Data were graphed and sorted to identify patterns of the use over time. Visitors to the websites were characterized by geographic distribution (country and city), language, and keywords used. Differences in the number of sessions, pageviews, and bounce rate were compared between years (2012 and 2013) and among months with Two-way ANOVAs.

Results

River Education Program. Since the REP was released in January 2012, it received 7219 sessions that viewed 12316 pages (Fig. 6-1a). A total of 12.5 % of the visitors were classified as returning visitors (906), while 87.5 % were new visitors to the website. During 2012 the monthly number of visits ranged from 81-326 while in 2013 the monthly visits ranged from 190-868. The highest number of visits was registered during September 2013. The site is visited most heavily during January-May and August-November (Fig. 6-2a). New visitors viewed an average of 1.49 pages with an average time expended in the site of 55 seconds; returning visitors viewed 3.2 pages with an average time of 205 seconds. The largest visit had duration of 45 minutes. A two-way ANOVA to compare the number of visitors per year and among months showed significant differences in the number of visits between years ($F_{1,11} = 33.6; p \leq 0.0001$) and among months ($F_{1,11} = 4.9; p = 0.007$). Significant differences in the page views were observed between years ($F_{1,11} = 681; p = 0.02$) and among months ($F_{1,11} = 3.5; p = 0.02$).

Visitors from 119 countries or territories visited the REP; most were from the United States mainland, Puerto Rico, Australia, United Kingdom, Canada, India, Philippines, Colombia, Indonesia, and Mexico (Fig. 3a). Visitors from United States mainland accessed the web page more frequently than any other country with more than 4676 visits in two years. The average bounce rate for these countries ranged between 92 (Mexico) to 61 % (Puerto Rico).

The percentage of users who accessed the site through search engines was 93 %; only 4 % reached the website through a referral site and only 3 % as a direct URL (Uniform Resource
Thirteen keywords were used at least 10 times to locate the site (Table 6-1). The most common keywords used to reach the web pages were ‘Abiotic and biotic factors’, ‘Taxonomic key’ and ‘Freshwater insects.’

Visitors in different nations chose different pages to visit. Comparison of the flow data for the United States, Puerto Rico, Australia and Canada showed that the starting pages were similar among the countries (Home Page, Physical Resources-Water, Rain Forest, Luquillo LTER and Abiotic and Biotic Factors). However, visitors from Australia and Canada moved to Archeology and River and Streams pages, while the visitors from the US and Puerto Rico also visited the Rain Forest, Biological Resources, and Luquillo-LTER.

The analysis of the visitors by their origin showed that in the United States the most visits were from Texas (N=879 sessions), California (N=270), Florida (N=257), Georgia (N=221), Illinois (N=219), and New York (N=207). Visitors from these states spent between 51 to 110 seconds on the site and visited 1.4 to 2.1 pages per session. North Dakota (N=5), South Dakota (N=5), and Delaware (N=1) were the states with the lower number of sessions in the REP.

The numbers of visits from Puerto Rico to the REP site were 205 in 2012 and 408 sessions in 2013; 248 of these sessions were originated in the San Juan Metropolitan Area, which included the municipalities of San Juan, Cataño, Bayamón, Carolina, Trujillo Alto, and Guaynabo; the other 365 visits came from additional cities around the island. The cities with the highest number of visitors registered were San Juan (N=148), Río Piedras (N=66), Caguas (N=44), Bayamón (N=25), Mayagüez (N=20), and Luquillo (N=19). The cities with the lower bounce rate and higher number of pages per session were Luquillo and Carolina, the cities nearest to the LEF. Users from Luquillo visited 3.2 pages per session for a 32% of bounce rate while users from Carolina visited 4.0 pages per session, resulting in a bounce rate of 40%. San Juan, Río Piedras, Caguas, Bayamon and Mayaguez had averaged bounce rates that ranged between 52
to 75%. In general each visitor viewed an average of 2.6 pages per session and spent an average of 128 seconds per session.

