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Ophiuroidea (Echinodermata) from the Central Mexican Pacific: an updated checklist including new distribution records

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Abstract The Central Mexican Pacific is an oceanographic transitional region with complex habitats and important conservation areas, but knowledge of its Ophiuroidea fauna is limited. A total of 61 localities on a variety of substrata were sampled between 2008 and 2014 using different methodology techniques. Twenty-four species were collected and members of the families Ophiocomidae, Ophiotrichidae and Ophiactidae were the most widespread. The new records of 28 species have relevance in terms of filling distribution gaps along the Mexican Pacific or extending their geographical distribution ranges. This considerable number can be attributed to a higher number of prospected localities and the diversification of collecting methods. An updated checklist from the study area is provided, including previous literature records and those found during this work, summarising 57 species. Islas Marías was the area with the highest number of species and with the highest value of taxonomic distinctness, which can be explained since these islands are considered as stepping stones for the dispersal of species in the Mexican Pacific. Despite the important diversity and composition of ophiuroids in our study area, a sample-based rarefaction curve suggests that at least 104 species can inhabit the area, so we recommend conducting more research in the region.

Keywords Brittle stars · Checklist · New distribution records · Substrata · Taxonomic distinctness

Introduction

The Ophiuroidea is the largest group among the Echinodermata, with 2064 described species worldwide (Stöhr et al. 2012). The Mexican Pacific possesses 125 species of ophiuroids, where the less diverse and explored are the areas of Jalisco (21), Nayarit (20), Michoacán (nine), Colima (eight) and Isla Isabel (nine), all of them located at the Central Mexican Pacific (CMP) (Granja-Fernández et al. 2015a). This region has a high marine biodiversity potential, as it is

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considered an oceanographic transitional area that combines fauna from the North and the South regions of the Mexican Pacific. Moreover, the CMP is complex due to the presence of extensive bays, coastal lagoons, estuaries, mangroves and coral reefs (Arriaga-Cabrera et al. 1998); furthermore, the CMP is important in conservation terms because it includes National Parks, Biosphere Reserves, Sanctuaries and Marine Priority Regions (Arriaga-Cabrera et al. 1998; Comisión Nacional de Areas Naturales Protegidas, CONANP 2005, 2007a, b).

The study of the ophiuroids in the CMP region began when Lütken and Mortensen (1899) recorded for the first time, from Islas Marías and at depths up to 1230 m, the species *Amphiura serpentina*, *Astrodia excavata*, *Dougaloplus notacanthus*, *Ophiacantha costata*, *Ophiacantha hirta*, *Ophiacantha moniliformis*, *Ophiernus adspersus annectens*, *Ophiomitra granifera*, *Ophiomitra partita*, *Ophiura* (*Ophiura*) *scutellata* and *Ophiomusium variabile*. Later, Clark (1940) contributed with the study of the ophiuroids of the region, adding the first records for Jalisco (*Diopederma daniana*, *Ophioderma variegata*, *Ophiolepis variegata*) and Colima (*Ophiolepis variegata*, *Ophiothrix* (*Ophiothrix*) *spiculata*), all of them distributed in shallow waters. In the same year, Ziesenhenne (1940) described the new species *Amphichondrius laevis*, *Amphiodia sculptilis*, *Ophiolepis plateia* and *Ophiophragmus lonchophorus*, with their type locality in Tenacatita Bay, Jalisco. Caso (1951) recorded for the first time at the CMP (Puerto Vallarta, Jalisco) the presence of *Ophiactis savignyi*, *Ophiocoma aethiops*, *Ophiocoma alexandri*, *Ophiolepis pacifica*, *Ophioderma teres* and *Ophionereis annulata*. Nowadays, the contributions on ophiuroids have been mostly focused on ecology and checklists from specific geographical areas. In this regard, Fuentes-Farías et al. (2005) provided the first records of ophiuroids (*D. daniana*, *O. aethiops*, *O. alexandri*, *O. annulata*, *O. savignyi*, *Ophiactis simplex*, *Ophiothela mirabilis*, *O.* (*O.*) *spiculata* and *Ophiothrix* (*Ophiothrix*) *rudis*) from Michoacán, all of them being the only species recorded to date for that state. Other important additions to the knowledge of ophiuroids in terms of taxonomy and new distribution records in the CMP were those by Luke (1982), Caso (1986) and Granja-Fernández et al. (2014, 2015a).

It is important to note that most of the studies on ophiuroids in the CMP had been mostly conducted in specific areas with a status of protection (Nayarit and Jalisco), such as Isla Isabel National Park, Islas Marías Biosphere Reserve (CONANP 2005, 2007a, b; Ríos-Jara et al. 2008a, b; Granja-Fernández et al. 2014, 2015a), Tenacatita Bay and Chamela Bay, which is considered as the first marine sanctuary in the Mexican System of Natural Protected Areas (Ziesenhenne 1940; López-Uriarte et al. 2009; Ríos-Jara et al. 2013; Granja-Fernández et al. 2014). Despite the above, there are areas such as Colima, Michoacán, the coast of Nayarit and Islas Marietas National Park that have been remained almost unstudied. It is important to highlight that most of the recent works that mention the presence of ophiuroids in the CMP are not exclusive of this taxon, since they provide general checklists of echinoderms and/or marine invertebrates, and their sampling effort is not conducted to collect especially ophiuroids (López-Uriarte et al. 2009; Ríos-Jara et al. 2008a, b, 2013). Due to the scarce numbers of studies focused specifically on ophiuroids, to the sampling effort conducted in just specific areas and because the CMP has biotic and abiotic mixed conditions with important protected areas, the goal of this work is to fill the gap of the knowledge of the Ophiuroidea in the CMP, providing an updated checklist, as well as important biological-ecological and geographical features of the species.

Materials and methods

Study area

The surveyed area comprises the continental shelf off the coast of Nayarit, Jalisco, Colima and Michoacán and their islands (Islas Marías, Isla Isabel, Islas Marietas), in the central portion of the Mexican Pacific (between 17°N and 22°N). The area is considered a conservation hotspot as it includes National Parks (Isla Isabel and Islas Marietas), Biosphere Reserves (Islas Marías), Sanctuaries (islands from Chamela Bay) and Marine Priority Regions (Bahía de Banderas, Mismaloya-Punta Soledad, Chamela-El Palmito, Punta Graham-El Carrizal, Cuyutlán-Chupadero, Maruata-Colola) (Arriaga-Cabrera et al. 1998; CONANP 2005, 2007a, b).

The water masses of the CMP are exposed to the transisthmic wind jets on the southwestern coast of México, where a pool of warm water is generated (Kessler 2006). The water circulation in the CMP has an annual variability characterised by the convergence of three current systems: (1) the cold California Current flowing to the Southeast, (2) the warm Coastal Costa Rica Current flowing northward and the warm water from the Gulf of California (Badán 1997), and (3) a semi-annual variability determined by average northwesterly flow during summer and a northeasterly flow during winter (De la Lanza 1991). The area has a narrow continental shelf with a width of only 7–10 km; the bottom of the continental shelf is irregular and increases abruptly towards the Middle American Trench that extends along the continent. The maxim depth in the CMP is up to 3500 m. The CMP is influenced by cyclones, tropical storms and ENSO (El Niño-Southern Oscillation) events, which produce abnormal increases and decreases in the mean temperature along the region (Filonov et al. 2000).

Sampling

A total of 61 localities from the states of Nayarit (12 on the coast of the state, five in Islas Marietas, three in Islas Marías, two in Isla Isabel), Jalisco (24), Colima (10) and Michoacán (five) were sampled between 2008 and 2014 (Table 1, Fig. 1). This work takes its results from a larger multi-disciplinary and inter-institutional programme assessing Ophiuroidea along the Mexican Pacific. The collecting methods were different, but all of them were next to coral and/or rocky reefs environments.

Ophiuroids are usually associated with other organisms; therefore, to avoid damaging healthy coral branches when collecting specimens, we used only dead natural fragmented branches of the coral *Pocillopora* spp. (~5 cm long) as recruitment substrata. Clean fragments were attached with plastic cables to two semi-spherical concrete structures with six steel rods, each placed on a sandy bottom at 5 m depth, next to the healthy *Pocillopora* coral colonies. After two months, the fragments were collected and packed into plastic bags, and all the collected organisms were separated and taxonomically identified. This sampling was conducted only in Islas Marietas.

During 2009–2014, in the South of Jalisco (7–27 m depth), organisms associated with sand and rock were collected using the following sampling method. Each month, with the help of a suction pump, 15 cm of sand and surface of rocks were pumped in an area of 50 × 50 cm (three replicates per station). The pump consisted of a PVC tube (180 cm long and 7.5 cm diameter) attached to a stainless steel diffusor (30 cm long) and connected to an air compressor. In the extreme of the tube, a bag with a mesh size of 0.5 mm was attached. The samples were sieved on the field with a mesh of 0.5 mm and packed into plastic bags for further identification. In 2014, in Nuevo Vallarta, Nayarit, samples on sand were obtained with the help of a Van Veen dredger of 2500 cm^3 (3–15 m depth).

Finally, collections were carried out in a variety of available substrata (algae, gorgonians, hydrozoan, live and dead stony corals, rhodoliths, rock, sand and sponges) in all sampling sites and at different depths (0 to 11 m). The sampling was carried out by hand collection with scuba diving. All the collected ophiuroids were anaesthetised using magnesium chloride buffered on seawater in order to prevent autotomy; afterwards, all the specimens were fixed and preserved in 70 % ethanol. The specimens were identified after Lütken (1856), Verrill (1867), Nielsen (1932), Ziesenhenne (1937, 1940), Clark (1939), Hendler et al. (1995), Hendler (2011) and Granja-Fernández et al. (2014). The specimens were deposited in the Colección de Equinodermos de la Universidad Autónoma Metropolitana-Iztapalapa, Colección de Invertebrados del Instituto Tecnológico de Bahía de Banderas, Colección de Invertebrados del Laboratorio de Ecología Marina del Departamento de Estudios para el Desarrollo Sustentable de Zonas Costeras, Universidad de Guadalajara, and in the Colección Nacional de Equinodermos "Dra. María Elena Caso Muñoz", Instituto de Ciencias del Mar y Limnología, Universidad Nacional Autónoma de México.

Analysis data

With all the collected specimens, a matrix of presence/absence per locality and a database with information specifying locality, substrata, depth and qualitative abundance of the species were elaborated. Due to the different collecting methods used during this study, a qualitative estimate of the abundance consisted merely of ranking the taxa within samples into a series of abundance classes, which, in this case, were employed as: very abundant (>1500 organisms), abundant (700–401 organisms), common (400–100 organisms) and rare (<50 organisms). An updated checklist including the collected species during this work was elaborated and completed with literature records (Lütken and Mortensen 1899; Clark 1940, 1970; Ziesenhenne 1940; Caso 1951, 1986; Luke 1982; CONANP 2005, 2007a, b; Fuentes-Farías et al. 2005; Maluf and Brusca 2005; Honey-Escandón et al. 2008; Ríos-Jara et al. 2008a, b, 2013; López-Uriarte et al. 2009; Hendler 2011; Granja-Fernández et al. 2013, 2014, 2015a) in order to provide a complete checklist of the ophiuroids inhabiting the CMP. The valid names and the systematics are according to Granja-Fernández et al. (2015a).

In order to determine if the observed species richness of ophiuroids from the CMP is complete, a sample-based rarefaction curve was performed using the non-parametric species richness estimator Chao2. For statistical purposes, the localities were considered as replicates inside each area (coast of Nayarit, Colima, Jalisco, Michoacán, Islas Marías, Isla Isabel, Islas Marietas). The expected number of the species as well as its confidence interval (95 %) was determined with a randomised order of samples with replacement for 1000 runs (Colwell et al. 2004). The analysis was performed with the software EstimateS 9.1.

The average taxonomic distinctness (Δ^+) and its variation (Λ^+) were estimated in order to have a better understanding of the Ophiuroidea diversity along the CMP. This index evaluates the taxonomic distance between each pair of individuals, defined by a Linnean classification tree (species, genus, family, orders, class) and can be used with a presence/absence matrix without taking into consideration the sampling methodology (Clarke and Warwick 2001). The analysis was performed with the PRIMER-E 7 software.

Table 1 Geographic coordinates of prospected areas along the Central Mexican Pacific

No.	Area	Locality	Coordinates: latitude north - longitude west
1	ISA	Las Monas	21°51′06.00″ - 105°52′47.00″
2	ISA	Bahía Rabijuncos	21°50′35.49″ - 105°52′50.94″
3	ISA	Las Pozas	21°50′29.00″ - 105°53′03.00″
4	MAR	Caleta, María Cleofas	21°19′12.70″ - 106°13′21.90″
5	MAR	Cleofas, María Cleofas	21°18′10.00″ - 106°13′30.00″
6	MAR	Carrizal, María Cleofas	21°17′32.70″ - 106°13′52.60″
7	NAY	Careyeros	20°46′10.00″ - 105°30′48.00″
8	NAY	El Anclote	20°46′15.19″ - 105°31′03.02″
9	NAY	Punta de Mita	20°46′02.60″ - 105°31′25.90″
10	NAY	La Lancha	20°45′34.70″ - 105°29′19.20″
11	NAY	El Tizate	20°45′31.30″ - 105°21′56.90″
12	NAY	Playa Paladium	20°45′05.46″ - 105°27′17.22″
13	NAY	Punta Pelícanos	20°45′02.32″ - 105°22′23.94″
14	NAY	Playa del CRIP	20°44′42.30″ - 105°22′58.96″
15	NAY	La Manzanilla	20°44′34.52″ - 105°23′13.75″
16	NAY	Bajo de las Viudas	20°43′59.90″ - 105°23′58.70″
17	MAT	Playa del Amor, Isla Redonda	20°42′14.10″ - 105°33′50.10″
18	MAT	Plataforma Pavonas, Isla Redonda	20°42′05.20″ - 105°33′54.00″
19	MAT	Túnel Amarradero, Isla Redonda	20°41′58.10″ - 105°33′57.10″
20	MAT	Área de Restauración, Isla Larga	20°41′55.38″ - 105°34′51.77″
21	MAT	Cueva del Muerto, Isla Larga	20°41′50.60″ - 105°34′58.10″
22	NAY	Nuevo Vallarta	20°41′24.31″ - 105°17′51.12″
23	JAL	Muelle de los Muertos	20°36′02.22″ - 105°14′21.45″
24	JAL	Los Arcos	20°32′44.83″ - 105°17′34.79″
25	JAL	Colomitos	20°30′44.07″ - 105°19′33.81″
26	JAL	Punta Caletas	20°30′23.46″ - 105°23′34.79″
27	JAL	Pelícanos	19°33′27.00″ - 105°06′28.00″
28	JAL	Isla Pajarera	19°33′23.87″ - 105°06′42.84″
29	JAL	La Palma	19°33′02.00″ - 105°06′23.00″
30	JAL	Isla Cocinas	19°32′46.00″ - 105°06′28.00″
31	JAL	Tenacatita poza de marea	19°16′53.58″ - 104°52′21.66″
32	JAL	Tenacatita zona arrecifal	19°16′49.62″ - 104°52′21.24″
33	JAL	Tenacatita intermareal	19°16′45.99″ - 104°52′21.83″
34	JAL	La Calechosa	19°14′18.29″ - 104°44′18.01″
35	JAL	La Virgencita	19°14′09.00″ - 104°44′57.00″
36	JAL	Centro de Caleta de Cuastecomates, zona somera	19°14′05.21″ - 104°44′06.59″
37	JAL	Laboratorio	19°13′52.50″ - 104°45′21.34″
38	JAL	Centro de Caleta de Cuastecomates, zona profunda	19°13′46.90″ - 104°44′27.28″
39	JAL	Zona de arena cercano a la zona de arrecife	19°13′46.54″ - 104°44′07.80″
40	JAL	Cuastecomate	19°13′45.33″ - 104°43′59.18″
41	JAL	Zona de arrecife cercano a la zona de playa	19°13′44.06″ - 104°44′07.23″
42	JAL	Cuastecomatito	19°13′12.90″ - 104°43′28.02″
43	JAL	Frente al Hotel Náutico-El Dorado	19°13′09.75″ - 104°42′25.73″
44	JAL	Frente a la Laguna del Tule	19°13′01.89″ - 104°41′55.81″
45	JAL	Las Monjas	19°12′54.54″ - 104°42′55.68″
46	JAL	Morro Chino, Laguna de Barra de Navidad	19°11′41.91″ - 104°41′35.68″
47	COL	La Audiencia 2	19°06′17.99″ - 104°21′06.63″
48	COL	La Boquita, zona somera	19°06′17.56″ - 104°23′53.58″
49	COL	La Boquita, poza de marea	19°06′12.57″ - 104°23′48.87″

Table 1 (continued)

No.	Area	Locality	Coordinates: latitude north - longitude west
50	COL	La Boquita	19°06′10.08″ - 104°23′37.92″
51	COL	La Audiencia 1	19°06′09.87″ - 104°21′01.15″
52	COL	Playa Veleros	19°06′02.58″ - 104°21′03.76″
53	COL	L′Recif	19°06′01.00″ - 104°24′24.00″
54	COL	Punto B	19°05′55.00″ - 104°23′24.00″
55	COL	Carrizales 2	19°05′48.30″ - 104°26′07.24″
56	COL	Carrizales 1	19°05′47.05″ - 104°26′20.10″
57	MICH	Morro de Enmedio	18°21′11.00″ - 103°31′02.00″
58	MICH	Isla Pájaros	18°21′09.00″ - 103°31′09.00″
59	MICH	Faro de Bucerías	18°21′08.00″ - 103°30′58.00″
60	MICH	Morro Chino	18°11′56.00″ - 103°08′10.00″
61	MICH	Caleta de Campos	18°04′11.00″ - 102°44′37.00″

ISA Isla Isabel; *MAR* Islas Marías; *NAY* coast of Nayarit; *MAT* Islas Marietas; *JAL* Jalisco; *COL* Colima; *MICH* Michoacán

