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BY-CATCH ASSOCIATED WITH FISHERIES OF *HETEROCARPUS VICARIUS* (COSTA RICA) AND *HETEROCARPUS REEDI* (CHILE) (DECAPODA: PANDALIDAE): A SIX-YEAR STUDY (2004-2009)

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ABSTRACT

Growing concern about the quantity and diversity of by-catch species caught in the bottom trawling nets of crustacean fisheries led us to compare the quantity of by-catch recorded in Chilean and Costa Rican deep-water shrimp fisheries by year, latitude, and bathymetry. We analyzed catches from 2143 trawl hauls between 2004 and 2009 from the fisheries of the northern nylon shrimp, *Heterocarpus vicarius*, and the kolibri shrimp, *Solenocera agassizii*, off Costa Rica and the Chilean nylon shrimp, *Heterocarpus reedi*, off Chile. A catch index was estimated to determine the quantity of by-catch retained for each kilogram of shrimp. The by-catch associated with the shrimp fisheries of Costa Rica and Chile was mainly fishes and crustaceans; by-catch species diversity was considerably higher in Costa Rica compared to that of Chile. In Chile, catches of *H. reedi* and by-catch were greater in the central and southern zone, whereas in Costa Rica, catches of shrimp (*H. vicarius*, *S. agassizii*) and by-catch were higher in the central zone. In terms of bathymetry, the largest catches of shrimp and by-catch came from the deep stratum (between 251 and 400 m) for both countries; the by-catch was noticeably larger in this stratum in Costa Rica. The catch index revealed that for every 1 kg of shrimp caught in Costa Rica, 5.7 kg of by-catch were caught; in Chile, this ratio was 1.1:1. However, the projected global by-catch was considerably higher for the fishery for *H. reedi* than for that of *H. vicarius*, which is related to the landed volumes of the target species in Costa Rica and Chile. The encouraging results in the *H. reedi*-fishery concerning technical measures to reduce by-catch and discards rates should be also considered for Central American deep-water shrimp fisheries.

KEY WORDS: by-catch, catch composition, deep-water shrimp, *Heterocarpus* spp., *Solenocera agassizii*

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INTRODUCTION

Benthic shrimp fisheries rely on trawl nets as the principal fishing gear (Kelleher, 2005; Watson et al., 2006; Foster and Vincent, 2010), and the use of trawls and dredges has increased globally since the 1950s (Watson et al., 2006). In general, bottom-trawling nets are considered to be largely nonselective, catching and retaining large quantities of species not targeted by the fishery; these species are commonly referred to as "by-catch" (Broadhurst, 2000). By-catch organisms are usually discarded due to the poor quality of their meat, a lack of commercial interest, the fact that the consumers are not accustomed to eating them, administrative restrictions, and other social-economic reasons. However, when returned to the sea, most of the by-catch has little or no chance of survival (Villaseñor, 1997). Another relevant aspect is that juveniles of the target resource may form an important part of the by-catch, which can negatively affect the commercial catches of the respective fisheries (Broadhurst et al., 1996; Kennelly et al., 1998; Zhou, 2008; Davies et al., 2009; Queirolo et al., 2011a). At present, the information available on the quantity and quality of by-catch extracted with bottom trawl nets is far from complete (Kelleher, 2005; Davies et al., 2009). This gap is related to the difficulty of verifying the information provided by fishermen and to the fact that the participation of scientific observers in commercial fishery operations is limited.

Interest in the by-catch associated with the extraction of commercial species has grown in terms of its analysis and evolution (Saila, 1983; Andrew and Pepperell, 1992; Alverson et al., 1994; Kennelly, 1995; Harrington et al., 2005; Zhou, 2008; Davies et al., 2009). Alverson et al. (1994) defined by-catch as "discarded catch plus incidental catch," with incidental catch defined as the "retained catch of non-targeted species." In turn, Davies et al. (2009) defined by-catch as $B = C_t - C_{lm}$, where B is the total biomass of the by-catch, C_t is the total biomass of the species caught in the fishery haul, and C_{lm} is the total catch landed or used. In by-catch analyses, by-catch tends to be defined as the percentage of undesired species with respect to the target species of the fishery, as a ratio of one to the other, or according to estimates of the total weight of the species that

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make up the by-catch in a given fishery, geographic region, or globally (Alverson et al., 1994; Olsen et al., 2000; Davies et al., 2009).

The existence of by-catch is a long-standing problem. The negative effects created by discarding portions of fishery catches have clearly led to a decline of marine ecosystems, constituting a major world-wide problem (Watson et al., 2006). Researchers are trying to evaluate the magnitude of this matter and have proposed measures for its mitigation and control (Graham, 1996; Hall et al., 2000; ECM, 2003; Harrington et al., 2005; Krag et al., 2008; Matsuoka, 2008; Davies et al., 2009). Specifically, trawling is considered to be the most harmful fishery operation in terms of the degradation of the marine floors, and this type of fishing is thought to cause serious problems for fishery sustainability (Broadhurst, 2000; Kelleher, 2005; Watson et al., 2006; Foster and Vincent, 2010). Shrimp trawling, particularly in the tropics, is considered to be the fishery that generates the highest discard levels (Cook, 2001; Kelleher, 2005). The ratio of by-catch to target resources in tropical and subtropical shrimp fisheries often varies between 1:5 and 1:10, whereas in temperate and coldwater regions, this ratio tends to be noticeably lower (Harris and Poiner, 1990; Kelleher, 2005).

Most commercial fishery activities in Costa Rica are concentrated off the Pacific coast, where the main target species of the deep-water fishery are the pandalid carideans *Heterocarpus affinis* Faxon, 1893 and *Heterocarpus vicarius* Faxon, 1893, as well as *Solenocera agassizii* Faxon, 1893 (Decapoda: Penaeoidea: Solenoceridae). The latter species is currently the most important in terms of annual shrimp landings (Wehrtmann and Nielsen-Muñoz, 2009; Wehrtmann et al., 2009, 2012). The values of by-catch (discard) in the Costa Rican shrimp fishery during 2000-2003 has been estimated at 44% or 11 000 ton/year (Davies et al., 2009), and the by-catch is generally 7.5 kg per 1 kg of shrimp (FAO, 2005).

In Chile, studies of the by-catch from trawl fishing began in the early 1970s (Acuña et al., 2005). Information on the resources caught with trawl nets used to extract hake, *Merluccius gayi* (Guichenot, 1848), and the Chilean nylon shrimp, *Heterocarpus reedi* Bahamonde, 1955, off the central coast of the country (Yáñez, 1974; Yáñez and Barbieri, 1974; Yáñez et al., 1974) revealed differences in the spatial and seasonal abundance of the available species, according to the kind of gear used. Qualitative descriptions of the by-catch species of the *H. reedi*-fishery were provided by other studies that focused on assessing the diversity of deep-water fauna off central Chile (Acuña et al., 2005; Orellana, 2006) and possibilities for reducing the by-catch (Queirolo et al., 2011b).