*Programa Educativo sobre Ríos.* The PER was designed to reach the Spanish-speaking communities. Since it was released in 2012, the webpage received 5116 sessions, where 4656 were new visits and 460 returning (Fig. 6-1b). The average number of pages viewed per visit was 1.3 pages per session and the average visit time was 57 seconds. In the PER an increase in the average monthly sessions were observed from February to July and from August to December. The smallest number of sessions was observed during January 2012 (N=24) and the largest in December 2013 (N=527). Higher numbers of page views were observed during November-December of each year (2012- 609 and 2013- 671 page views) (Fig. 6-1b). Highly significant differences were observed in the number of visitors to the website among months (F<sub>1,11</sub>=9.7; p< 0.0001) and between years (F<sub>1,11</sub>=36.7; p< 0.0001). The monthly page views ranged between 38 to 609 in 2012 and 168 to 665 during 2013. The comparisons of monthly page views between years (F<sub>1,11</sub>=35.7; p< 0.0001) and among months (F<sub>1,11</sub>=12.5; p< 0.0001) were also highly significant (Fig.6-1b, 6-2b).

Visitors from 48 countries reached the Programa Educativo sobre Ríos during 2012 and 2013. The most common visitors were from Mexico (N = 1340), Colombia (N = 1101), Puerto Rico (N = 656), Venezuela (N = 435), United States (N = 291), Spain (N = 232), El Salvador (N=168), Peru (N=161), Argentina (N=153), Ecuador (N=103), and Guatemala (N=98) (Fig. 6-3b). Visits from another 37 countries were observed in the PER. Most of these visitors (95%) reached the website after a search in their preferred browser, 4% from direct traffic, and 1% from referral traffic. Of the 5116 sessions, 744 reached PER using the following keywords: “Factores Abióticos y Bióticos del Río” (Abiotic and Biotic factors of the Stream), “Claves Taxonómicas” (Taxonomic Keys), “Bosque Lluvioso el Yunque” (EL Yunque Rain Forest), “Terminología de Ríos” (Stream Glossary), and “Petroglifos Taínos” (Taino Petroglyph) (Table 6-1). The visitors
from Puerto Rico were primarily from San Juan (N=187), Caguas (N=127), Bayamón (N=44), Ponce (N=44), and Mayagüez (N=25). More than 40% of visits (N=277) were from the San Juan metropolitan area.

Discussion

The River Education Program and the Programa Educativo sobre Ríos websites were developed to make ecological information from research at the Luquillo Experimental Forest easily accessible to local people and the general public. Our analyses clearly show that people from Puerto Rico and other countries are interested in obtaining this information to understand the importance of ecological resources of a tropical rainforest. Education about the streams and rivers of Puerto Rico plays an important role in the understanding more about these ecosystems (Reagan and Waide 1996; Brokaw et al. 2012). The information provided to the visitors to these websites likely helped them to understand the ecosystems, their services and the importance of sustaining these ecosystems. Current efforts contribute to making the general public more successful in searching available resources.

Overall, the results of this study point to a positive use of the web-based education program by the visitors. These websites were designed to reach the local public of Puerto Rico, but the impacts were observed internationally. Not only do local individuals who use the websites tend to have higher number of sessions, they also are more likely to explore more pages, and tend to search deeper into the content of the websites. The high number of visits suggests that the River Education Program and Programa Educativo sobre Ríos have useful content. These results are encouraging signs that web-based communication technologies can have a positive impact on a wide audience. The analyses of keywords and the major search engines show that the number of visits was increasing through time and may be likely to continue doing so.
The numbers of visits suggest that many people view the content; most visits to the sites are of very short duration. The low number of pages viewed per visit and the low amount of time spent on each page probably reflect either that visitors find the information quickly in their first visit, or that the website does not sufficiently reflect their interest. This observation supports previous reports where Internet users tend to move quickly from one site to another, clicking on the first thing that draws their attention (Krug 2006). The increasing access to the REP.PER sites through search engines reflected that the public is looking for information about freshwater ecosystems. The tendency to search information through search engines is now commonplace in Internet users.

The most popular content areas were the web pages about water and abiotic and biotic factors. Most of the users arrived to these web pages after a search using the keywords “abiotic biotic factors”, “taxonomic keys”, “El Yunque Rainforest”, and “freshwater insects”. Other keywords can be separated by technical topics (e.g. Hirudinae, river ecosystem, Atyidae, food web) and vernacular or local words (e.g. taino petroglyph, snails, streams and rivers, Yukiyu, and buruquena). This result reflects the behavior of two focal groups: 1) people with knowledge in ecological process (e.g. students, investigators), and 2) people interested in recreation (e.g. tourists and local individuals). The research and focused web visitors use technical terminology, visit different pages in the website, look for a deeper search and repeat the visit returning directly to the page of interest (direct traffic) (Booth and Jensen 2009). Meanwhile, users looking for tourist information (browsing visitors) are people who search the site for specific information about an activity or location. This type of visit would likely result in higher bounce rates, lower numbers of page views, and shorter sessions.