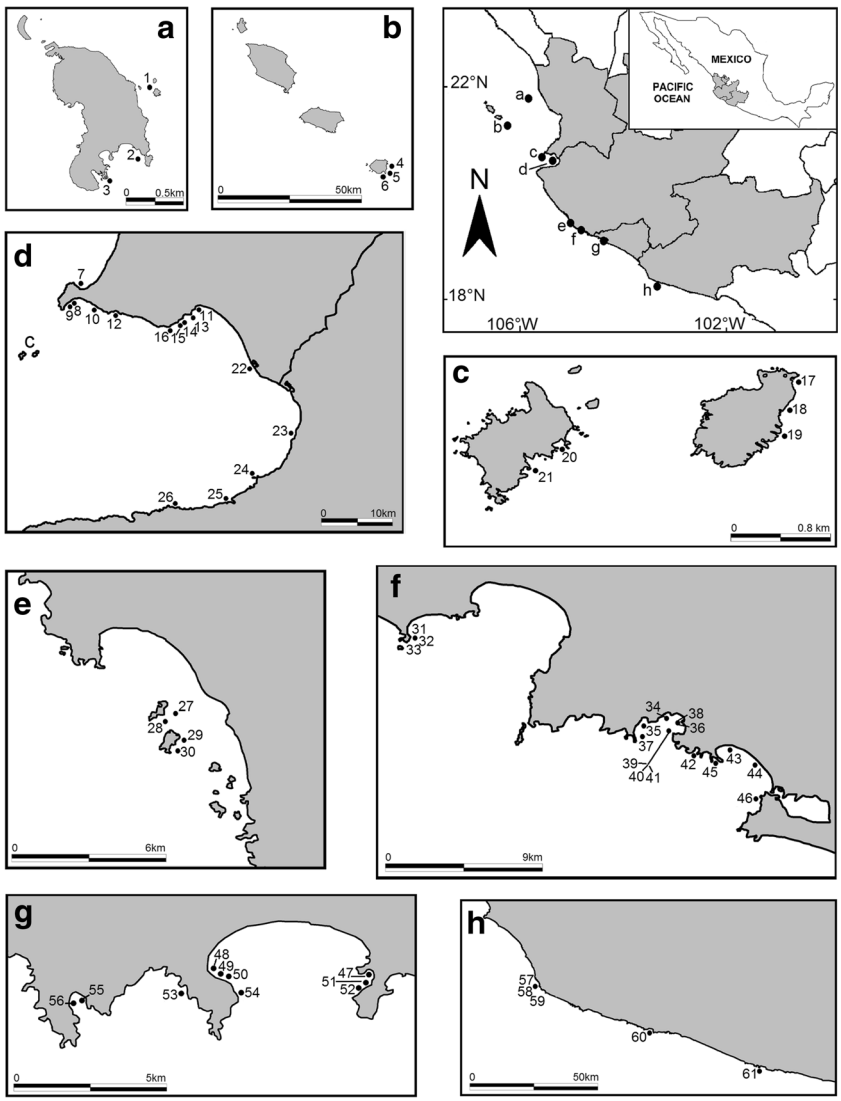

Fig. 1 Study area representing the 61 localities along the Central Mexican Pacific. **a** Isla Isabel; **b** Islas Marías; **c** Islas Marietas; **d** coast of Nayarit and Jalisco; **e**, **f** South coast of Jalisco; **g** Colima; **h** Michoacán. The numbers correspond to those listed in Table 1

Results

A total of 24 species of Ophiuroidea from 61 localities from the CMP were collected (Table 2). The species were classified in seven families (Amphiuridae, Ophiotrichidae, Ophiactidae, Ophionereididae, Ophiocomidae, Ophiodermatidae and Ophiolepididae) and 16 genera (*Amphiodia*, *Amphipholis*, *Microphiopholis*, *Ophiocnida*, *Ophiophragmus*, *Ophiostigma*, *Ophiothela*, *Ophiothrix*, *Hemipholis*, *Ophiactis*, *Ophionereis*, *Ophiocoma*, *Ophiocomella*, *Ophioderma*, *Ophiuroconis* and *Ophiolepis*). The families with the highest number of species were Amphiuridae (eight) and Ophiodermatidae (four); the family Ophionereididae was represented by one species (Table 2).

At the species level, the ophiuroids *Ophiocoma alexandri*, *Ophiocoma aethiops*, *Ophiothrix* (*Ophiothrix*) *rudis*, *Ophiothrix* (*Ophiothrix*) *spiculata*, *Ophiothela mirabilis*, *Ophiactis savignyi*, *Ophiactis simplex* and *Ophionereis annulata* were the most widespread in the CMP and were collected in a higher type of substrata (i.e. algae, live and dead stony coral, gorgonian, rock, sponge) (Table 2). On the other hand, *Amphiodia sculptilis*, *Ophiophragmus lonchophorus*, *Ophiophragmus marginatus*, *Hemipholis gracilis*, *Ophioderma* sp. and *Ophiuroconis bispinosa* were collected in just one locality. It is important to note that the following species were found inhabiting only one substrate, sand: *A. sculptilis*, *Microphiopholis platydisca*, *O. lonchophorus*, *O. marginatus*, *H. gracilis*, *O. bispinosa*, *Ophiolepis crassa*,

Table 2 Species of ophiuroids collected during this study, including geographical and ecological features. The numbers of the localities correspond to those in Table 1

Species	Localities	Substrata	Depth (m)	Qualitative abundance
Amphiodia sculptilis	38	sd	27	R
Amphipholis squamata	8, 12, 13, 20, 21, 31, 33, 36, 48, 55	al, cr, dc, rk, sd	0–18	R
Microphiopholis platydisca	22, 55	sd	4	R
Ophiocnida hispida	34, 37, 42, 43, 46, 52	dc, rk, sd	3–15	R
Ophiophragmus lonchophorus	22	sd	9–10	R
Ophiophragmus marginatus	22	sd	3–6	C
Ophiophragmus papillatus	12, 19, 41	rk	6–7	R
Ophiostigma tenue	19, 39, 41	rk, sd	7–8	R
Ophiothela mirabilis	16, 17, 18, 19, 20, 21, 23, 24, 25, 26, 28, 34, 36, 37, 40, 42, 47, 50, 52, 55, 56, 58	gr, sp	0–18	VA
Ophiothrix (*Ophiothrix*) *rudis*	5, 6, 8, 9, 10, 11, 12, 14, 15, 16, 34, 41, 61	al, cr, gr, rk	1.5–11	A
Ophiothrix (*Ophiothrix*) *spiculata*	1, 2, 14, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 34, 35, 37, 39, 40, 41, 42, 45, 46, 47, 48, 49, 50, 51, 52, 55, 56, 57, 58, 59, 60	al, cr, dc, gr, rk, sp	0–15	A
Hemipholis gracilis	22	sd	3–15	R
Ophiactis savignyi	1, 2, 7, 9, 11, 12, 13, 14, 15, 16, 18, 19, 20, 21, 24, 25, 27, 28, 29, 30, 33, 34, 35, 37, 41, 42, 48, 50, 52, 55, 56, 58, 59	al, cr, dc, gr, rk, rd, sp	0–9	A
Ophiactis simplex	2, 3, 11, 14, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 34, 35, 36, 37, 39, 40, 41, 42, 46, 50, 52, 56, 58, 59, 60	al, cr, dc, gr, hz, rd, rk, sd, sp	0–11	VA
Ophionereis annulata	5, 6, 7, 8, 9, 10, 11, 13, 14, 15, 19, 20, 27, 28, 31, 33, 37, 40, 42, 45, 46, 48, 49, 50, 52, 54, 55, 56, 57	sd, rk	0–15	C
Ophiocoma aethiops	4, 5, 6, 7, 8, 9, 11, 12, 13, 14, 15, 18, 19, 20, 21, 25, 27, 28, 30, 31, 33, 34, 35, 37, 40, 41, 42, 45, 46, 47, 48, 49, 50, 51, 52, 53, 54, 55, 56, 57, 58, 59	al, cr, dc, hz, rk	0–15	C
Ophiocoma alexandri	1, 2, 5, 6, 7, 8, 9, 12, 13, 14, 15, 18, 19, 20, 21, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 39, 40, 41, 42, 45, 46, 47, 48, 49, 50, 51, 52, 53, 54, 55, 56, 57, 58, 59	cr, dc, gr, hz, rd, rk, sd	0–15	A
Ophiocomella schmitti	7, 9, 11	al, cr, sp	0.10–0.30	R
Ophioderma panamensis	8, 9, 14, 15, 19, 20, 21, 31, 33, 37, 40, 42, 45, 47, 48, 49, 51, 52	rk, sd	0–10	C
Ophioderma teres	47, 51, 56	rk	0–2	R
Ophioderma sp.	5	rk	9.6	R
Ophiuroconis bispinosa	36	sd	18	R
Ophiolepis crassa	18, 19, 20, 21	sd	5–10	R
Ophiolepis pacifica	5, 19, 21	sd	5.5–10.8	R