Considering the discussions of and concerns with the sustainability of deep-water fisheries and the impacts caused by trawl fishing (Alverson et al., 1994; FAO, 2003; Althaus et al., 2009), the present study analyzes the by-catch levels associated with deep-water shrimp fisheries carried out off Costa Rica (*H. vicarius* and *S. agassizii*) and Chile (*H. reedi*). These two fisheries were selected, not only because of their economical importance in Latin America, but principally because detailed by-catch data are available for a prolonged and comparable time period. Moreover, these fisheries refer to species of the same genus, distributed in different geographic zones along the Pacific coast of Latin America, but in similar depth ranges. The principal objectives of this work are: 1) to compare – over time, latitude and bathymetry – the extraction of species associated with these resources in two biogeographic regions, and 2) to determine the catch index (CI). The results may contribute to our understanding of the ecological impacts of these deep-water fisheries and may facilitate the development of adequate management measures for each of the fisheries analyzed.

MATERIALS AND METHODS

This analysis of by-catch species relies on a historic data series compiled during research projects carried out between 2004 and 2009. Data from the Costa Rican fisheries of the northern nylon shrimp (*H. vicarius*) and the kolibri shrimp (*S. agassizii*) were gathered as a part of a scientific monitoring program of deep-water shrimp carried out off the Pacific coast between 08°18′ and 10°12′N. The Chilean data were taken from assessment cruises done on nylon shrimp (*H. reedi*) between 21°34′ and 38°29′S. In both Costa Rica and Chile, the fishery operations were performed with trawl nets with mesh sizes of 50 to 76 mm (2″ and 3″, respectively); no special devices were employed to allow the escape or elimination of the by-catch. The hauls lasted between 20 in Costa Rica and 30 min in Chile, and the overall trawling depth range was from 102 to 653 m.

Data were collected by scientific personnel aboard commercial shrimp vessels used for the research (length overall: 18-22 m). For each haul, specially designed data sheets were completed with the fishery's operational data, setting and retrieval positions (using GPS readings), trawling depth (using the vessel's echo sounder), and the catch composition detailed by species. The catch was weighed (recorded in kg) on board immediately after retrieval. The by-catch species were quantified by separating them from the target resource for each haul. The target catch (Costa Rica: *H. vicarius*, *S. agassizii*; Chile: *H. reedi*) was placed in plastic bins arranged on the deck of the vessel and later weighed and counted to determine the total catch in weight.

The by-catch species were identified using the following literature: Costa Rica: Bussing and López (1993), Garth (1958), Haig (1960), Hendrickx and Salgado-Barragán (1991), Hendrickx (1995a, 1995b, 1995c, 1995d, 1997, 2000), Hendrickx and Estrada-Navarrete (1996), Keen (1971) and Martin and Davis (2001); Chile: Pequeño (1994), Andrade and Báez (1980), Retamal (1981) and Meléndez and Meneses (1989). Species that could not be identified on board were separated and kept for identification on land by specialists.

The databases generated in both countries were reviewed prior to processing. For the general analysis of the information available, we used only those hauls defined by the fishermen as being commercial catches, i.e., those in which >10 kg (Costa Rica) or >20 kg (Chile) of the target species were caught. Later, for purposes of comparison, the records were grouped by year, zone and depth. To determine possible associations of fauna for *H. vicarius*, *S. agassizii* and *H. reedi* in terms of latitude, we grouped the fishery hauls into three study sectors, i.e., the northern, central and southern zones. The latitudinal limits for these sectors in both countries are presented in Fig. 1. The records of both countries were also grouped into three depth ranges: 100 to 250 m, 251 to 400 m, and 401 to 650 m; the latter depth group refers only to Chile, because in Costa Rica all hauls analyzed were carried out at depth above 400 m.

After grouping the data by zone and depth, the catch per unit effort (CPUE) was calculated for the target species and the by-catch for each of the two countries. Subsequently, we determined the arithmetical mean values ($\bar{x}$) with their standard deviations (s). Since all catch data showed an asymmetric distribution, we applied the natural logarithm in order to obtain a Gaussian distribution, which permitted to fulfill the assumption of normality necessary to carry out the analysis of variance (Sokal and Rohlf, 1969).

To establish possible differences between CPUEs (of both target species and by-catch) concerning zones, depth ranges and countries, the data were analyzed by an analysis of variance (one factor ANOVA) with a significance value of $\alpha = 0.05$. When data did not comply with the homogeneity of variance for the comparison of the means, a Kruskal-Wallis (KW) non-parametric test was used.

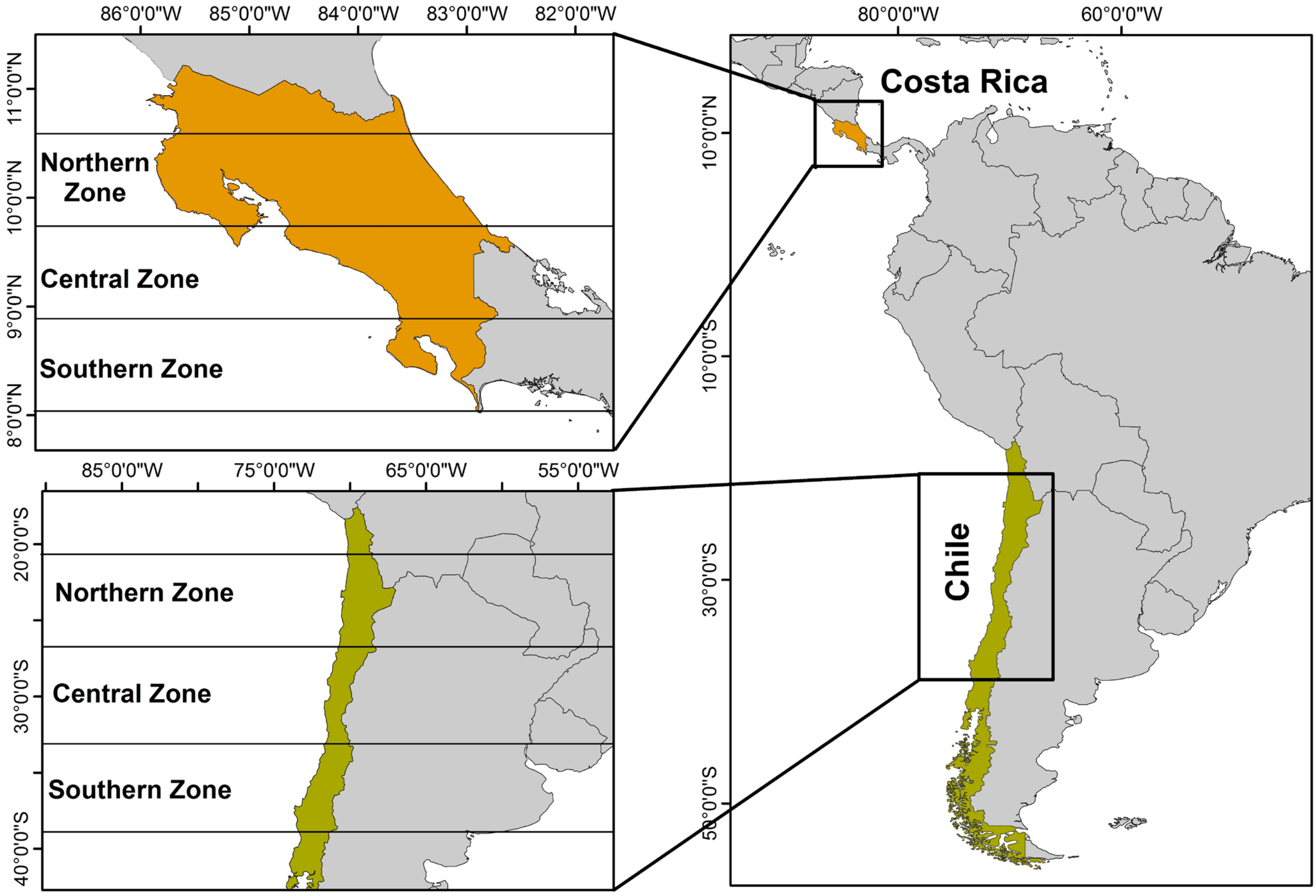

Fig. 1. Identification of the study zones in Costa Rica and Chile. This figure is published in colour in the online edition of this journal, which can be accessed via http://booksandjournals.brillonline.com/content/1937240x.