The second group of website visitors appears to be looking for general information about El Yunque and its resources. This group is composed of local people and tourists who search to identify recreational sites in the forest. These findings are congruent with observations by
Kartchner (2003) that most of the people who visit the El Yunque National Forest are looking for a site to relax, spend time with family, and enjoy the natural setting. People who visit the streams at El Yunque seek to identify the appropriate pools or areas around streams for different types of use (Santiago and Loomis 2009). Both studies showed an interest in the water as a recreational resource.

Most visits to the websites occurred during the months of January to May and August to November. These users reached the websites through a search engine with precise keywords. These visitors discovered the selected web pages, and likely obtained the ecological information they wanted and then exited the websites. The duration of the visits was relatively short. The times of high use in the websites are congruent with the academic semesters of the universities and schools in United States and Puerto Rico. During these months the students start looking up information for their research, projects, laboratories or exams. Higher average of use of the sessions and the lower bounce rates in the PER during the months of June and July coincide with the Luquillo-LTER Research Education for Undergraduates Program (REU). In the REU program the students develop research projects and the mentors promote the use of the website as source of scientific information and articles (personal observation).

The geographical origin of the visitors coincides with the usage of the web pages during the academic semester. Most of the visits to the websites were from states of the United States (e.g. Texas, California, New York, Illinois, Florida, Georgia) with higher concentrations of Hispanics (including Puerto Ricans) and universities with connections to research centers in Puerto Rico. The users from Puerto Rico came from cities with higher concentrations of people, and higher-education centers: San Juan, Bayamón, Mayagüez, Caguas, and Cayey.

The websites and their resources were used primary by people from outside of Puerto Rico rather than local residents. The differences may be the results of low knowledge locally about the Internet as well as language problems. English speakers used the River Education
Program more frequently than those who speak other languages; meanwhile as expected, the Programa Educativo sobre Rios was used primarily by visitors from Spanish-speaking countries. According to available data, the Internet in the United States is used by 78% of all English speakers, 77% of Latinos who are English dominant or bilingual, but only 32% of the Spanish-dominant Latinos (Fox and Livingston 2007). Only two-thirds of the population in Puerto Rico use or have access to the internet; most of the users tend to be younger and educated (Internet World Stats Miniwatts Marketing Group 2011). Puerto Rico is among the most advanced telecommunication markets in America, with 2 million Internet users, and there is a large Spanish speaking population in the mainland United States. Internet users on the island apparently prefer to visit local websites and previously known web pages (SME Digital and Mobile Behavioral Study Puerto Rico 2014). Increasing Spanish language content available online removes a barrier to access and will increase the use among Spanish-speaking populations.

Geographic variability in the website users was considerable in Puerto Rico. Users seeking information occurred most frequently in the regions surrounding the San Juan Metropolitan Area. Not surprisingly, we observed a pattern of a higher prevalence of Internet use in regions with a greater proportion of people with higher education. This observation is also likely exacerbated by the fact that the most rural communities in Puerto Rico still have limited or poor Internet access. In Puerto Rico 60% of the population has Internet access, and 80% of the users connect to the Internet from their jobs or universities (SME Digital and Mobile Behavioral Study Puerto Rico 2014).

In conclusion, we demonstrate rapid uptake of multimedia tools designed to present the ecological information derived from research at LEF to the general public. The use of these tools showed a gradually increase with positive results and comments. Most users of the sites were people with knowledge of the Internet, seeking information about ecological aspects, and English speaking. Ecological education and outreach efforts should continue to explore the use of
available methods of dissemination, as well as community based programs or activities, and organizations, to supplement and encourage use of the internet as a source of information. To further increase the number of visitor on the websites it may be valuable to create links to social media. Web-based scientific information offers important opportunities for access to an increasing amount of knowledge and information. One role of professional researchers is to ensure that the learning environment provided takes account of users’ needs and ensures that they effectively understand the ecological information. Online learning has advantages, but web-based learning should not always be viewed as the method of choice because barriers (such as inadequate equipment) can easily detract from student learning. The technology can be applied appropriately for most users but cannot be used everywhere because some people still have particular limitations to access the Internet.

