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Article

Aquatic Invasive Species in the Protected Areas of the Yucatan Peninsula and Adjacent Marine Zone, Mexico

Eduardo Rendón-Hernández [1,*], Luis Amado Ayala-Pérez [2], Jordan Golubov [2], Ricardo Torres-Lara [3] and Brenda Iliana Vega-Rodríguez [4]

[1] Doctorado en Ciencias Biológicas y de la Salud, Universidad Autónoma Metropolitana. Ciudad de México, 04960, México
[2] Departamento El Hombre y su Ambiente, Universidad Autónoma Metropolitana–Xochimilco. Ciudad de México, 04960, México
[3] Departamento de Ciencias, Universidad de Quintana Roo. Quintana Roo, 77019, México
[4] Laboratorio de Ecología Aplicada, Universidad Autónoma Metropolitana–Xochimilco. Ciudad de México, 04960, México
* Correspondence: occelott@gmail.com

Abstract: Biological invasions are one of the main causes of biodiversity loss globally, affecting the quality of ecosystem services, economy and public health. Research on the presence, distribution, impacts and introduction pathways of invasive alien species is essential for understanding and tackling the invasion process. Continental, coastal and marine aquatic ecosystems of the Yucatan Peninsula concentrate a high number of native species richness; however, the states that are in the region (Campeche, Yucatan and Quintana Roo) also have the largest loss of natural capital at the national level. The presence of aquatic invasive species has contributed to this downward trend, mainly in protected areas. For this research, an analysis in the national biodiversity information system, the global biodiversity information facility, and the specialized scientific literature was carried out to determine the presence of aquatic invasive species within the protected areas of the Yucatan Peninsula and adjacent marine zone. The results indicate that there are 22 documented aquatic invasive species in 25 protected areas, which were classified into the following taxonomic groups: marine macroalgae (3 species), plants (2), inland and marine fish (11), crustaceans (2), mollusks (2) and hydrozoans (2). Fifteen of these species had a very high invasiveness score, six were high and one had a medium score. This research will be useful to strengthen regional public policy and guide decision makers on the management of aquatic invasive species, mainly for those that are seriously affecting aquatic ecosystems such as *Pterygoplichthys disjunctivus* and *P. pardalis* in freshwater protected areas and *Pterois volitans* in marine protected areas.

Keywords: biological invasions; Caribbean Sea; freshwater protected areas; Gulf of Mexico; introduction pathways; invasive species management; marine protected areas; risk assessment

1. Introduction

Invasive alien species are a threat to global biodiversity, ecosystem services, economies and public health [1–3]. Ecological impacts of invasive alien species include the disruption of food webs, competition for resources and space, changes in nutrient cycling and modifications in physical characteristics, with cascading effects on biodiversity at all trophic levels, from individuals (including extinctions) to ecosystems [1,4,5]. Economic costs caused by invasive alien species can arise through a wide variety of impacts, such as damage to productive activities, infrastructure and public health, and extend to the costs of prevention, control or eradication [6,7]. According to the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, the global economic cost of invasive

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alien species exceeded US$423 billion annually in 2019, with costs having at least quadrupled every decade since 1970 [3].

Invasions interact synergistically with other environmental problems, increasing their global impact, such as changes in land and sea use, and climate change [3]. In recent decades, climate change has compounded the effects of species redistribution [8] such that, in the future, invasive alien species will continue to establish and spread and be a significant cause of biodiversity loss worldwide [3]. The number of invasive alien species is expected to increase 36% over the next three decades [6,9], requiring enormous resources to manage their impacts [2].

Aquatic ecosystems can be severely threatened by invasive alien species; as they can substantially change the structure of native communities and alter ecosystem functioning [6; 10]. Aquatic invasive species can alter community composition; reduce species' richness and therefore diminish the ability of biotic resistance [11]. In the freshwater ecosystems; biodiversity is depleting alarmingly due to the introduction of invasive species; which cause; among other things; alteration of food webs [12,13]. Invasions of nonnative fish could also interrupt resource flows and have far reaching effects on interconnected ecosystems [14]. Marine invasive species may negatively impact coastal societies; affecting ecosystem services such as food provision; tourism and recreation [15] and they can decrease economic production of activities based on marine environments and resources such as fisheries; aquaculture; and marine infrastructure [3,16]. These effects have related social impacts through decreases in employment in economic activities directly affected by marine invasive species but also through decreases in people's welfare from the reduced quality of their surroundings [16]. Aquatic invasive species are therefore a major challenge for people in all regions and countries [3,11]

Biological invasions are regarded as one of the most critical threats to protected areas, as they disrupt the proper functioning of ecological systems, the main reason why they were established [17–19]. However, in many cases, protected areas are changing to modified landscapes due to anthropogenic activities, providing pathways for the introduction of invasive species [12,17]. One of the most significant problems in the management of biological invasions is that when the presence of a species is noticeable, it is generally already widely distributed in the receiving ecosystem. An early detection and rapid response strategy is cost effective for managers and having an updated system of the presence of species and their impacts helps determine the best strategy for their management, control or eradication. This paper presents a diagnosis of the presence of aquatic invasive species in the protected areas of the Yucatan Peninsula and the adjacent marine areas, which include the southeastern Gulf of Mexico and the Mexican Caribbean, which may be useful for decision-making on the restoration and conservation of the region's aquatic ecosystems.

2. Methods

2.1. Study Area

The Yucatan Peninsula in southeastern Mexico includes three states (Campeche, Yucatan and Quintana Roo), bordered by the Caribbean Sea, the Gulf of Mexico, and Guatemala and Belize. In this region of high biodiversity, there are several priority regions for conservation: 1) biogeographic provinces (Peten and Yucatan) [20]; 2) hydrological regions (Laguna de Terminos, Sur de Campeche, Calakmul, Anillo de cenotes, Contoy, Isla Mujeres, Corredor Cancun-Tulum, Cozumel, Cenotes Tulum-Coba and Sian Ka'an) [21]; 3) marine regions (Laguna de Terminos, Cayos Campeche, Escarpe Campeche, Arrecife Alacranes, Sonda de Campeche, Dzilam-Contoy, Punta Maroma-Nizuc, Tulum-Xpuha, Sian Ka'an, Xcalak-Majahual, Cozumel and Banco Chinchorro) [22] and 4) terrestrial regions (Petenes-Ria Celestun, Dzilam-Ria Lagartos-Yum Balam, Sian Ka'an-Uaymil-Xcalak and Silvituc-Calakmul) [23]. In this territory there are 40 protected areas of federal jurisdiction, classified into four protection categories: Biosphere Reserve, Flora and Fauna Protection Area, National Park and Wildlife Sanctuary [24]. In these protected areas, there are diverse aquatic ecosystems, among which

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the following stand out: rivers, lakes, waterholes, cenotes, petenes, mangroves, lagoons, seagrass meadows and coral reefs [20–24].

2.2. Information Analysis

To determine the presence of aquatic invasive species in protected areas of the Yucatan Peninsula and adjacent marine zone, we analyzed the National Biodiversity Information System [25]; the Global Biodiversity Information Facility [26]; scientific papers consulted on electronic platforms Springer Nature Lync, SciELO, redalyc, PubMed and Google Scholar with combinations of the following keywords: "*aquatic invasive species*, *invasive alien macroalgae*, *invasive alien plants*, *invasive alien hydroids*, *invasive alien mollusks*, *invasive alien crustaceans*, *invasive alien fish*, *protected areas*, *peninsula of Yucatan*, *Campeche*, *Yucatan*, *Quintan Roo*, *Mexican Caribbean and southeast Gulf of Mexico*", as well as the conservation and management programs of the protected areas [27–46] and the taxonomic lists in white papers of Arrecifes del Golfo de Mexico-Sur and Bajos del Norte National Parks [47,48]. Also, the introduction pathways of aquatic invasive species were identified with references to their presence in the protected areas, the IUCN's Global Invasive Species Database [49] and the Compendium Invasive Species of the Centre for Agricultural Bioscience International [50].

For this research, aquatic invasive species were considered those found in freshwater and marine ecosystems that have been analyzed through the Rapid Invasiveness Assessment Method (MERI for its acronym in Spanish), which determines the invasiveness risk of alien species for Mexico [51]. The determination of the MERI value is based on the following considerations: a) invasiveness documented in other regions of the world, b) relationship with nearby invasive taxa, c) vector of other invasive species, d) risk of introduction, e) risk of establishment, f) spread risk, g) health impacts, h) economic and social impacts, i) ecosystem impacts and j) impacts on biodiversity [51].

To determine similarity of species in protected areas and identify potential connectivity regions, we generated a dendrogram using the Jaccard index with the PAST statistical program [52]. Jaccard's index varies between 0 and 1; a value of 0 indicates no species in common, while a value of 1 indicates that the sites have maximum similarity in species composition.

3. Results

Twenty-two aquatic invasive species were found in 25 of the 40 protected areas (9 Biosphere Reserves, 6 Flora and Fauna Protection Areas, 9 National Parks and a Wildlife Sanctuary; Figure 1). These species were classified into six taxonomic groups: a) macroalgae, b) plants, c) hydrozoans, d) mollusks, e) crustaceans, and f) fish (Table 1). The 25 protected areas have a total surface of 14,682,654.45 ha, of which 12,491,665.27 correspond to marine surface and 2,190,989.18 to terrestrial surface and inland waters (CONANP 2025). According to the Convention on Biological Diversity [53] categorization, the introduction pathways of aquatic invasive species focused on: a) Release in nature (fishery in the wild, including game fishing); b) escape from confinement (aquaculture, aquaria, ornamental purpose, live food); c) transport – stowaway (fishing equipment, ship/boat ballast water, ship/boat hull fouling); e) corridor (interconnected waterways/basins/seas; Table 2).

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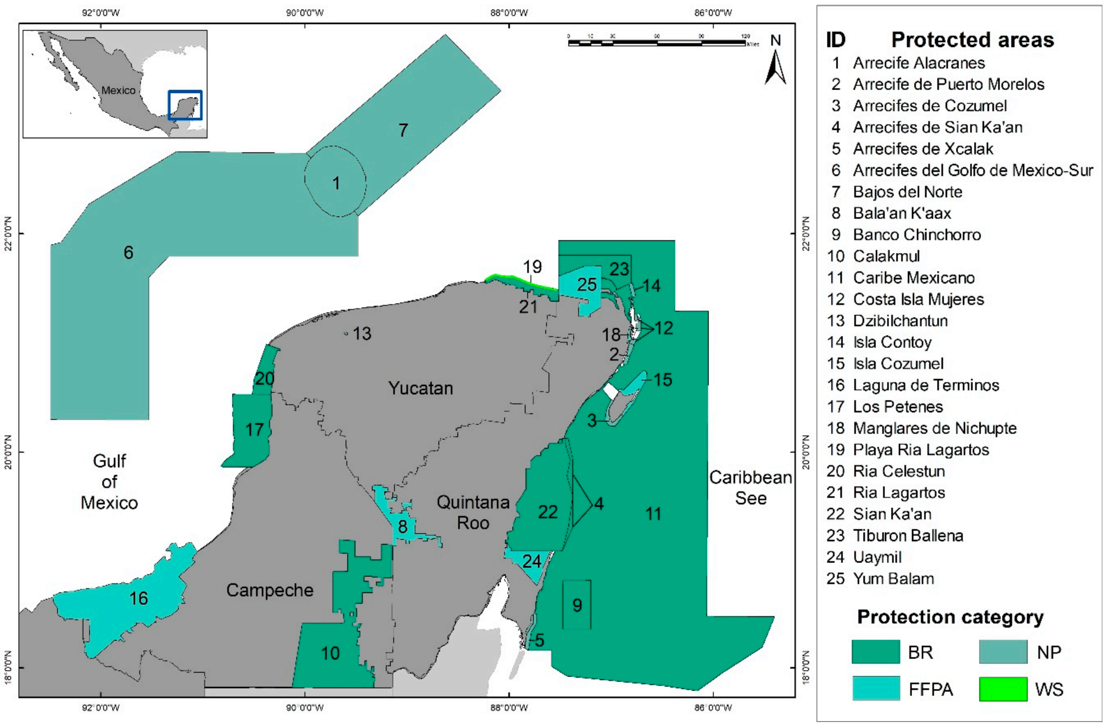

Figure 1. Map of the protected areas of the Yucatan Peninsula and adjacent marine zone with presence of aquatic invasive species. The acronyms of the protection categories correspond to: BR-Biosphere Reserve, FFPA-Flora and Fauna Protection Area, NP-National Park, WS-Wildlife Sanctuary.

Regarding the invasiveness index, 15 species have a very high level of invasiveness, six at high level, and one with a medium level (Table 1), representing a severe threat to the aquatic ecosystems of protected areas of the region. The species *Caulerpa taxifolia*, *Eichhornia crassipes*, *Oreochromis mossambicus* and *Cyprinus carpio*, in addition to having a very high level of invasiveness, are species listed among the 100 worst invasive alien species in the world (Table 2).

Laguna de Terminos Flora and Fauna Protection Area (Figure 1), which contains coastal, marine, and freshwater ecosystems, was the protected area with the highest presence of aquatic invasive species (N=13, Figure 2), The aquatic invasive species with the highest presence in protected areas were: *Caulerpa verticillata* in 18 areas, and *Pterois volitans* in 16. (Figure 2), which is evidence of their wide distribution in the marine environment. The most representative taxonomic group was fish, with nine freshwater species and two marine species (Table 1; Figure 1).

According to the similarity analysis, high similarities we found for Arrecife de Puerto Morelos-Arrecifes de Sian Ka'an-Arrecifes de Xcalak-Costa Isla Mujeres-Isla Contoy, with the species *Caulerpa verticillata*, *Ulva lactuca* and *Pterois volitans*; Arrecifes de Cozumel-Caribe Mexicano-Isla Cozumel-Yum Balam, with the species *Caulerpa verticillata* and *Pterois volitans*; Bajos del Norte-Tiburon Ballena, with the specie *Pterois volitans*, and Manglares de Nichupte-Playa Ria Lagartos with the specie *Caulerpa verticillata* (Table 1; Figure 2; Figure 3). Among the protected areas with intermediate values, we found: Arrecife Alacranes-Arrecifes del Golfo de Mexico-Sur, with the species *Caulerpa taxifolia*, *Caulerpa verticillata*, *Plumularia setacea* and *Pterois volitans*, and Ría Celestun-Ria Lagartos, with the species *Panaeus monodon* and *Caulerpa verticillata* (Table 1; Figure 2; Figure 3). The protected area with the least similarity was Laguna de Terminos, which concentrates 59% of the aquatic invasive species reported for the region, of which 61.53% are found only in this protected area [*Tarebia granifera*, *Charybdis* (Charybdis) *helleri*, *Parachromis motaguensis*, *P. managuensis*, *Ctenopharyngodon idella*, *Cyprinus carpio*, *Pterygoplichthys disjunctivus* and *P. pardalis*; