Ecology and management of the invasive lionfish *Pterois volitans/miles* complex (Perciformes: Scorpaenidae) in Southern Costa Rica

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Abstract: Invasive species alter ecosystem integrity and functioning and are considered one of the major threats to biodiversity on a global scale. The indopacific lionfish (*Pterois volitans* [Linnaeus, 1758] / *miles* [Bennet, 1882] complex) is the first non-native marine fish that has established itself in the Western Atlantic. It was first reported in Florida in the 1980s and then spread across the entire Caribbean in subsequent years. In Costa Rica, lionfish were first sighted by the end of 2008 and are now present in all South Caribbean reefs. Lionfish are a major problem for local fisherman by displacing native fish species. The aim of this study was to determine population density, size and diet of lionfish populations at four study sites along the Southern Caribbean coast of Costa Rica. Two of the sites were located inside the National Park Cahuita where regular lionfish removal occurs, whereas the other two study sides do not experiment this kind of management. Total length and wet weight of >450 lionfish individuals were determined between March and June 2011. Three relative metrics of prey quantity (percent number, percent frequency, and percent weight) were compared from ~300 lionfish caught with the polespear in shallow waters (<7m depth). Population density was assessed weekly through visual transect surveys. Our results showed that lionfish preyed mostly upon teleosts and crustaceans. Teleosts dominated lionfish diet in percent frequency (71%) and percent weight (85%), whereas crustaceans had the highest percent number (58%). The top five teleost families of dietary importance were Pomacentridae, Acanthuridae, Blennidae, Labridae and Serranidae. The average total length (±SD) of lionfish was 18.7(±5.7)cm and varied significantly between sites (p<0.001). Mean density of lionfish was 92fish/ha with no significant differences between sites. Smallest fish and lowest densities were found at the two sites inside the National Park Cahuita. Despite management efforts on a regional scale, nationwide efforts are ineffective and lionfish control activities are poorly implemented. We conclude that there is an urgent need to develop an improved institutional framework for local lionfish control that promotes effective coordination among the relevant stakeholders in order to deal with invasive lionfish in Costa Rica. Rev. Biol. Trop. 63 (1): 213-221. Epub 2015 March 01.

Key words: invasive species, *Pterois volitans/miles* complex, ecology, management, Costa Rica.

Invasive species pose a threat to ecosystem integrity and functioning. They account for nearly 40% of all animal extinctions and are thus considered one of the greatest drivers of biodiversity loss on a global scale (Hassan, Scholes, & Ash, 2005; Secretariat of the Convention on Biological Diversity, 2006). In 2005, the Millennium Ecosystem Assessment concluded that the introduction rate continues to be extremely high causing a significant impact also on marine biodiversity. The IUCN list of the "100 World's Worst Invasive Alien Species", which assessed species in terms of their spread capacity, ecological potential or economic impact, lists the Indopacific red lionfish (*Pterois volitans/miles* complex) as an important invasive species (Luque et al., 2014).

The Indopacific lionfish (*P. volitans/miles* complex) was the first marine fish to become established and to convert into one of the key invasive species in the Western Atlantic. It was first reported in Florida in the 1980s and then spread across the entire Caribbean region, including Mexico, Cayman Islands, Puerto Rico, Belize, Honduras, Colombia and Venezuela (Betancur-R. et al., 2011; Schofield, 2010). This rapid invasion was facilitated by several biological characteristics of the species, including great reproductive potential, wide larval and egg dispersal, a generalist diet, effective anti-depredatory defenses, and plasticity in habitat use (Cure, McIlwain, & Hixon, 2014; Morris, 2012). Additionally, prey naïveté and lack of predators and parasites in the recipient communities favored its rapid expansion and establishment (Côté, Green, & Hixon, 2013; Morris et al. 2009). Lionfish displace commercial species (Raymond, Albins, & Pusack, 2014) and consume a variety of native fish and invertebrate species (Green, Akins, Maljković, & Côté, 2012) which can have a substantial impact on the structure and integrity of marine systems. For instance, lionfish invasion was responsible for a 65% reduction of prey fish biomass in the Bahamas. In Costa Rica, lionfish were first noted by local fishermen along the Southern Caribbean coast by the end of 2008 (H. McDonald 2011, pers. comm.) and were officially reported in the marine protected area of Cahuita National Park and Gandoca-Manzanillo Wildlife Refuge in April 2009 (Molina-Ureña, 2009; Schofield, 2009). Local fishermen have noticed that the catch of native fish species, such as snappers and groupers, has significantly declined since the invasion of the indo-pacific lionfish. At the moment, lionfish are present in all the South Caribbean reefs of Costa Rica and constitute about half of the catch in traps near Manzanillo and Sixaola (Fundación Trichechus, 2013). Such high catch levels, suggest negative impacts not only on coral reef ecosystems but also on local livelihoods through predation of local resources (Frazer, Jacoby, Edwards, Barry, & Manfrino, 2012). However, lionfish consumption as a food fish has been promoted as an effective localized control mechanism, providing a nutritional food source and at the same time reducing pressure from local fisheries resources (Morris et al. 2011; Morris, & Whitfield, 2009).

In 2012, The Regional Lionfish Committee launched the Regional Strategy for the Control of Invasive Lionfish in the Wider Caribbean. This document is directed towards the government and other stakeholders and aims at: a) facilitating collaboration among stakeholders, b)encouraging research and monitoring, c) encouraging new regulations and policies, iv) controlling lionfish populations, and e)providing education, information and outreach mechanisms (Gómez Lozano et al., 2013).

In Costa Rica, the National System of Conservation Areas (SINAC) developed a strategy to achieve a medium-term action plan in order to educate stakeholders and to monitor and control the lionfish population in the Caribbean in 2010. Although workshops and outreach programs are occasionally conducted, there is no active coordination within the various government institutions and lionfish control is thus poorly implemented. As part of the SINAC's proposed research strategy, biological and ecological aspects of the species and other population characteristics should be determined. It is of primary importance to investigate population density and structure as this allows for assessing the degree of infestation and ongoing population dynamics. Another important aspect is to investigate the diet of the lionfish in order to draw conclusions about the most affected species by lionfish predation and to quantify its impacts on forage fish communities. Therefore, the aim of this study was to determine population density, size and diet of the lionfish populations established along the Southern Caribbean coast of Costa Rica.

MATERIALS AND METHODS

Study site: Lionfish populations were studied along the Southern Caribbean of Costa Rica, where the coastline exhibits areas with fringing and patchy reefs. A total of four study sites were investigated. The two sites Perezoso (9°44’30” N - 82°49’19” W) and Puerto Vargas (9°44’14” N - 82°48’35” W) were located inside of the National Park Cahuita (NPC), where periodical lionfish removals take place under the control of the national environmental agency (MINAE). The sites Puerto Viejo (9°39’32” N - 82°45’19” W) and Manzanillo (9°38’12” N - 82°39’09” W) are not subject to such systematic removal, nonetheless the latter is located inside a Mixed Wildlife Refuge (Refugio Nacional de Vida Silvestre Gandoca-Manzanillo, REGAMA).

The NPC is about 22 400ha in size, of which about 600ha are composed of coral reef substrate (SINAC, 2013). The fringing reefs of NPC consist of three ridges; one prominent ridge along the Cahuita Point with a length of 5km, and two minor ridges at each of its sides. In the lagoon, there are various patches of reef, seaweed and calcareous structures (Cortés et al., 2010a). The area between Puerto Viejo and Manzanillo presents coral reef patches that are severely degraded due to high levels of sedimentation, eutrophication and commercial extraction (Cortés, Jiménez, Fonseca, & Alvarado, 2010b; Salazar, Lizano, & Alfaro, 2004). The REGAMA is administered with the active participation of local communities and the authorities of MINAE (SINAC, 2013). The refuge embraces 5 013ha of terrestrial and 4 436ha of marine area, of which 80% belong to private owners and only 20% belong to the state (Cortés et al., 2010a). The area comprises fringing coral reefs around prominent rocky points and reef patches in lagoons and areas protected from direct wave impact (Cortés et al., 2010b).

Fish sampling and analysis: Fish for biometric and dietary analysis were caught with a polespear. Total length (cm) and wet weight (g) were measured from 327 lionfish obtained from the four sites, 46 fish obtained at two additional shallow water sites (Punta Uva and Coccles), as well as from a sample of 85 fish captured with weir traps at a depth of 80-90m, provided by local fishermen from Manzanillo. Stomach content was analyzed for the 373 lionfish caught in the shallow waters along the Southern coast of Costa Rica. The sample of 85 fish obtained from the fish traps presented either empty or everted stomachs. Stomach content was identified to lowest possible taxon, prey items were counted and wet weight was determined. Percent frequency of occurrence (%F), percent composition by number (%N) and percent composition by weight (%W) were calculated in order to determine dietary importance (Hyslop, 1980; Morris, & Akins, 2009). The five most important families of fish in the diet were identified using a modified form of index of relative importance (IRI; Pinkas, Oliphant, & Iverson, 1971): $IRI_a=F_a \cdot (N_a+W_a)$, for a particular family *a*. We used the gravimetrical (W) instead of the volumetric (V) percentage values for its calculation because it is easier to use in the field and its accuracy is comparable.