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Literature Cited


Table 6-1  List of the frequently used-keywords to search information and the number of sessions observed in the REP and PER websites during 2012-2013.

<table>
<thead>
<tr>
<th>Keywords (REP)</th>
<th>Number of Sessions</th>
<th>Keywords (PER)</th>
<th>Number of Sessions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biotic and abiotic factors of rivers</td>
<td>1710</td>
<td>Factores bióticos y abióticos/Biotic and Abiotic Factors of Rivers</td>
<td>433</td>
</tr>
<tr>
<td>Taxonomic key</td>
<td>57</td>
<td>Claves taxonómicas/Taxonomic Keys</td>
<td>259</td>
</tr>
<tr>
<td>Freshwater insects</td>
<td>53</td>
<td>Bosque Lluvioso El Yunque/El Yunque Rain Forest</td>
<td>30</td>
</tr>
<tr>
<td>Hirudinidae</td>
<td>45</td>
<td>Terminología ríos/River Terminology</td>
<td>22</td>
</tr>
<tr>
<td>Taíno petroglyphs</td>
<td>40</td>
<td>Taínol petroglifo/ Taíno Petroglyphs</td>
<td>21</td>
</tr>
<tr>
<td>Streams and rivers in El Yunque</td>
<td>33</td>
<td>Crustáceos de agua dulce/Freshwater Crustacea</td>
<td>17</td>
</tr>
<tr>
<td>River Education Program</td>
<td>28</td>
<td>Caracoles/ Snails</td>
<td>13</td>
</tr>
<tr>
<td>River ecosystem plants and animals</td>
<td>14</td>
<td>Ríos y quebradas en El Yunque/ River and Streams from El Yunque</td>
<td>12</td>
</tr>
<tr>
<td>Luquillo LTER</td>
<td>12</td>
<td>Bacterias/ Bacteria</td>
<td>11</td>
</tr>
<tr>
<td>El Yunque monthly temperature</td>
<td>11</td>
<td>Yukiyu</td>
<td>11</td>
</tr>
<tr>
<td>River habitats</td>
<td>11</td>
<td>Hongos/ Fungi</td>
<td>9</td>
</tr>
<tr>
<td>Bacteria in El Yunque</td>
<td>10</td>
<td>Oro en los ríos de El Yunque/Gold in Rivers of El Yunque</td>
<td>9</td>
</tr>
<tr>
<td>Rivers and streams food web</td>
<td>10</td>
<td>Bosque de Tabonuco/Tabonuco Forest</td>
<td>8</td>
</tr>
</tbody>
</table>
Table 6-2  Landing pages for the user of the websites and the percentage of sessions in the REP and PER during the years 2012 and 2013.