In case of significant differences between zones or depths, we applied *a posteriori* multiple comparisons in order to determine which groups presented differences. The Tukey test was used when variance homogeneity was complied; if not, we utilized the Games-Howell test (Sokal and Rohlf, 1969). All analyses were carried out with the statistic program SPSS v.15.0.

In order to determine the amount of by-catch obtained with each fishery haul per kg of deep-water shrimp, we calculated the catch index (CI) as follows (Alverson et al., 1994):

$$CI = \frac{\sum \text{Catch of by catch (kg)}}{\sum \text{Catch of objective shrimp (kg)}}$$

This index was calculated for different levels of shrimp catches in order to elucidate how the by-catch varied according to greater or lower catches of the target shrimps. Finally, the CI was used to project the catches of the main species obtained as by-catch per country during the study period. In Costa Rica, the global by-catch was estimated using annual landings of both *H. vicarius* and *S. agassizii*. In Chile, this estimate was calculated in relation to the annual global catch quotas of *H. reedi*.

RESULTS

The data bases compiled between 2004 and 2009 covered a total of 2143 hauls (Table 1), from which we analyzed 1618 hauls with catches of the target resources, i.e., *H. vicarius* + *S. agassizii* in Costa Rica and *H. reedi* in Chile. During this time span, a total of 216 hauls were carried out in Costa Rica (Fig. 2), 1402 were done in Chile (Fig. 3).

Catch Composition

The proportions of deep-water shrimp and by-catch differed for the fisheries of the two countries studied. In Costa Rica, the by-catch constituted between 82.3 and 96.8% of the total annual catch in the period analyzed (Fig. 4). Moreover, the by-catch increased as of 2007, coinciding with an important reduction in the catch levels of *H. vicarius* and *S. agassizii*. In Chile, the proportion of the by-catch ranged from 35.9% (2006) to 57.1% (2008) (Fig. 4).

One important characteristic of the shrimp fisheries analyzed from Costa Rica and Chile was the high diversity of the by-catch. In general terms, the composition by taxonomic group was similar in these two regions, dominated by fishes, followed by crustaceans, mollusks and other groups (Fig. 5). Species richness of the by-catch was considerably higher in Costa Rica than in Chile; usually there were twice the number of species per taxonomic group in Costa Rica compared to those recorded in Chile, and the difference was even more pronounced in mollusks (Costa Rica: 25 spp.; Chile: 3 spp.). The catch in weight of the target species was noticeably different between the two countries: on average, the target species made up 9.2% of the total catch in Costa Rica and 55.4% of the total catch in Chile (Table 2). In Costa Rica, the by-catch of *H. vicarius* consisted mostly of diverse crustacean species (62.1%), whereas in Chile, the most rel-

Table 1. Projects dealing with deep-water shrimp fisheries from 2004 to 2009, whose data were used for the present study: *Heterocarpus vicarius* and *Solenocera agassizii* in Costa Rica and *Heterocarpus reedi* in Chile. *Number of haul with deep-water shrimp catches.

Year	Name of the project	Executing unit	Study period	Latitudinal range	Depth range (m)	Number of hauls*
2004	"Direct assessment of nylon shrimp between Regions II and VIII (FIP 2004-10)"	School of Marine Sciences/The Pontifical Catholic University of Valparaíso, Chile	Jul 04-Sep 04	23°00′-37°00′ L.S.	120-548	251
	"Development of standards for a sustainable fishery of the deep water shrimp *Heterocarpus vicarius* (No. 111-A4-508)" 2004	Unit for Fishery Research and Aquaculture (UNIP) of the Research Center for Marine Science and Limnology (CIMAR), University of Costa Rica	Jan 04-Dec 04	08°20′-10°12′ L.N.	210-347	37
2005	"Direct assessment of nylon shrimp and prawn between Regions II and VIII (FIP 2005-08)"	School of Marine Sciences/The Pontifical Catholic University of Valparaíso, Chile	Jul 05-Aug 05	24°30′-37°00′ L.S.	150-651	315
	"Development of standards for a sustainable fishery of the deep water shrimp *Heterocarpus vicarius* (No. 111-A4-508)" 2005	Unit for Fishery Research and Aquaculture (UNIP) of the Research Center for Marine Science and Limnology (CIMAR), University of Costa Rica	Jan 05-Dec 05	08°46′-10°05′ L.N.	102-331	41
2006	"Direct assessment of nylon shrimp between Regions II and VIII (FIP 2006-11)"	Catholic University of the North/University of Concepción/Fisheries Development Institute of Chile (Instituto de Fomento Pesquero, IFOP)	Oct 06-Dec 06	24°12′-36°42′ L.S.	154-653	232
	"Development of standards for a sustainable fishery of the deep water shrimp *Heterocarpus vicarius* (No. 111-A4-508)" 2006	Unit for Fishery Research and Aquaculture (UNIP) of the Research Center for Marine Science and Limnology (CIMAR), University of Costa Rica	Jan 06-Dec 06	08°18′-09°31′ L.N.	172-329	29
2007	"Development of standards for a sustainable fishery of the deep water shrimp *Heterocarpus vicarius* (No. 111-A4-508)" 2007	Unit for Fishery Research and Aquaculture (UNIP) of the Research Center for Marine Science and Limnology (CIMAR), University of Costa Rica	Jan 07-Dec 07	08°18′-08°45′ L.N.	146-292	40
2008	"Direct assessment of nylon shrimp between Regions II and VIII (FIP 2008-17)"	Catholic University of the North/University of Concepción, Chile	Jan 08-Dec 08	25°16′-36°41′ L.S.	124-517	330
	"Development of standards for a sustainable fishery of the deep water shrimp *Heterocarpus vicarius* (No. 111-A4-508)" 2008	Unit for Fishery Research and Aquaculture (UNIP) of the Research Center for Marine Science and Limnology (CIMAR), University of Costa Rica	Jan 08-Dec 08	08°19′-09°34′ L.N.	146-256	35
2009	"Direct assessment of nylon shrimp between Regions II and VIII (FIP 2009-16)"	Catholic University of the North/University of Concepción, Chile	Aug 09-Nov 09	25°08′-36°21′ L.S.	108-575	274
	"Development of standards for a sustainable fishery of the deep water shrimp *Heterocarpus vicarius* (No. 111-A4-508)" 2009	Unit for Fishery Research and Aquaculture (UNIP) of the Research Center for Marine Science and Limnology (CIMAR), University of Costa Rica	Aug 09-Nov 09	09°15′-09°34′ L.N.	155-292	34