Visual transect surveys were conducted weekly between March and June 2011 with snorkel equipment in shallow coastal areas to a depth of seven meters. Structurally similar areas where chosen across the four sites and transect length varied between a minimum of 15 up to 43m depending on particular site conditions. Transect width was kept fixed at 5m. At least six replicates were carried out per site and a total of 26 transects covering an area of 2 725m^2 were completed. Lionfish density per transect was calculated and overall abundance was then obtained as the mean of the transect abundances (Green, & Côté 2009; Morris, & Whitfield 2009; White, 2011; Whitfield et al., 2007).

Statistical analysis was performed with R (Studio version 0.97.332). To test for significant differences (at an α level of 0.05) in fish length between the different sampling locations a one-way analysis of variance (ANOVA) was carried out followed by Bonferroni post-hoc testing. A non-parametric Kruskal wallis test was performed to examine differences in fish density among the four individual sites. Length-to-weight relationship for total body weight was calculated according to the equation $W=a\cdot L^b$, where W is the wet weight (in g), and L is the total length (in cm). The constants a and b were estimated via nonlinear regression and are based on the total of 485 lionfish caught along the Caribbean coast of Costa Rica.

RESULTS

Dietary analysis: From the total of 373 of fish caught in the shallow waters only 298 lionfish were used for stomach content analysis, because approximately 19% of fish presented empty stomachs and 1% lost their stomach during the capturing process. A total of 13 families of teleosts were found and eleven species could be identified, as well as three orders of crustaceans (Table 1). In three particular cases two species of seaweed and one species of green algae were detected. Teleost fish dominated the lionfish diet in percent frequency (71.1%) and percent weight (84.8%), whereas crustaceans exceeded fish contribution in percent number (58.3%). The last finding was related to a very high number of juvenile crustaceans (418 individuals) that were found in the stomachs of eight lionfish. Following the IRI, the most important teleost families in Costa Rican lionfish diet were Pomacentridae, Acanthuridae, Blennidae, Labridae and Serranidae, in descending order of importance.

Biometry: Of the four shallow sites, lionfish caught in Perezoso were the smallest in length, followed by Puerto Vargas, Puerto Viejo and Manzanillo harbouring the largest fishes (Fig. 1). Lionfish from deeper waters were at least 1.3 times larger than lionfish from any of the shallow sites. Mean length (±SD) of the population sampled in the Southern Caribbean of Costa Rica was 18.7(±5.7)cm (n=458, including 28 lionfish sampled at Punta Uva and Cocles). Total length varied significantly between sites (ANOVA, F=106.2, p<0.001), and the only sites with similar length were Perezoso in relation to Puerto Vargas, and Puerto Vargas in relation to Puerto Viejo (Bonferonni post hoc test). Growth parameters for the length-weight-relationship were estimated as $a=2.35 \times 10^{-2}$ and b=2.81 (Fig. 2).

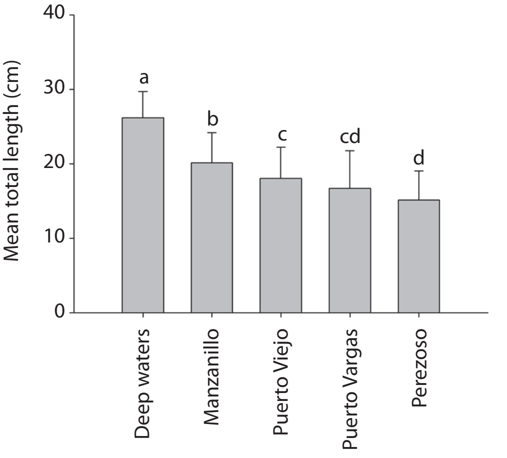

Fig. 1. Mean total length of lionfish sampled at four shallow sites in the Southern Caribbean of Costa Rica plus one sample of 85 fish caught at a depth of about 80-90 meters. (Letters on top of the bars indicate statistically homogenous groups).