<table>
<thead>
<tr>
<th>River Education Program</th>
<th>Programa Educativo en Ríos</th>
</tr>
</thead>
<tbody>
<tr>
<td>Landing Page</td>
<td>Sessions (%)</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Physical Resources-Water</td>
<td>65.0</td>
</tr>
<tr>
<td>Abiotic and Biotic-Factors</td>
<td>5.0</td>
</tr>
<tr>
<td>Home</td>
<td>4.1</td>
</tr>
<tr>
<td>El Yunque Tropical Rain Forest</td>
<td>3.4</td>
</tr>
<tr>
<td>Luquillo-LTER</td>
<td>3.2</td>
</tr>
<tr>
<td>Archeology</td>
<td>2.4</td>
</tr>
<tr>
<td>Taxonomic Keys-annelida Leeches</td>
<td>2.2</td>
</tr>
<tr>
<td>Ecosystems and Landscapes</td>
<td>2.0</td>
</tr>
<tr>
<td>Taxonomic Keys-Freshwater Insects</td>
<td>1.8</td>
</tr>
<tr>
<td>El Yunque Rivers and Streams</td>
<td>1.8</td>
</tr>
<tr>
<td>Vegetation</td>
<td>1.7</td>
</tr>
<tr>
<td>Glossary</td>
<td>1.6</td>
</tr>
<tr>
<td>Taxonomic Keys</td>
<td>1.6</td>
</tr>
<tr>
<td>Literature</td>
<td>1.5</td>
</tr>
<tr>
<td>Rivers and Streams</td>
<td>1.4</td>
</tr>
</tbody>
</table>
Fig. 6-1 Monthly number of sessions and pageviews of the users of the websites during the years 2012 and 2013: a) River Education Program, b) Programa Educativo sobre Ríos. Gray area represent number of pageviews and black area number of visits to the REP and PER.
Fig. 6-2 Average monthly sessions (± Standard Error) and bounce rates (± SE) for the REP (a) and PER (b) during the years 2012 and 2013. Closed circle represent bounce rate, open square the sessions in the REP and closed gray square the sessions in the PER.
Fig. 6-3 Percentage of sessions per country or territories in the REP (a) and PER (b) websites during 2012 (open bar) and 2013 (closed bar).
The symptoms of the “Urban Stream Syndrome” (Walsh et al. 2005) flashy hydrographs, elevated concentration of nutrients and contaminants, altered channel morphology, reduced biodiversity and incorporation of non-native-tolerant species were found in the tropical streams of Puerto Rico. The increase in urbanization as a threat to aquatic ecosystems, particularly tropical island stream ecosystems, is of growing concern due to small amount of space available for development. Urbanization within the riparian zone was considerably high in the lower valleys near the coast compared to those upstreams or in the mountains where the urbanization was minimum.

Insular tropical freshwater ecosystems are dominated by an unique native fauna of macroinvertebrates and fishes adapted to survive flashiness (Ramírez et al. 2009), frequent floods, and droughts (Covich et al. 2006). For example atyids shims have modified hairy-chelae to capture fine organic particules and strong legs that permit the exploitation and survival of flashy and steep streams. The other three families of decapods (Palaemonidae, Xiphocarididae, and Pseudothelphusidae) are adapted to survive under these conditions but do not show modifications in their appendages.

In the Caribbean the decapod freshwater fauna is represented by 5 families (Atyidae, Palaemonidae, Pheudothelphusidae, Astacidae, and Xiphocarididae). All the shrimp and crab families were found across all ecological life zones in Puerto Rico. The richest rivers, Río Bayamón, Río Mameyes and Río Sabana, were located in the north part of the island. The relatively rich and unaltered environment, presence of organic matter, longitudinal connectivity and the physical-chemical variables may provide the conditions for which these streams are important areas for the conservation of these aquatic animals. The diversity of freshwater
decapod fauna found in Puerto Rico was expected for an island of its size. It is comparable to that of Hispaniola (19 taxa) and Jamaica (21 taxa). Detailed examination indicated that the species-area relation among the Greater and Lesser Antilles was observed; larger islands have more number and diverse habitats in contrast with the smaller ones (Losos & Losos 1996). The diversity of the freshwater decapod group in the Caribbean Archipelago tends to be controlled primarily by the size of the island and the dispersion of the organisms. All freshwater shrimp in the Caribbean exhibit an amphidromous life cycle where adults reproduce in the high elevation sections of the streams and the larvae need to spend time in the estuary until metamorphose and migrate to the upper locations of the freshwater bodies. This results in a common species pool capable to colonize and migrate among the islands (Chapter 2).

The anthropogenic stressors increase the environmental pressure on macroinvertebrate communities that can alter the biota in tropical streams (Ramírez et al. 2012). Urbanization decreased the species richness and abundance of decapods communities in highly urbanized valleys when were compared to forested headwaters or suburban reaches in different streams. Also, the abundance of species and community structures in each stream showed variations among different land-uses. However, the species richness was still relatively species rich even in the urbanized watershed (11 of the 18 species that occur in Puerto Rico). Macrobrachium faustinum and Xiphocaris elongata were the most tolerant species in the impacted sections of the streams. Our study suggested that the loss of species richness and abundance of freshwater decapods in urban streams was the result of a series of human stressors that degrade decapod habitat. Urban streams reflected the impact of human activities in their hydrology, geomorphology, water quality and aquatic biota. The effect of these stressors had an impact in the species assemblages as well in the energy inputs in the stream. Changes in the land use increased the erosion, sedimentation and water flow that changed the habitat heterogeneity and the abundance and diversity of decapods in the stream. The relatively rich and unaltered
environment, presence of organic matter, longitudinal connectivity and the physical-chemical variables may provide the conditions for which these streams are important areas for the conservation of these aquatic animals. The alterations of the terrestrial environment as well the construction of barriers to migration changed the local energy inputs and the longitudinal connectivity among streams sections. These changes affected the organization and functions of the stream communities (Paul and Meyer 2001) (Chapter 3).