Substrata = *al* algae; *cr* stony coral; *dc* dead stony coral; *gr* gorgonian; *hz* hydrozoan; *rd* rhodolithe; *sd* sand; *rk* rock; *sp* sponge

Qualitative abundance = *A* abundant; *C* common; *R* rare; *VA* very abundant

Ophiolepis pacifica; rock: *Ophiophragmus papillatus*, *Ophioderma teres* and *Ophioderma* sp. According to the qualitative abundances obtained during this study, two species can be considering as very abundant, four as abundant, four as common and 14 as rare (Table 2).

Nayarit and Jalisco were the areas with the highest number of species (16), followed by Colima (12) and Michoacán (eight). Regarding the islands, 13 species were collected at Islas Marietas, six at Islas Marías and four at Isla Isabel. Islas Marietas localities represented the highest number of species of the entire region: Túnel Amarradero (12), Área de Restauración (10) and Cueva del Muerto (10) (Table 2). According to previous records of ophiuroids from the CMP, we found a total of 28 new distribution records: ten from Islas Marietas (*Amphipholis squamata*, *O. panamensis*, *O. crassa*, *O. papillatus*, *O. tenue*, *O. mirabilis*, *O. annulata*, *O. savignyi*, *O. simplex* and *O. pacifica*), one from Islas Marías (*Ophioderma* sp.), six from the coast of Nayarit (*A. squamata*, *H. gracilis*, *Ophiocomella schmitti*, *O. panamensis*, *O. loncophorus* and *O. papillatus*), five from Jalisco (*A. squamata*, *O. papillatus*, *Ophiostigma tenue*, *Ophiothrix* (*Ophiothrix*) *rudis* and *Ophiuroconis bispinosa*) and six from Colima (*A. squamata*, *Microphiopholis platydisca*, *Ophiocnida hispida*, *Ophioderma panamensis*, *O. teres* and *O. mirabilis*).

The number of collected species during this work and the records from the literature sum a total of 57 from the CMP (Table 3). For the entire study area, according to the estimator Chao2 and its confidence intervals, the expected number of species was higher (up to 104) than the number of observed species (57), indicating that the checklist of ophiuroids from this area is not yet complete (Fig. 2). The taxonomic distinctness index (Δ^+) indicated that all the areas comprising the CMP are inside the 95 % confidence limit; in this regard, the coast of Nayarit showed a value near to the lower limit and the Islas Marías displayed a value above the upper limit of confidence (Fig. 3). The results indicated that Islas Marías had the highest value of taxonomic distinctness, as well as the highest number of species of all the areas in the CMP, which suggests that these islands are represented by different taxonomical groups (genera). If we compare the areas of the CMP with that of the Southern Mexican Pacific (Guerrero and Oaxaca) in terms of taxonomic distinctness and the number of species of ophiuroids, the analysis showed that both areas displayed similar patterns (Fig. 3).

Discussion

This study includes new species distribution records for Islas Marietas (ten), the coast of Nayarit (six), Colima (six), Jalisco (five) and Islas Marías (one), and many of them have

Table 3 Updated checklist of valid species of Ophiuroidea from the Central Mexican Pacific region according to literature records and the collected species during this work