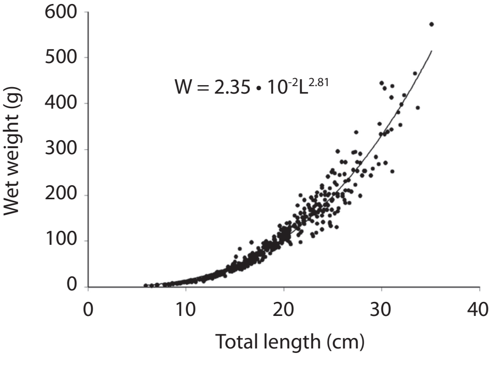

Fig. 2. Length-weight relationship of 458 lionfish collected along the Southern Caribbean coast of Costa Rica.

Lionfish density: Lionfish density was highest in Manzanillo (162±218fish/ha), followed by Puerto Viejo (81±80fish/ha), Puerto Vargas (70±93 fish/ha) and Perezoso (62±99) (Fig. 3). The mean density calculated for

TABLE 1
Composition of lionfish diet in the Southern Caribbean of Costa Rica sorted by taxa

	Frequency	%O (n=298)	%N (n=924)	%P (total=500.4g)
Teleosts	381	71.1	41.2	84.8
Acanthuroidei	45	6.7	4.9	7.7
Acanthuridae	45	6.7	4.9	7.7
A. bahianus	1	0.3	0.1	0.2
A. coeruleus	2	0.7	0.2	1.1
Blennioidei	43	10.4	4.6	12.1
Blenniidae	19	5.4	2.1	7.6
Ophioblennius atlanticus	12	4.0	1.3	5.0
Gobioidei	12	3.0	1.3	3.0
Gobiidae	12	3.0	1.3	3.0
Gobiosoma grosvenori	1	0.3	0.1	<0.1
Holocentroidei	2	0.7	0.2	2.0
Holocentridae	2	0.7	0.2	2.0
Holocentrus rufus	2	0.7	0.2	2.0
Labroidei	55	12.0	5.9	17.3
Labridae	25	4.0	2.7	4.8
Thalassoma bifasciatum	15	2.3	1.6	2.5
Pomacentridae	30	8.0	3.2	12.5
Abudefduf saxatilis	1	0.3	0.1	0.3
Mycrospathodon chrysurus	2	0.7	0.2	0.6
Stegastes sp.	27	7.4	2.9	11.53
S. adustus	1	0.3	0.1	0.29
Percoidei	15	5.0	1.5	6.8
Apogonidae	1	0.3	0.1	1.3
Apogon maculatus	1	0.3	0.1	1.3
Chaetodontidae	1	0.3	0.1	0.3
Chaetodon sp.	1	0.3	0.1	0.3
Gerreidae	2	0.7	0.2	0.3
Haemulidae	1	0.3	0.1	0.6
Anisotremus surinamensis	1	0.3	0.1	0.6
Priacanthidae	2	0.7	0.2	1.6
Scianidae	3	1	0.3	1.4
Serranidae	5	1.7	0.5	2.6
Not identified fish	208	52.3	22.5	33.2
Crustaceans	539	28.2	58.3	15.0
Decapods	116	25.2	57.8	12.9
Prawn	110	24.2	57.1	12.5
Caridea	25	6.7	2.7	5.3
Crabs	6	2.0	0.6	0.5
Brachyura	6	2.0	0.6	0.5
Stomatopoda	5	1.7	0.5	0.4
Gonodactylidae	5	1.7	0.5	0.1
Neogonodactylus oersetedii	1	0.3	0.1	<0.1
Chlorophyta				
Halimeda sp.	1	0.3	0.1	<0.1
Seagrass	3	1.0	0.3	0.1
Syringodium filiforme	1	0.3	0.1	<0.1
Thalassia testudinum	2	0.7	0.2	0.1

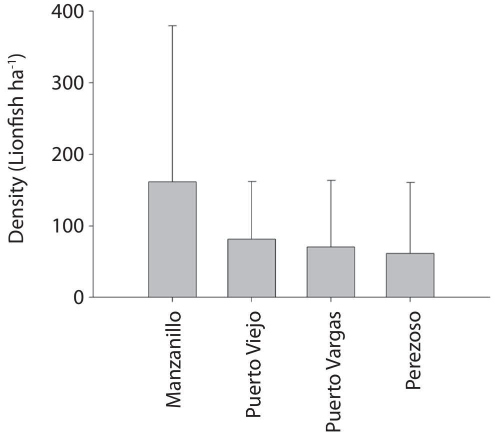

Fig. 3. Average density of lionfish at four sites along the Southern Caribbean Coast of Costa Rica. (Black bars indicate standard deviation).

the Southern Caribbean of Costa Rica was 92±130fish/ha. Differences between sites reached up to 100 fish, but statistical analysis revealed no significant differences (KW, $\chi 2=1.48$, $p=0.84$).