Alterations and changes in the local input of organic matter in the streams resulted in altered food web among low-impact, mid-impact and high-impact streams in Puerto Rico. The carbon source for the primary, secondary and tertiary consumers were similar among streams; variations were observed mainly in the amount of $\delta^{15}$N. The enrichment in $\delta^{15}$N had an impact in all the tropic levels but primary change the order of the consumers positioning all together. The urban rivers of Bayamón and Rio Piedras had concentrations of $\delta^{15}$N higher than the normal and in some occasions were three times the values observed in the reference stream of Sabana. An excess in $\delta^{15}$N marked a difference in trophic levels of the food web from urban streams in comparison with the reference stream where the anthropogenic inputs are minimal. This showed the importance of the organic matter in the ecosystem and the dependence of the freshwater biota on the terrestrial inputs. Apparently the impact of the human activities on the stream and watershed had a direct influence in the health and services of the ecosystem (Chapter 4).

Comparison of growth patterns of *Atya lanipes* and *Xiphocaris elongata* in 2nd order streams of Luquillo Mountains showed that these tropical shrimp have: a) a relatively long live (> 15 years) with a slow growth rate; b) annual growth rates for *Atya* and *Xiphocaris* were 0.27 and 0.1 mm carapace length over the 10 year period; c) difference in growth rates between individuals of *A. lanipes* and *X. elongata* over a range of temperatures, and time. In these streams water temperature and food were the most important factors that influenced the growth rate. Inter-site differences in growth rate could also be attributed to variability in retention of the leaf-litter
inputs from the riparian forest. Also, we found that hurricane and leaf-litter input affected growth rates in some pools (Chapter 5).

Communicate results of any research is always difficult. Scientific investigations have become more specialized and complicated to be transmitted and understood by the general public (Bucchi 1996). Luquillo Mountains is the living laboratory for diverse researches that cover from the effect of radiation on the forest (Odum 1970) to climate change and global warming models (Comarazamy et al. 2013). Based in our experiences with the scientific community and the general public we developed some educational tools those present the scientific information in a common language and accessible for the general public (e.g. website, field activities, and training program for teachers and students). In the present study we demonstrated the necessity to increase the sources of ecological information available to the general public and the interest of the local people to learn and understand their natural resources. We found a gap of information between the scientists and the general public. The usage of these tools showed a gradually increase with positive results and comments. Our results suggest that ecological education and outreach efforts should explore the use of available and trusted methods of dissemination, as well as community based programs or activities, and organizations, to supplement and encourage use of the internet as a source of information (Chapter 6).
LITERATURE CITED


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Roger Jones
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EDUCATION

2013
Ph.D. in Ecology
Utah State University, Logan, Utah (Advisor: Todd A. Crowl)

1999
M.Sc. in Biology
Dissertation: Abundances, Richness and Life Histories of Freshwater Decapods of Puerto Rico
University of Puerto Rico, Rio Piedras (Advisor: Alberto Sabat)

1994
B.S. in Biology
Magna Cum Laude
University of Puerto Rico, Rio Piedras

RESEARCH INTERESTS
I am interested in biogeography, conservation, taxonomy, and systematics of freshwater crustacean invertebrates of the Neotropics. I use two approaches to understand tropical diversity and to answer questions about their biogeographic patterns, natural history, and evolutionary history. I work on the most diverse groups of freshwater decapods (Atyidae, Palaemonidae, and Pseudothelphusidae) in the Caribbean. I am also interested in the question of the effect of anthropogenic factors on the diversity, abundance, distribution of other native and exotic freshwater invertebrates (phenology, longitudinal connectivity, habitat, niche, and life cycle) in urban and forested streams.

RESEARCH AND WORK EXPERIENCE

Teaching Experience
2013
Instructor. Center for Environmental Research and Conservation, Columbia University, New York, New York.

2011-2012
Teaching Assistant (International Forestry & Natural Resources Management), Utah State University, Logan, Utah.

2011
Instructor. Center for Environmental Research and Conservation, Columbia University, New York, New York.

2011
Teaching Assistant (General Ecology), Utah State University, Logan Utah

2000-2007
Instructor (Zoology, Invertebrate Zoology, and General Biology), Department of Biology, University of Puerto Rico, Rio Piedras.

2000-2007
Laboratory Coordinator (Zoology and Botany Labs), Department of Biology, University of Puerto Rico, Rio Piedras.

1992-1994  Undergraduate Teaching Assistant (Zoology and General Ecology), Department of Biology, University of Puerto Rico.

Research Experience
2007-2013  Research Assistant. Luquillo-Long Term Experimental Research (Luq-LTER). Institute of Tropical Ecosystems, University of Puerto Rico, Rio Piedras. Primary Investigators: Todd A. Crowl (Utah State University) and Alan P. Covich (University of Georgia).


POSITIONS HELD
2012-2013  iUTAH, Education, Outreach and Diversity-Communication Team
2000-2013  Environmental Scientist. Ferdinand Quiñones, PE, Consulting Water Resources and Environmental Engineer
2010-2012  Graduate Student Representative Luquillo LTER
2006-2007  Academic Assistant, Department of Biology. UPR-RP
2005-2007  Representative, Biology Department at UPR, Middle States Association
2002-2005  Invertebrate Curator, Zoology Museum, Department of Biology, University of Puerto Rico, Rio Piedras.
1997-1998  Graduate Student Representative, Graduate Biology Committee, UPR-RP.
PUBLICATIONS

Peer reviewed


Publications in preparation
Pérez-Reyes, O., Crowl, T.A., Covich, A.P. Comparison of Neotropical decapod communities across an urban-forest land use gradient in Puerto Rican streams. (Urban Ecosystems).

Pérez-Reyes, O., Crowl, T.A., Covich, A.P. Comparison of trophic relationships in contrasting tropical streams in Puerto Rico: a stable isotopic study of food webs in urban and forested watersheds. (Freshwater Biology).

Pérez-Reyes, O., Crowl, T.A., Covich, A.P. Effects of elevation, food supplies, and water temperature on growth rates of freshwater topical shrimp in stream pools in the Luquillo Mountains, Puerto Rico. (Freshwater Biology).


Web Publications
2012 River Education Program- Educational website about how to live downstream. (https://sites.google.com/a/ites.upr.edu/luquillo-lter/)

Technical Reports
2009 Biological Consultant (Flora and Fauna Survey)- Cayo Vistas, Fajardo.
2008 Biological Consultant (Freshwater Fauna and Flora Survey)- Department of Public Living, Vieques.
2006 Biological Consultant (Fauna and Flora Survey)- Improvements Patillas-Arroyo Puerto Rico Aqueduct and Sewer Authority.
2005 Biological Consultant (Freshwater Fauna Survey)- Puerto Rico Aqueduct and Sewer Authority, Río Grande, Puerto Rico.
2005 Biological Consultant (Tree Inventory and Mitigation Plan)- Marina Las Gaviotas
Development, Urbanización San Tomás, Naguabo.
2005 Biological Consultant (Tree Inventory and Mitigation Plan)- Landfill Technologies Corporation, Fajardo, Puerto Rico.
2004 Biological Consultant (Flora and Fauna Survey; and Tree Inventory and Mitigation Plan)- Betterroads- Empresas Díaz, El Olímpico, Salinas, Puerto Rico.
2004 San Miguel Resort Wetland Delineation (Freshwater Fauna Survey), Luquillo, PR
2004 Biological Consultant (Flora and Fauna Survey)- Department of Transportation, PR-22, Arecibo- Aguadilla
2003 Biological Consultant (Flora and Fauna Survey)- Department of Transportation, PR-2, Arecibo- Aguadilla.
2003 Biological Consultant (Flora and Fauna Survey)- Betterroads- Empresas Díaz, Los Úcares, Salinas Puerto Rico.
2002 Biological Consultant (Freshwater Fauna Survey)- Development of the Río Grande de Arecibo Estuary Model. SuperAqueduct, Puerto Rico Aqueduct and Sewer Authority.