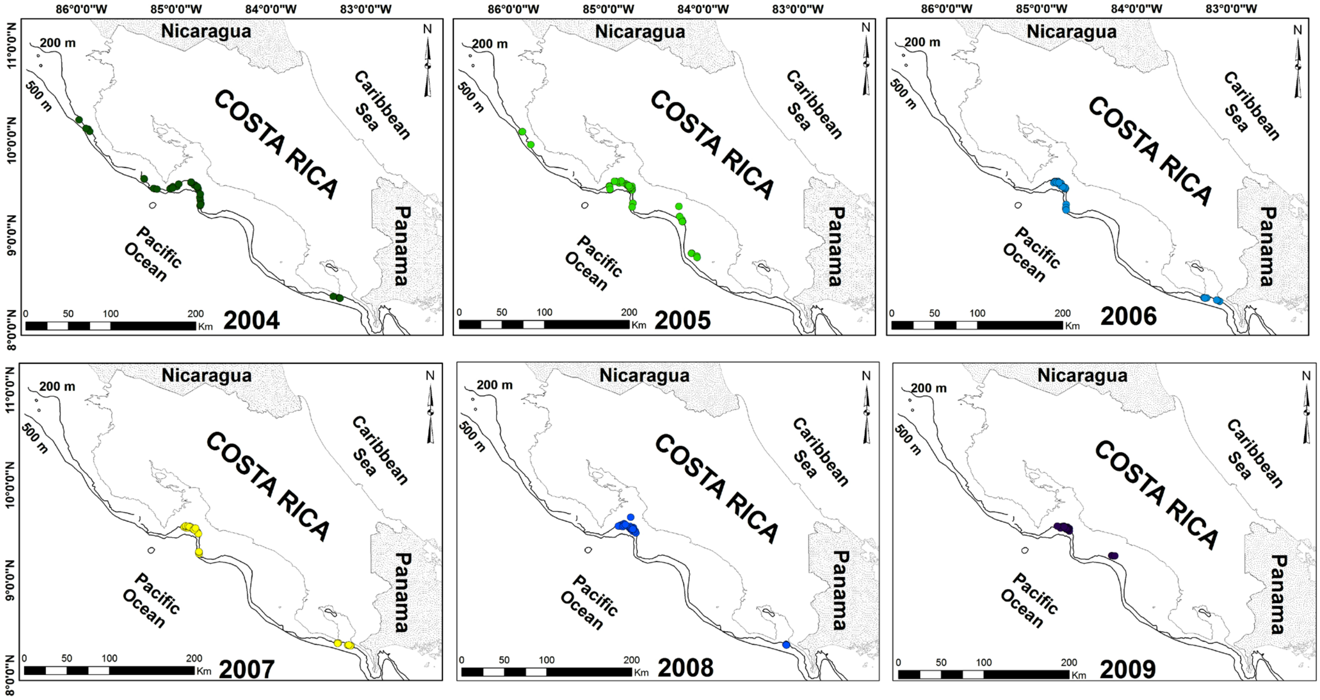

Fig. 2. Distribution of hauls carried out in the frame of a scientific monitoring program for deep-water shrimps (*Heterocarpus vicarius* and *Solenocera agassizii*) along the Pacific coast of Costa Rica (2004-2009). This figure is published in colour in the online edition of this journal, which can be accessed via http://booksandjournals.brillonline.com/content/1937240x.

evant by-catch groups were crustaceans (22.9%) and fishes (21.1%) (Table 2).

In Costa Rica, the most common crustaceans were *Squilla biformis* Bigelow, 1891 (12.1%) and *Pleuroncodes monodon* (H. Milne Edwards, 1837) (12.5%). Although no detailed identification of the fish species present in each haul was recorded during 2004-2009, this group made up on average 28.4% of the total weight caught in the study period (Table 2). In Chile, the crustaceans that contributed the most in weight were the squat lobsters *Cervimunida johni* Porter, 1903 (11.0%) and *Pleuroncodes monodon* (3.4%). In the fish group, the main resources associated with the catches of *H. reedi* were South Pacific hake (*Merluccius gayi*), rat-tail (*Caelorhynchus fasciatus* (Günther, 1878)) and bigeye

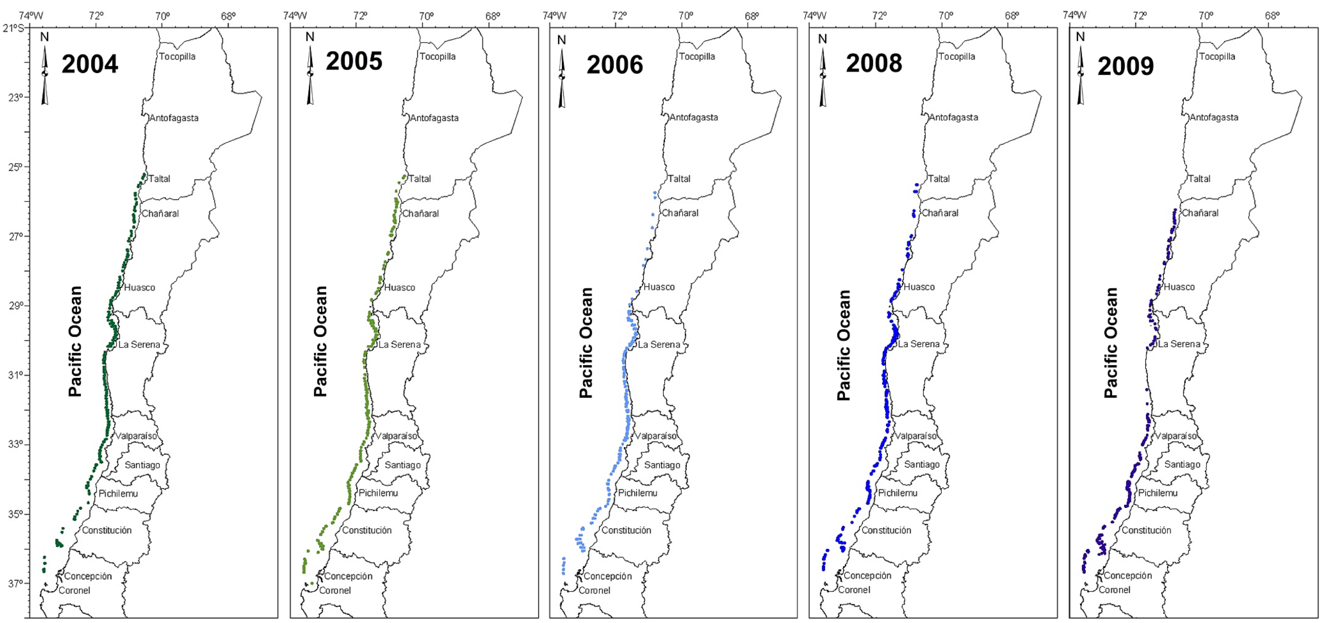

Fig. 3. Distribution of hauls along the Pacific coast of Chile carried out as part of assessment cruises for *Heterocarpus reedi* (2004-2009). This figure is published in colour in the online edition of this journal, which can be accessed via http://booksandjournals.brillonline.com/content/1937240x.

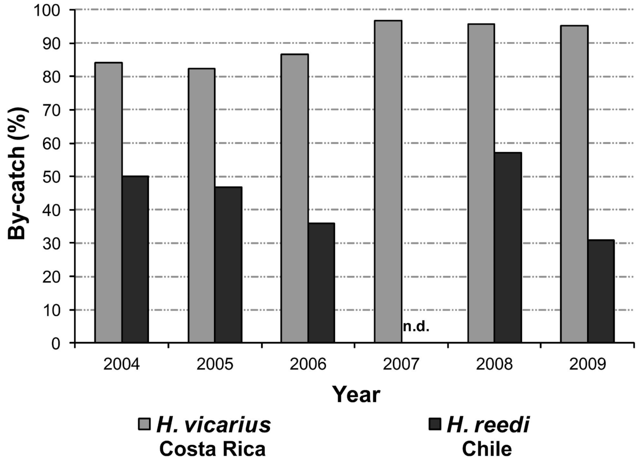

Fig. 4. Comparison of mean by-catch per year (expressed as percent of total catch) recorded during research projects in Chile and Costa Rica (2004-2009). n.d. = no data available.

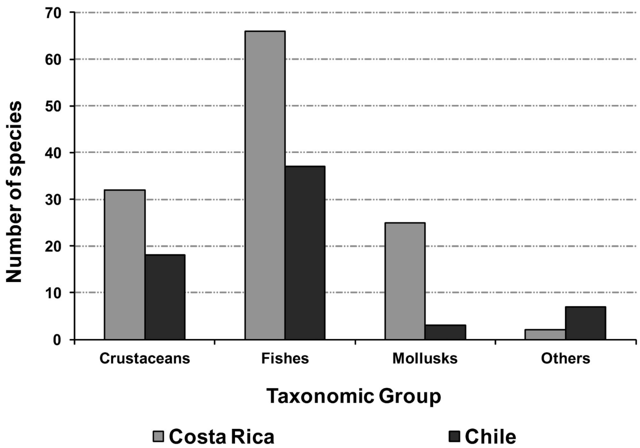

Fig. 5. Number of species per taxonomic group in the by-catch of deep-water shrimps in Costa Rica and Chile (2004-2009).

Table 2. Composition (by percentage) of the catch in weight (kg) for taxonomic groups in Costa Rica and Chile (2004-2009).

Year	Shrimp	Fishes	Crustaceans	Mollusks	Others	Total catch (kg)
Costa Rica						
2004	12.1	14.0	73.8	0.0	0.0	9919
2005	17.4	27.0	55.4	0.1	0.1	7640
2006	12.7	35.2	51.9	0.1	0.0	2132
2007	2.7	12.6	84.6	0.1	0.0	12 233
2008	3.7	36.2	59.1	0.6	0.4	6629
2009	4.2	44.4	51.1	0.2	0.1	8148
Total (%)	9.2	28.4	62.1	0.2	0.1	
Chile						
2004	49.9	38.1	10.2	1.7	0.1	64 898
2005	53.3	35.2	10.7	0.5	0.3	120 271
2006	64.1	16.2	19.3	0.5	0.0	65 701
2007						0
2008	42.9	10.6	45.8	0.7	0.0	163 360
2009	69.1	16.1	14.8	0.1	0.0	150 867
Total (%)	55.4	21.1	22.9	0.6	0.1	

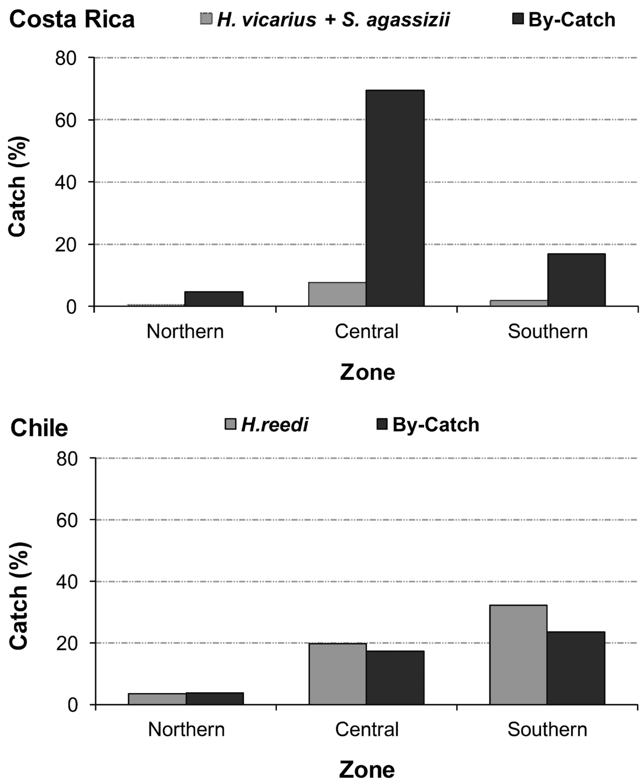

Fig. 6. Average deep-water shrimp catches and by-catch (expressed as percent of total catches), by zone (2004-2009).

flounder (*Hippoglossina macrops* Steindachner, 1876) with 9.1%, 3.5% and 3.2%, respectively.

Analysis of CPUE of Target Species and By-catch

In Costa Rica, the central zone accounted for more than 60% of all the by-catch obtained during the study period in all three zones (Fig. 6). Considering the low number of hauls carried out in the northern Pacific zone of Costa Rica, only the central and southern zones were compared statistically: we did not detect significant differences regarding the CPUEs of neither the two target species (ANOVA; $F = 0.159$; $p = 0.690$) nor the by-catch (ANOVA; $F = 0.317$; $p = 0.574$). In Chile, the highest percentage of total catches of *H. reedi* was recorded for the southern zone (Fig. 6); however, the highest average CPUE (682.5 kg/h) was obtained in the southern zone of Costa Rica (Tables 3 and 4). The statistical analysis revealed that the CPUEs of both the target species *H. reedi* (ANOVA; $F = 40.64$; $p = 0.000$) and the by-catch (KW; $\chi^2 = 39.76$; $p = 0.000$) increased significantly from north to south. Moreover, and in contrast to the situation in Costa Rica, landings of the target species (*H. reedi*) were always higher than that of the by-catch.

The catch analyses of the two target species in Costa Rica per depth range revealed that the extracted average volumes between 100-250 and 251-400 m were similar; no hauls were carried out deeper than 400 m (Fig. 7). By-catch was more abundant in the depth range of 100-250 m. In Chile, highest values for *H. reedi* and by-catch were recorded between 251-400 m, followed by the depth range of 100-250 m (Fig. 7). In Costa Rica CPUEs values of the target species were higher

Table 3. Deep-water shrimp CPUE (kg/h) values per zone, depth and country, n = number of hauls (2004-2009).