DISCUSSION

Teleosts dominated lionfish diet in the Southern Caribbean of Costa Rica in percent weight and percent frequency. This is similar to results reported from the Bahamas (Morris, & Akins, 2009) and the Netherlands Antilles (McCleery, 2011) which showed that the invasive lionfish is a piscivorous generalist predator. The most common prey items were herbivorous fish (e.g. Pomacentridae, Acanthuridae and Blennidae). On coral reefs, herbivorous fish present an important functional group as they control algal growth (Bellwood, Hughes, Folke, & Nyström, 2004; Hughes, 1994; Hughes et al., 2007). Thus, through predation on herbivorous fish, lionfish contribute to current coral-algal phase shifts that are affecting coral reefs on a regional scale throughout the Caribbean (Barbour, Allen, Frazer, & Sherman, 2011). The second most common prey were crustaceans. However, a large number of juvenile crustaceans (418 individuals) were found in only eight lionfish stomachs, with up to 85 individuals per lionfish. Inclusion of these eight lionfish samples increased crustacean percent number from 24% to 58%, and thus represents a substantial increase over a short timeframe and limited number of lionfish. Possibly, this change was related to the breeding season of a single crustacean species in particular. However, it was not possible to identify these juveniles to a lower taxonomic unit given their small size and advanced degree of decomposition. Such high levels of lionfish predation on crustaceans have not been reported previously. Therefore this finding is alarming especially with regard to its impact on mortality rates of crustaceans and vulnerability of their juvenile life stage to lionfish predation. The diet was also composed of Serranid fish which are -as well as shrimps and lobsters- of high commercial value due to use in food consumption (Polunin, & Roberts, 1993; Vannuccini, 2003).

We found lionfish at all study sites along the Southern Caribbean coast of Costa Rica. Mean density was 3.6 times higher than lionfish density reported from its native range in Kenya (25.1 fish/ha; Darling, Green, O´Leary, & Côté, 2011). Although, we conducted a thorough lionfish-focused search, i.e. focusing on cryptic habitats, lionfish densities reported here have to be considered conservative estimates, given that visual surveys generally tend to underestimate the density of cryptic species (Brock, 1982; Stewart, & Beukers, 2000). For instance, a recent study found that conventional belt transects fail to detect more than half of the lionfish within their boundaries (S. Green, unpublished data, as cited in Morris, 2012). Moreover, current guidelines for lionfish monitoring recommend a transect width of 10m in order to account for its patchy distribution (Morris, 2012). The two sites with slightly less lionfish abundance were found inside the NPC, where periodic removals of the invasive species occur and this tendency might indicate efficacy of current control efforts. This is reinforced by the fact that the smallest mean length was detected for these sites; lionfish removals present an unintended bias towards larger fish, as nearly all fishing gears do, since small fish are less visible and harder to catch with a pole-spear (Barbour et al., 2011). It is important to mention that in Puerto Viejo, a private organization was conducting lionfish removals in 2010, but was forced to stop its efforts because of the lack of a clear legislation. Possibly, this former control effort caused lionfish densities in Puerto Viejo to be lower than in Manzanillo. The extent to which removal efforts effectively reduce lionfish numbers is still unknown, but most likely it will only be feasible at local scales within high-priority areas, where continuous fishing pressure can be carried out over multiple consecutive years (Barbour et al., 2011; Green et al., 2012; Morris, 2012).

While the first lionfish in Costa Rica were sighted by the end of 2008, its dispersion to deeper waters has not been reported until February 2011, when local fishermen started capturing the invasive fish in weir traps installed at depth of about 80-90m (H. McDonald, personal communication, August 2011). According to anecdotal comments, occurrence and quantity of trapped lionfish was still augmenting in 2011, indicating that lionfish invasion in the Southern Caribbean of Costa Rica has still been in a dynamic stage and not reached saturation at that point in time. The comparably larger sizes detected for the deeper waters could be related to the different fishing gear employed, habitat preferences of larger fish, or hitherto unknown ecological factors affecting the distribution of the species.