Phylum Echinodermata Brugiére, 1791
Class Ophiuroidea Gray, 1840
Order Euryalida Lamarck, 1816
Family Asteroschematidae Verrill, 1899
Asteroschema sublaeve Lütken and Mortensen, 1899 MAR
Family Asteronychidae Verrill, 1899
Astrodia excavata (Lütken and Mortensen, 1899) MAR
Family Gorgonocephalidae Ljungman, 1867
Astrocaneum spinosum (Lyman, 1875) MAR
Order Ophiurida Müller and Troschel, 1840
Family Ophiacanthidae Ljungman, 1867
Ophiacantha costata Lütken and Mortensen, 1899 MAR
Ophiacantha hirta Lütken and Mortensen, 1899 MAR
Ophiacantha moniliformis Lütken and Mortensen, 1899 MAR
Ophiomitra granifera Lütken and Mortensen, 1899 MAR
Ophiomitra partita Lütken and Mortensen, 1899 MAR
Family Ophiuridae Müller and Troschel, 1840
Gymnophiura mollis Lütken and Mortensen, 1899 MAR
Ophiernus adspersus annectens Lütken and Mortensen, 1899 MAR
Ophiura (*Ophiura*) *scutellata* (Lütken and Mortensen, 1899) MAR
Ophiura (*Ophiuroglypha*) *irrorata irrorata* (Lyman, 1878) MAR
Family Amphiuridae Ljungman, 1867
Amphichondrius laevis Ziesenhenne, 1940 JAL
Amphiodia assimilis (Lütken and Mortensen, 1899) MAR
Amphiodia occidentalis (Lyman, 1860) NAY
Amphiodia platyspina Nielsen, 1932 NAY
Amphiodia sculptilis Ziesenhenne, 1940 JAL
Amphiodia violacea (Lütken, 1856) NAY
Amphiodia (*Amphispina*) *digitata* Nielsen, 1932 NAY
Amphiodia (*Amphispina*) *urtica* (Lyman, 1860) NAY, MAR
Amphipholis elevata Nielsen, 1932 MAR
Amphipholis pugetana (Lyman, 1860) NAY
Amphipholis squamata (Delle Chiaje, 1828) MAT, NAY, JAL, COL
Amphiura serpentina Lütken and Mortensen, 1899 MAR
Dougaloplus notacanthus (Lütken and Mortensen, 1899) MAR
Microphiopholis platydisca (Nielsen, 1932) NAY, COL
Microphiopholis puntarenae (Lütken, 1856) MAR
Ophiocnida hispida (Le Conte, 1851) MAR, JAL, COL
Ophiophragmus lonchophorus Ziesenhenne, 1940 NAY, JAL
Ophiophragmus marginatus (Lütken, 1856) NAY, JAL
Ophiophragmus papillatus Ziesenhenne, 1940 MAT, NAY, JAL
Ophiostigma tenue Lütken, 1856 ISA, MAT, JAL
Family Ophiotrichidae Ljungman, 1867
Ophiothela mirabilis Verrill, 1867 ISA, MAT, NAY, JAL, COL, MICH
Ophiothrix galapagensis Lütken and Mortensen, 1899 MAR
Ophiothrix (*Ophiothrix*) *rudis* Lyman, 1874 MAR, MAT, NAY, JAL, MICH
Ophiothrix (*Ophiothrix*) *spiculata* Le Conte, 1851 ISA, MAR, MAT, NAY, JAL, COL, MICH

Table 3 (continued)

Family Ophiactidae Matsumoto, 1915
Hemipholis gracilis Verrill, 1867 NAY, JAL
Ophiactis savignyi (Müller and Troschel, 1842) ISA, MAR, MAT, NAY, JAL, COL, MICH
Ophiactis simplex (Le Conte, 1851) ISA, MAR, MAT, NAY, JAL, COL, MICH
Family Ophionereididae Ljungman, 1867
Ophionereis albomaculata E.A. Smith, 1877 ISA, MAR
Ophionereis annulata (Le Conte, 1851) MAR, MAT, NAY, JAL, COL, MICH
Family Ophiocomidae Ljungman, 1867
Ophiocoma aethiops Lütken, 1859 ISA, MAR, MAT, NAY, JAL, COL, MICH
Ophiocoma alexandri Lyman, 1860 ISA, MAR, MAT, NAY, JAL, COL, MICH
Ophiocomella schmitti A.H. Clark, 1939 NAY, COL
Ophiocomella sexradia (Duncan, 1887) MAR
Family Ophiodermatidae Ljungman, 1867
Diopederma daniana (Verrill, 1867) JAL, MICH
Ophioderma panamensis Lütken, 1859 ISA, MAR, MAT, NAY, JAL, COL
Ophioderma teres (Lyman, 1860) MAR, NAY, JAL, COL
Ophioderma sp. MAR
Ophioderma variegata Lütken, 1856 MAR, NAY, JAL
Ophiuroconis bispinosa Ziesenhenne, 1937 JAL
Family Ophiolepididae Ljungman, 1867
Ophiolepis crassa Nielsen, 1932 MAR, MAT
Ophiolepis pacifica Lütken, 1856 MAR, MAT, NAY, JAL
Ophiolepis plateia Ziesenhenne, 1940 JAL
Ophiolepis variegata Lütken, 1856 MAR, NAY, COL, JAL
Ophiomusium lymani Wyville-Thomson, 1873 MAR
Ophiomusium variabile Lütken and Mortensen, 1899 MAR, JAL

ISA Isla Isabel; *MAR* Islas Marías; *MAT* Islas Marietas; *NAY* coast of Nayarit; *JAL* Jalisco; *COL* Colima; *MICH* Michoacán

relevance in terms of filling their distribution gap in México or extending their general geographical distribution range. Some ophiuroids have been previously reported for the CMP in other studies (Granja-Fernández et al. 2015a) and, of

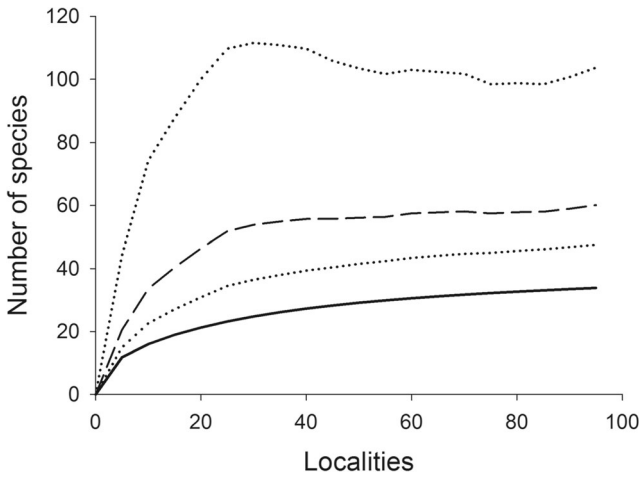

Fig. 2 Sample-based rarefaction curve of the Ophiuroidea from the Central Mexican Pacific region according to the number of localities. *Dotted lines* confidence interval (±95 %); *solid line* expected average richness; *dashed line* observed richness