Deep-water shrimp	Costa Rica			Chile		
	n	Media (kg/h)	Standard deviation	n	Media (kg/h)	Standard deviation
Zone						
Northern	6	19.6	16.9	256	327.6	304.0
Central	169	53.4	87.8	722	505.7	442.0
Southern	26	77.2	132.1	422	682.5	635.8
Depth (m)						
100-250	112	40.1	71.1	251	648.1	662.9
251-400	89	74.8	113.4	985	541.0	473.8
401-650	–	–	–	164	252.9	227.3

in 251-400 m (74.8 kg/h), whereas CPUEs values for by-catch were higher in 100-250 m (604.5 kg/h) (Tables 3 and 4). However, no statistically significant differences of the CPUEs among the depth ranges were recorded neither for the target species (KW; $\chi^2 = 1.649$; $p = 0.199$) nor for the by-catch (ANOVA; $F = 2.923$; $p = 0.089$).

In Chile, CPUEs of both the target species and the by-catch decreased with depth, with the highest catch rates in the depth range of 100-250 m. CPUEs of both the target species (KW; $\chi^2 = 102.93$; $p = 0.000$) and its by-catch (ANOVA; $F = 27.11$; $p = 0.000$) were significantly different between depth ranges. Further statistical analysis provided evidence that there were no significant differences of the CPUEs comparing the ranges of 100-250 m and 251-400 m neither for *H. reedi* (Games-Howell; $p = 0.381$) nor for the by-catch (Tukey; $p = 0.331$). However, CPUEs of the target species (Games-Howell; $p = 0.000$) and the by-catch (Tukey; $p = 0.000$) were statistically different at depth > 400.

Overall average CPUEs for the target species was 55.4 and 526.4 kg/h in Costa Rica and Chile, respectively; the values for both countries were statistically significant different (KW; $\chi^2 = 448.73$; $p = 0.000$). In the case of the by-catch (Fig. 8), the mean CPUE for Costa Rica (598.0 kg/h) was significantly higher (KW; $\chi^2 = 47.37$; $p = 0.000$) than the same value for Chile (340.8 kg/h).

Table 4. By-catch CPUE (kg/h) values per zone, depth and country, n = number of hauls (2004-2009).

By-catch	Costa Rica			Chile		
	n	Media (kg/h)	Standard deviation	n	Media (kg/h)	Standard deviation
Zone						
Northern	6	956.6	726.4	256	288.6	477.3
Central	169	543.4	694.9	722	321.1	482.0
Southern	26	870.0	1830.4	422	406.2	449.4
Depth (m)						
100-250	112	604.5	793.0	251	474.9	624.3
251-400	89	589.9	1070.8	985	335.7	449.3
401-650	–	–	–	164	166.0	217.8

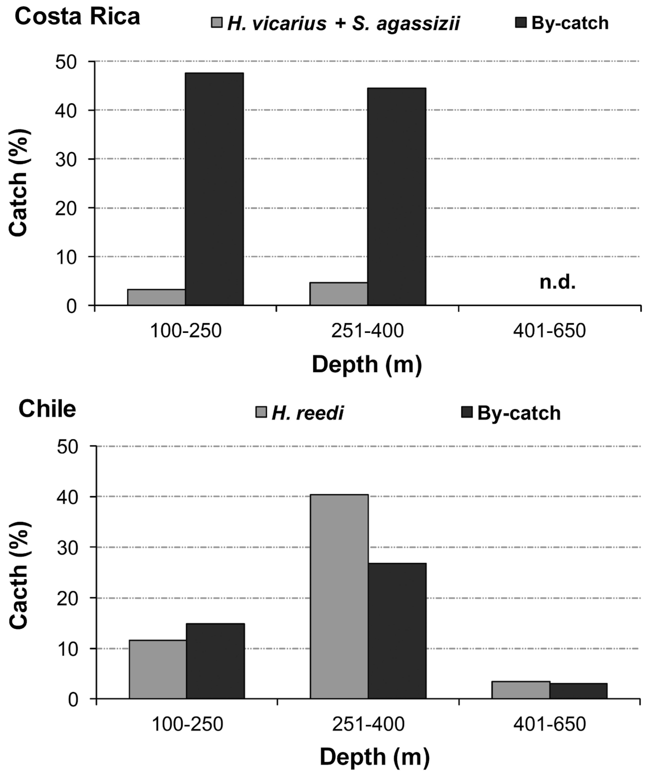

Fig. 7. Average deep-water shrimp catches and by-catch (expressed as percent of total catches), by depth range (2004-2009). n.d. = no data available.

Catch Index (CI)

The catch index (CI) revealed that the quantity of by-catch in weight obtained for each kg of shrimp was noticeably greater in Costa Rica than in Chile (Fig. 9). A comparison of catches of the target species with those of the by-catch revealed in both countries a close relationship between high by-catch levels and low catches of the target species; this situation changed when the retention of the desired species incremented (Fig. 10, Table 5).

In Costa Rica, considering for example catches greater than 10 kg of the target species (*H. vicarius* and *S. agassizii*), for each kg of shrimp an average of 5.7 kg of by-catch organisms were caught (CI = 1:5.7). In Chile, when considering hauls with catches of *H. reedi* greater than 20 kg, for

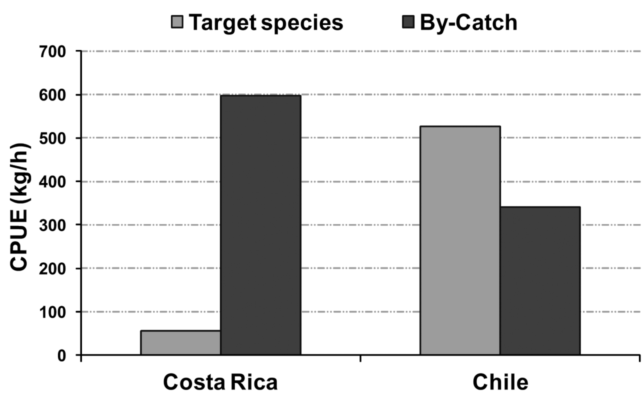

Fig. 8. CPUE values for deep-water shrimp catches and by-catch per country (Costa Rica, Chile: 2004-2009).

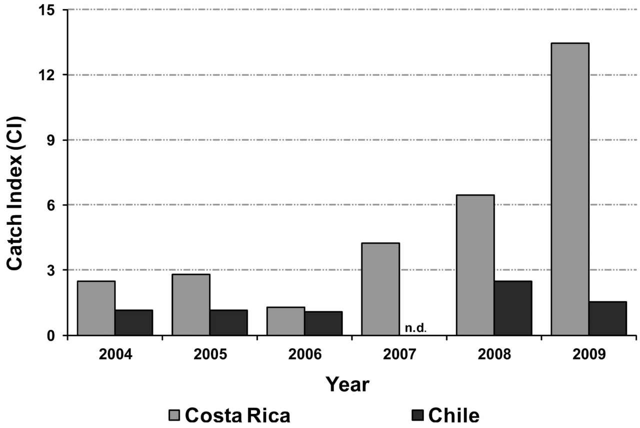

Fig. 9. Average annual catch index determined for the *Heterocarpus vicarius* and *Solenocera agassizii* (Costa Rica) and *H. reedi* (Chile) fisheries (2004-2009).