HONORS, AWARDS AND FELLOWSHIPS

2013 PhD Award, Graduate Studies Office, Utah State University.
2013 Travel Award (North American Benthological Society, Florida), Dean Office, Natural Resources College, Utah State University.
2012 iUTAH Graduate Fellowship.
2012 Travel Award (Congreso Latinoamericano de Macroinvertebrados Acuaticos, Costa Rica), Dean Office, Natural Resources College, Utah State University.
2011 Utah State University, Watershed Department and Ecology Center. Graduate Support and Assistantship.
2010 Travel Award (Society of Integrative and Comparative Biology, Seattle), Utah State University, Watershed Department and Ecology Center.
2009 Travel Award (North American Benthological Society, New Mexico), Watershed Department and Ecology Center, Utah State University.
2007 Utah State University, Watershed Department and Ecology Center. Graduate Support and Assistantship.
2005 Who’s Who Among America’s Teacher
2002 Who’s Who Among America’s Teacher
2001 Howard Hughes Foundation. Use of Multimedia in Botany and Zoology Laboratories.
1999 Dr. José Ramón Ortiz Award- Graduate School of Biology, Department of Biology, University of Puerto Rico, Río Piedras Campus.
1998 Travel Award from President Office of the University of Puerto Rico- Annual Meeting of the Society of the British Ecological Society, United Kingdom.
1997 Travel Award from President Office of the University of Puerto Rico- Annual Meeting of the Society of the British Ecological Society, United Kingdom.
1994 Dean List, University of Puerto Rico, Río Piedras.

GRADUATE AND UNDERGRADUATE STUDENTS

Graduate
2012 Javier Sánchez-Cáceres, MS-Candidate, commitee member, Universidad de Costa Rica, San José. Expected Graduation May 2014.
Undergraduates

2012 Tyler Nelson. Utah State University, REU.
2012 Kristina Krome, Williams College, REU.
2011 Ashley Simone Curry, California State Polytechnic University, REU.
2009 Tanner J. Williamson, University of Vermont, REU.
1999 Alfredo Tirado, University of Puerto Rico.
1999 Ernesto J. Ayala, University of Puerto Rico.

PROFESSIONAL SERVICES

Journal Manuscript Review
- Latin American Journal of Aquatic Research
- Acta Cientifica

Research Collaborations
- Rennata Manconi- Università degli Studi di Sassari · Dipartimento di Scienze della Naturae del Territorio, Italy.
- Fernando Mantellato- Universidad de São Paulo, Brazil
- Yogani Govender- Conservation Trust of Puerto Rico

PROFESSIONAL ORGANIZATIONS

British ecological Society (BES)
Society of Integrative Comparative Biology (SICB)
Invertebrate Biology (IB)
The Crustacen Society (TCS)
North American Benthological Society (NABS)
Macroinvertebrados Latinos y Ecosistemas (Macrolatin@s)

PRESENTATIONS AND ABSTRACTS


Pérez-Reyes, O., Tirado, A. (1999) Differences in eggs size and clutch size of the prawn Atya lanipes. British Ecological Society, United Kingdom

Tirado, A., Pérez-Reyes, O. (1999) Biological and pathological aspects of parasitism in the branchial chamber of Macrobrachium spp. by infestation with Probopyrus sp. British Ecological Society, United Kingdom


Tirado, A., Pérez-Reyes, O. (1997) Interactions between the parasite Probopyrus oviformis with its host Macrobrachium spp. (Decapoda: Palaemonidae). British Ecological Society, United Kingdom
WORKSHOPS ATTENDED

- The Zais Model for Curriculum Design. Presenter: Gregory A. Cajete
- Designing Effective Educational Signage for Schoolyard Gardens and Habitats. Presenter: Zackery Zdinak
- Elements of Effective Diverse Education: Getting the Numbers to Dance for American Indian Students. Presenter: Jim Barta
- Great Tips for Teaching Kids Outside. Presenter: Miriam Grahm
- Exploration of Landforms through Text Features and Hands-on Experiences Presenters: Amy Taylor and Marilyn Watland-Wright
- Making Science Real. Presenter: Dr. Carla Endres

MEDIA COVERAGE

2008 Nueva especie de camarón en río metropolitano. Masslive.com

OUTREACH

- How many animals are out there?. Bioblitz, University of Puerto Rico, Bayamón Campus.
- Schoolyard, Luq-LTER. Decapodos de Puerto Rico: Importancia y Distribución.

MAIN REFERENCES

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