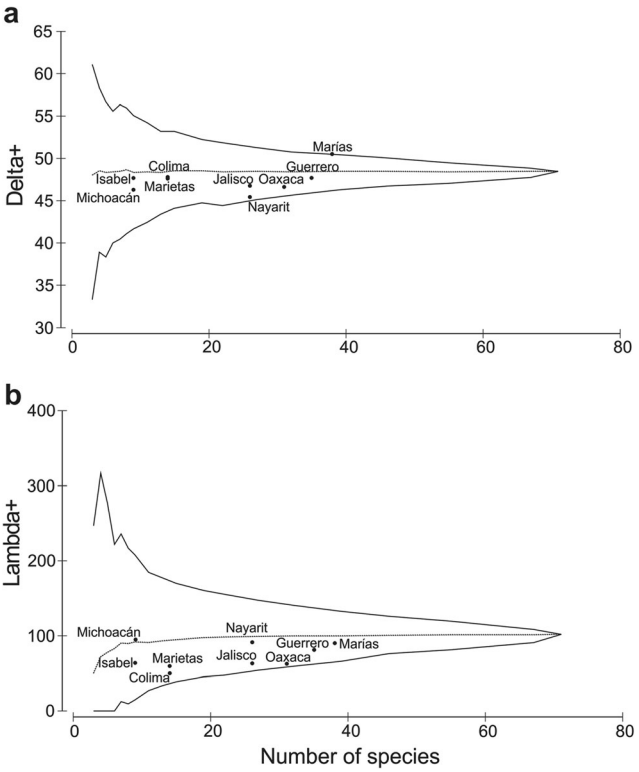

Fig. 3 Taxonomic distinctness analysis of the Ophiuroidea from the Central Mexican Pacific region. **a** Average (delta: Δ^+). **b** Variation (lambda: Λ^+). *Solid line* 95 % confidence limit; *dotted line* Δ^+ average value

these, the presence of ten species was confirmed for the CMP during this work in the same as well as new areas: *H. gracilis*, *O. savignyi*, *O. simplex*, *O. hispida*, *O. panamensis*, *O. teres*, *O. pacifica*, *O. annulata*, *O. mirabilis* and *O.* (*O.*) *rudis*. These species are conspicuous not only in the CMP but also in the rest of the Mexican Pacific, with a wide distribution along the Eastern Pacific (Solís-Marín et al. 2013; Granja-Fernández et al. 2015a). *Ophionereis annulata* has a symbiotic relationship with the polynoid polychaete *Malmgreniella cf. variegata* in two localities from Jalisco and one from Colima (Granja-Fernández et al. 2013). In this work, this association was found in Carrizales (Colima) and Túnel Amarradero, Isla Redonda, Islas Marietas (Nayarit), being the latest the northernmost record observed for this association in the Eastern Pacific.

The new report of *A. squamata*, *M. platydisca* and *O. tenue* in the study area is relevant, as these species had not been previously reported in the CMP, notwithstanding they had their distributions in both the northernmost (Gulf of California, Baja California and Baja California Sur) and southernmost areas (Southern Mexican Pacific region) of the Mexican Pacific (Honey-Escandón et al. 2008; Granja-Fernández et al. 2015a, b). There are three species having their distribution in most of the countries comprising the Tropical Eastern Pacific (Solís-Marín et al. 2013). Nevertheless, in

México, they have been reported exclusively in the northern (*Ophiuroconis bispinosa* and *Ophiolepis crassa*) or the central parts (*Ophiocomella schmitii*) of the country (Granja-Fernández et al. 2015a). Despite the sampling effort along the Mexican Pacific since 2007, the only areas in which *O. crassa* and *O. bispinosa* were found were Islas Marietas and Jalisco (personal observation), which represent the southernmost records of the species in México. On the other hand, *O. schmitii*, a six-armed species of the family Ophiocomidae, was previously reported from Colima and Islas Revillagigedo (Granja-Fernández et al. 2015a), but during this work, it was collected in the coast of Nayarit, representing the northernmost record of the species in the Mexican Pacific. Considering that the latest ophiuroids have been recorded in Central and South America (Solís-Marín et al. 2013), there is a high probability of finding them in the Southern Mexican Pacific region.

The most remarkable new records correspond to *O. lonchophorus*, *O. papillatus* and *Ophioderma* sp. *Ophiophragmus lonchophorus* is only known from Tenacatita (Jalisco) and had not been reported since its description by Ziesenhenne (1940) in other areas from the Eastern Pacific. During this work, this species was collected on the coast of Nayarit; therefore, these findings represent a range extension of almost 165 km north of the type locality. On the other hand, the only report of *O. papillatus* in the Eastern Pacific is from the states of Oaxaca and Guerrero in Mexico (Granja-Fernández et al. 2014), but in this work, we collected it in Jalisco, Islas Marietas and other localities on the coast of Nayarit, which represents also a range extension of 740 km north. Finally, *Ophioderma* sp. is a new species in the process of description and had been recorded from Guerrero and Oaxaca; therefore, its new record in Islas Marías during this work represents a range extension of 670 km north (see Granja-Fernández et al. 2015a for more information).

Although the CMP is characterised as a highly biodiverse region, the considerable number of new records of ophiuroids can be attributed to a more intensive–extensive sampling; in other words, a higher number of prospected localities and the diversification of the collecting methods allowed recording species that were not collected in other studies (i.e. Ríos-Jara et al. 2008a, b, 2013; López-Uriarte et al. 2009). The different sampling techniques allowed us to observe that collecting specimens by hand is the best method because it obtained 75 % of the total of the collected species (*A. squamata*, *O. aethiops*, *O. alexandri*, *O. annulata*, *O. crassa*, *O. hispida*, *O. mirabilis*, *O. pacifica*, *O. panamensis*, *O. papillatus*, *O. teres*, *O. savignyi*, *O. schmitti*, *O. simplex*, *Ophioderma* sp., *O. tenue*, *O.* (*O.*) *rudis*, *O.* (*O.*) *spiculata*). Furthermore, the advantage of the latest collecting method is the ability of finding organisms in a greater variety of substrata (live and dead stony corals, gorgonians, hydrozoan, rock, sand, algae, rhodoliths and sponges), but, generally, the most conspicuous and/or bigger species (disc diameter > 10 mm) are the only ones collected. Other sampling techniques such as suction pump and dredge in specific substrata (sand and rock) allowed collecting some species that were not found by hand collection, that are buried in sand and that are of a smaller size (disc diameter < 5 mm). Using a suction pump, a total of 54 % of the species were collected (*A. sculptilis*, *A. squamata*, *O. aethiops*, *O. alexandri*, *O. annulata*, *O. hispida*, *O. lonchophorus*, *O. bispinosa*, *O. savignyi*, *O. simplex*, *O. tenue*, *O.* (*O.*) *rudis*, *O.* (*O.*) *spiculata*). Furthermore, two species, *A. sculptilis* and *O. bispinosa*, were collected using only this method and in a specific substrata (sand). The use of a dredge was also important, even though only 17 % of the total collected species were obtained by this method (*H. gracilis*, *M. platydisca*, *O. lonchophorus*, *O. marginatus*), and all of them (except *O. lonchophorus*) were collected just by dredging. It is important to highlight that dredging allowed obtaining a major quantity of organisms and of a larger size (disc diameter < 5 mm) in comparison to the suction pump method. Finally, the species associated with the coral *Pocillopora* spp. were *A. squamata*, *O. savignyi*, *O. simplex* and *O.* (*O.*) *spiculata*, being this common since Granja-Fernández et al. (2014) reported the association of these species (except *A. squamata*) with stony corals in the Mexican Pacific. It is of relevance to note that all of the collected specimens in this substratum were juvenile, which corroborates with the fact that stony corals are an important key habitat in the Mexican Pacific, as they provide nursering, concealment, breeding space and feeding for juvenile organisms (Spalding et al. 2001; Granja-Fernández et al. 2014).

According to the results obtained during this work, the species with the highest qualitative abundance in the CMP were *O. mirabilis*, *O.* (*O.*) *spiculata*, *O.* (*O.*) *rudis*, *O. savingyi*, *O. simplex* and *O. alexandri*, all of them being the most conspicuous too, distributed in almost all the sampled localities (>50 %). The high abundance as well as the wide distribution of these species is very common along the Eastern Tropical Pacific (Ríos-Jara et al. 2008a; Alvarado et al. 2010; Granja-Fernández et al. 2014), since Ophiocomidae, Ophiotrichidae and Ophiactidae are the most specious families in tropical shallow waters (Hendler et al. 1995). A total of 14 species were considered as rare in the CMP; of these, eight inhabited exclusively on sand. Despite the suction pump and dredging representing effective sampling methods in terms of finding new distribution records, the low number of performed replicates can denote the lowest abundance of the rare collected species. A major sampling effort in this substratum by this methodology has to be considered in further studies in order to obtain a most real relative abundance of the species.

In the most recent updated checklist of ophiuroids from the Mexican Pacific, Granja-Fernández et al. (2015a) recorded 20 species from the coast of Nayarit, 36 from Islas Marías, 21

from Jalisco, nine from Michoacán, nine from Isla Isabel and eight from Colima, and despite the authors not including Islas Marietas in their checklist, the CONANP (2007a) documented four species from these islands. If the number of species per area reported in Granja-Fernández et al. (2015a) and CONANP (2007a) is summarised with the present results, the numbers are as follows: 38 from Islas Marías, 26 from the coast of Nayarit, 26 from Jalisco, 14 from Colima and 14 from Islas Marietas. We did not find new records of species in Michoacán and Isla Isabel, so the number of species in these sites remains as nine, respectively.

The CMP region comprises a total of 57 species of ophiuroids and Islas Marías is the area with the highest richness, and Michoacán and Isla Isabel with the lowest. The highest richness recorded at Islas Marías also represents the highest value of taxonomic distinctness of the entire CMP, which can be explained because 18 species inhabit only in these islands, all of them from deeper waters (>500 m). The above is not unusual since Islas Marías is considered a stepping stone for the dispersal route of species and individuals to and from the Islas Revillagigedo, the Gulf of California and the Central and Southern Mexican Pacific (López-Pérez et al. 2015). In fact, all the collections in deep waters in the CMP had been performed only at Islas Marías (Lütken and Mortensen 1899), and since most of the deeper species inhabiting these islands have been recorded in Central and South America as well (Solís-Marín et al. 2013), it is highly probable to find the same species during a deep water exploration along the Mexican Pacific. In the case of the low species richness observed at Michoacán, sampling has not been effective, mostly due to the difficulty in accessing the area. This could explain the lowest number of species and, probably, the numbers might differ if the sampling increased. Moreover, the low number of species for Isla Isabel was related to the limited number of sampling localities and to the fact that only a few types of substrata were explored (i.e. Ríos-Jara et al. 2008a, b; Granja-Fernández et al. 2014).

On the other hand, if the CMP (57 species) is compared with the Southern Mexican Pacific (46 species) (Granja-Fernández et al. 2015b) in terms of Ophiuroidea composition, the former possesses more species despite a smaller coastal line (~613 km and ~1,125 km, respectively). The higher number of species in the CMP can be attributed to species from deep waters that have been collected only in Islas Marías. Although they have differences in area extension, both regions are similar in species composition as they share 43 % of the species, 67 % of the genera and 77 % of the families. It is important to emphasise that the analysis suggests that the CMP and the Southern Mexican Pacific are similar in taxonomic distinctness, regardless of the total number of species attributed to their similarity on oceanographic and substrata conditions (Arriaga-Cabrera et al. 1998; Kessler 2006). It could be suggested that it is highly probable that the following ophiuroids distributed in the southernmost part of the Mexican Pacific can inhabit the CMP too: *Amphichondrius granulatus*, *Amphiodia psara*, *Amphiophiura superba*, *Amphiura arcystata*, *Asteronyx longiffisus*, *Ophiomisidium leurum*, *Ophiomusium glabrum*, *Ophiomyxa panamensis*, *Ophionereis perplexa* and *Stegophiura ponderosa*. In addition, there is a significant number of species of ophiuroids that can be potentially collected in the CMP, since they are distributed from the northernmost part of the Mexican Pacific to South America (Solís-Marín et al. 2013; Granja-Fernández et al. 2015a).

The results evidence that the CMP region is very important in terms of Ophiuroidea diversity and composition in the Mexican Pacific, but, despite that, this study recorded only 57 species and 28 new distribution records; according to our models, at least 104 species can inhabit the area. We detected some points that we consider relevant in order to obtain a most complete checklist of the ophiuroids from the CMP in future works: (1) the current study is a multi-disciplinary and inter-institutional work, which allowed combining different collecting methods, resulting in the collection of species that had never been reported in previous studies. For this reason, we recommend to increase sampling by different methods in as many types of substrata as possible in order to collect a higher number of species; (2) despite the fact that we carried out the collections in 61 localities (most of them unexplored areas), there are still many other areas and habitats (i.e. mangroves, small islands) with a high potential for finding ophiuroids; (3) most of the studies conducted in the CMP come from shallow waters, so we suggest to conduct exploration in deep waters. This study contributes to the knowledge of Ophiuroidea fauna within protected and unprotected areas of the CMP, and might provide useful information for conservation and management purposes and enhances the relevance of the region. Despite the improvement, the CMP must be studied thoughtfully, since it plays a significant biogeographic role contributing to the dispersal and permanence of species, and, moreover, possesses ophiuroids that are only found in this region considering the entire Eastern Tropical Pacific.

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