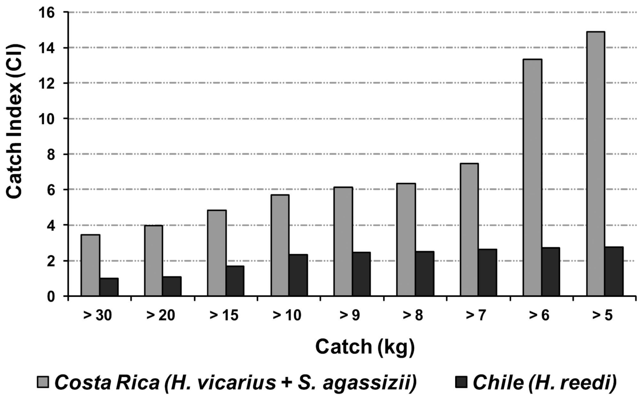

Fig. 10. Average estimated catch indexes for different minimum catch amounts of deep-water shrimps in Costa Rica (*Heterocarpus vicarius* and *Solenocera agassizii*) and Chile (*Heterocarpus reedi*) during the study period 2004-2009. Numbers over bars indicate CI values.

Table 5. Catch indexes obtained for the *Heterocarpus vicarius* and *Solenocera agassizii* fisheries of Costa Rica and the *H. reedi* fishery of Chile (2004-2009). n = number of hauls.

Year	Catch index according to different levels (kg) of captured shrimps								
	>30	>20	>15	>10	>9	>8	>7	>6	>5
Costa Rica									
2004	1.9	2.8	2.7	3.7	5.0	5.9	5.8	15.2	17.0
2005	2.6	2.4	3.3	4.8	4.8	4.8	5.0	7.8	7.9
2006	1.0	1.4	1.6	3.0	3.0	3.3	3.3	5.9	5.9
2007	4.2	4.5	4.0	3.8	5.2	5.2	5.2	27.0	27.0
2008	7.7	5.9	5.7	6.1	6.1	6.3	9.6	9.6	11.4
2009	12.3	12.6	15.4	15.1	15.1	15.1	17.7	18.0	22.3
n	35	47	70	91	95	100	107	114	123
Chile									
2004	1.1	1.1	1.3	1.8	1.9	2.1	2.1	2.3	2.3
2005	1.0	1.1	1.3	1.7	1.9	2.1	2.1	2.2	2.2
2006	0.9	1.1	1.2	1.4	1.4	1.3	1.5	1.5	1.5
2007	–	–	–	–	–	–	–	–	–
2008	1.0	1.0	2.7	3.8	4.0	4.0	4.4	4.4	4.3
2009	1.0	1.1	1.6	2.6	2.7	2.7	2.7	2.7	3.0
n	1344	1402	1473	1531	1544	1567	1576	1582	1589

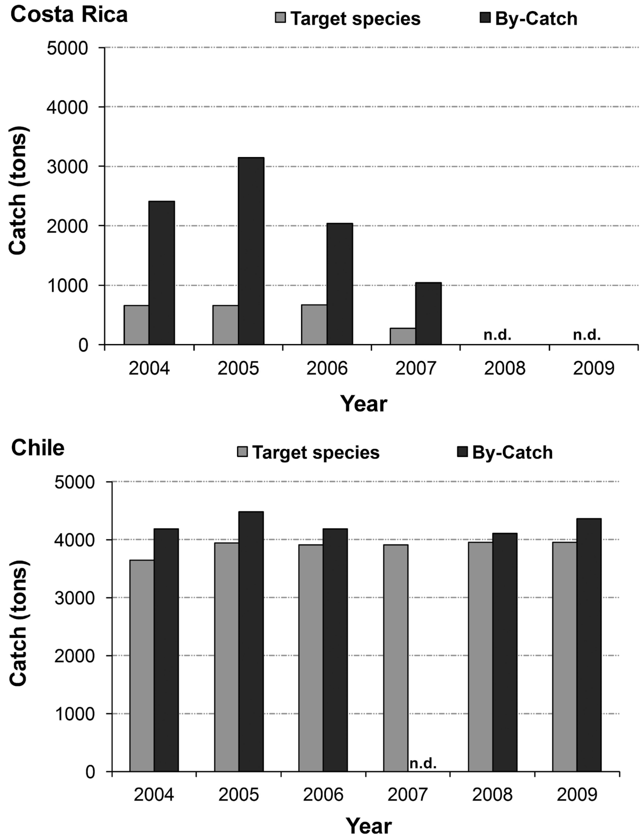

Fig. 11. Estimated global annual by-catch for the *Heterocarpus vicarius* and *Solenocera agassizii* (Costa Rica) and *Heterocarpus reedi* (Chile) fisheries (2004-2009). n.d. = no data.

each kg of shrimp, 1.1 kg of by-catch was recorded (CI = 1:1.1). In Costa Rica, the CI incremented notoriously as of 2008, reaching a ratio of 1:15.1 in 2009 (Table 5).

According to the average catch indexes (CI) of each country and the annual landings recorded for Costa Rica (2004-2007) and Chile (2004-2009), the annual reported by-catches for the *H. vicarius* and *S. agassizii* fisheries were 1041 to 3147 ton and for the *H. reedi* fishery were 4103 to 4476 ton (Fig. 11). The amount of by-catch extracted annually in Chile showed a certain degree of stability (4058 to 4476 ton) and was associated with similar landings (3644 to 3956 ton) between years. In Costa Rica, however, the by-catch value peaked in 2005, followed by a sustained drop in the total amounts that was directly associated with the decline of the *H. vicarius* fishery following that year.

Discussion

The proportion of by-catch in Costa Rica for each of the years analyzed was notoriously greater than the target resource catches, with values of up to 96.8% (mean 90.8%) of the total catch (Fig. 4). Likewise, Sarmiento-Náfate et al. (2007) found that the by-catch of the shrimp fisheries in Mexico can reach up to 96.7% of the total catch. On the contrary, for the Chilean trawl fishery of *H. reedi*, Melo et al. (2006) estimated that the catches consisted mainly of the resource target, with only 35% being by-catch; a similar value was found in the present research. In general, and according to various direct assessments carried out for *H.*

reedi (Arana et al., 2004, 2006; Acuña et al., 2007, 2009, 2010), it seems safe to assume that in Chile, the by-catch associated with the *H. reedi*-fishery is generally less than 50% of the total catch measured in weight. The observed differences of by-catch rates between the Costa Rican and Chilean deep-water shrimp fisheries are in agreement with the conclusion of Gillett (2008) that in terms of the quantity of by-catch extracted, problems are less severe in the cold-water trawl fisheries as opposed to those in tropical waters.

The by-catch in the Costa Rican deep-water shrimp fishery was highly diverse when compared to that of the *H. reedi*-fishery in Chile. This pattern is not surprising, considering that Costa Rica is known for its high biodiversity, including the marine realm (Wehrtmann and Cortés, 2009). The catches in both countries contained relatively similar percentages in terms of the number of species per taxonomic groups (Fig. 5). However, we observed substantial weight differences between these groups: crustaceans predominated (62.1%) in the *H. vicarius* fishery, whereas similar percentages of fishes (21.1%) and crustaceans (22.9%) were found in the *H. reedi*-fishery (Table 2). On the other hand, at species level, the composition of fauna was different in these two regions. In Costa Rica, the crustacean by-catch was mainly made up of *Squilla biformis*, *Plesionika trispinus* Squirres and Barragan, 1976, and *Pleuroncodes monodon* (Wehrtmann and Echeverría-Sáenz, 2007). In Chile, however, the by-catch of the nylon shrimp fishery was made up of several fish species, being the South Pacific hake (*Merluccius gayi*) the most important one (Melo et al., 2003; Acuña et al., 2005; Orellana, 2006; Queirolo et al., 2011b).

The composition of the by-catch observed in the *H. vicarius*-fishery coincided with that reported by Puentes et al. (2007) for the fisheries for *Solenocera agassizii* and *Farfantepenaeus* spp. carried out in the Colombian Pacific, where the by-catch was dominated mainly by 54 fish and 11 crustacean species. It should also be noted that, in Colombia, mollusks, and other benthic taxonomic groups were poorly represented. However, this might be a result of the relatively short study period (one year), and it might be speculated that not all by-catch species were separated and identified, because Puentes et al. (2007) mentioned as mollusk just one squid species, not even one bivalve or gastropod species.

According to Hall et al. (2000), tropical shrimp fisheries present average CI values from 1:3 to 1:15. Other studies (Harris and Poiner, 1990; Andrew and Pepperell, 1992; Alverson et al., 1994; Ambrose et al., 2005) have reported this index to be 1:5 in temperate zones and 1:10 in tropical zones, depending on the availability and reliability of the data generated in each of the fisheries analyzed. The CI estimated for Costa Rica fell within the ranges indicated by the aforementioned authors, averaging 5.7 kg of by-catch for each kg of shrimp caught (1:5.7). The CI in Chile, considering catches of *H. reedi* in hauls with over 20 kg of the target species, however, was 1:1.1, which was lower than indicated by earlier estimates for temperate waters (Harris and Poiner, 1990; Kelleher, 2005).

In Costa Rica, practically all of the by-catch obtained in the deep-water shrimp fishery is discarded, even those species that have commercial value in other Central American countries (Wehrtmann and Nielsen-Muñoz, 2009). Sarmiento-Náfate et al. (2007) found a similar situation for the Gulf of Tehuantepec, Mexico, where only 10% of the by-catch was used for commercial purposes. According to Kelleher (2005), one of the main problems associated with discards is the use of small vessels with limited space for storing the catches. Other problematic factors include the difficulty of conservation and low prices at local markets.

In contrast, an important fraction of the by-catch from the *H. reedi*-fishery is not discarded, as it contains species of commercial interest. Thus, landings of South Pacific hake and squat lobsters are authorized in quantities that do not exceed (for each of these) 10% of the total catch in weight of the target resource (Ley General de Pesca y Acuicultura, Chile, 1992). Catches of these species were considered to be by-catch in the present research. If the portion of by-catch that is of commercial interest is taken in account, the by-catch ratio or CI will decrease at least by 9.1%, from 1:1.1 to 1:1.0.

On the other hand, it should be taken in consideration that the by-catch in both countries was quantified by using data from fishery hauls with and also without the presence of the resource target obtained in direct assessment projects. This generated an overestimation of the by-catch values obtained for each kg of shrimp caught and, therefore, an erroneous perception of the real levels of by-catch extracted. Hence, it is likely that the values indicated by Oceana (2005) for Chile (81.2%) were overestimates, as they considered the entirety of the hauls carried out during assessment projects of crustaceans, and did not represent the actual catches of the commercial fleet.

The results of the present research revealed differences in the quantity of by-catch according to the fishery zone, the depth at which the extractive operations were carried out (Table 4), and catch concentrations of the target species (Fig. 9, Table 5). These findings suggest that the density of the by-catch could be relatively constant over the trawled bottoms, whereas the shrimps are concentrated in certain zones and depths, which results in different indexes found in relation to the variation in the catches of the target species. This situation shows that the data used to calculate the by-catch must be considered carefully since the use of different minima of catch per haul of the target species can distort this index noticeably.

We assume that the captains dedicated to crustacean fisheries know the zones and depths in which the foci of abundance of the target resource are found, leading to high catches and relatively few by-catch in these areas. Nevertheless, it is also likely that the proportion of the by-catch increases each time that the captain perform fishery hauls beyond the normal aggregation sites of the target resource or when occasionally prospecting on bottoms in search of new fishing spots.

The projected global by-catch was considerably higher for the *H. reedi*-fishery than for the *H. vicarius*-fishery (Fig. 11). This apparent contradiction was related to the landed volume of each of these species: although in Costa Rica the percentages of by-catch were higher than those recorded in Chile, the landings between 2004 and 2006 did not exceed 672 ton, with yearly by-catch figures ranging between 2039 ton and 3147 ton. Furthermore, in 2007, the by-catch dropped (1041 ton) along with the reduction of the target catch (278 ton). In turn, in Chile, the landings of the industrial sector remained stable, fluctuating between 3644 and 3956 ton (2004-2009) and the projected by-catch was between 4187 and 4354 tons per year.

Several authors have tried to determine the total by-catch at a global level. The estimates exceeded 38.5 million tons, or 40.4% of the global landings of marine resources (Davies et al., 2009), which represents hypothetical economic losses near one billion dollars annually (Cook, 2001; FAO, 2003). Thus, it is urgently important to adopt measures to reduce the by-catch and discard rates (Harrington et al., 2005; Zhou, 2008). The elimination of resources of low economic value and/or that do not comply with the fishery regulations (*e.g.* below the minimum size) constitutes mortalities that are not taken into consideration in the fishery statistics, leading to biased estimations of the biomass of exploited resources. At the same time, this situation impedes determining the mortality levels to which the non-target species of the fishery are subjected (Alverson et al., 1994; Kennelly, 1995; Alverson and Hughes, 1996; Hall et al., 2000; Zhou, 2008).

The present study shows high volumes of by-catch resulting from the fisheries for *H. vicarius* and *H. reedi*. This by-catch should be reduced in order to conserve the extracted resources and protect the marine environment. Several mitigation measures have been suggested for the shrimp trawl fishery, but these only achieve partial results since they do not restrict the use of trawl nets as part of the extractive activities. The most recent research on the by-catch was aimed at determining how to reduce the catch of these organisms, carrying out technological modifications of the nets in order to increase selectivity (Broadhurst, 2000; ECM, 2000; Queirolo et al., 2011a) and incorporating the use of escape devices to diminish the retention of undesired species (Kennelly, 2007). Other indirect actions should aim at using the presently discarded and unused species and assigning economic incentives to businesses and fishermen in order to involve them in the development of ideas and projects intended to decrease the by-catch in their extractive operations (Cerda et al., 2009). Unlike the Costa Rican case, in Chile management measures include prohibitions on landings of by-catch species of other commercial species and on returning discarded specimens to the sea. Although these measures have contributed partially to the desired objective, the fishermen do not always comply with them, despite being subjected to substantial fines. Therefore, greater attention has been paid to the search for technological solutions. In the case of the nylon shrimp fishery, the use of square meshes of 56 mm and the use of grids (by-catch reduction devices) to separate the by-catch from the target catch have reduced the by-catch by around 40%, with a loss of the target catch of around 10% (Queirolo et al., 2011a). Considering that shrimp trawl fisheries, and tropical shrimp fisheries in particular, are the single greatest source of discards (Kelleher, 2005), we strongly support additional studies aimed to reduce the by-catch and discard rates in tropical shrimp fisheries. The encouraging results in the *H. reedi*-fishery (Queirolo et al., 2011a) should be used to introduce these technical measures also in Central American deep-water shrimp fisheries.

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