Due to the severity of the lionfish invasion in the Caribbean, the International Coral Reef Initiative (ICRI) is concerned with designing and implementing a strategic plan to control the lionfish as a way to reduce its effects in the region and provide a framework to facilitate the regional response (Gómez Lozano et al., 2013). Despite all this regional initiative in the country, it has not been institutionalized, so the efforts have been sporadic and uncoordinated. Even though strategic lines have been proposed and some control actions implemented, we are still far from reducing the effects of lionfish on ecosystem services regarding coral reef communities.

A local inter-institutional strategy should be developed in collaboration with stakeholders from the environmental and the fisheries sector, from universities and local communities. The framework for management and control in the country should focus on several main aspects: **a)** identify potential key areas for lionfish control based on their ecological and socio-economic value, accessibility and degree of infestation **b)** coordinate lionfish removals in those key protection areas to reach a level where continuous fishing pressure can aim at reducing invasive population densities **c)** set up a regular fixed monitoring program that covers coral sites along the coast, but also includes ecosystems such as coastal lagoons, wetlands, and mangroves, **d)** launch an awareness-raising campaign and an early warning system to prevent lionfish introduction to the Pacific coast **e)** improve communication among stakeholders and develop participatory plans in the management decision-making processes along with training and education for a better coordination in control of this species with coastal communities.

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RESUMEN

Ecología y manejo del pez león *Pterois volitans/ miles* **complex (Perciformes: Scorpanidae) en el Caribe sur de Costa Rica.** Las especies invasoras alteran la integridad y el funcionamiento de los ecosistemas y se consideran una de las mayores amenazas para la biodiversidad a nivel global. El pez león (*Pterois volitans* [Linnaeus, 1758]/ *miles* [Bennet, 1882] complex) del Indo-Pacífico es el primer pez marino no-nativo que se ha establecido en el

Atlántico oeste. Fue reportado por primera vez en Florida en los años 80´s y se propagó en todo el Caribe en los años subsiguientes. En Costa Rica, el pez león se reporto por primera vez a finales del 2008 y hoy en día se encuentra en todos los arrecifes del Caribe Sur. El pez león es un grave problema para los pescadores locales por desplazar a los recursos pesqueros nativos. El objetivo de este estudio fue determinar la densidad poblacional, talla y la dieta de las poblaciones del pez león en cuatro sitios de muestreo a lo largo de la costa del Caribe Sur de Costa Rica. Dos de los sitios fueron localizados dentro del Parque Nacional Cahuita donde se efectúan remociones periódicos del pez león, mientras que los otros dos sitios no experimenten este tipo de manejo. Se midieron la longitud total y el peso fresco de >450 individuos entre marzo y junio 2011. Se compararon tres medidas relativas para el análisis estomacal (composición por número, por frecuencia y por peso) de ~300 individuos capturados con un arpón marino en las aguas someras (<7m profundidad). La densidad poblacional fue estimada a partir de transectos visuales semanales. Nuestros resultados muestran que el pez león se alimentó principalmente de teleósteos y crustáceos. Los teleósteos dominaron la dieta en cuanto a composición por frecuencia (71%) y composición por peso (85%), mientras que los crustáceos prevalecieron en cuanto a composición por número (58%). Las cinco familias más importantes en la dieta del pez león fueron los Pomacentridae, Acanthuridae, Blennidae, Labridae y Serranidae. La longitud total media (±DE) fue 18.7(±5.7)cm y varió significativamente entre los sitios (p<0.001). La densidad media fue de 92 peces/ha y no fue estadísticamente diferente entre los sitios. Los peces con la menor talla y las densidades poblacionales más bajas fueron encontrados en los dos sitios dentro del Parque Nacional Cahuita. A pesar de los esfuerzos de manejo que existen a nivel regional, las estrategias nacionales son deficientes y las actividades para el control de la especie invasiva son escasos en Costa Rica. Es preciso desarrollar un marco institucional para el control local del pez león que incluye todo los implicados y que promueva la coordinación efectiva entre ellos.

Palabras clave: especies invasoras, pez león (*Pterois volitans / miles* complex), dieta, densidad, manejo, Costa Rica.

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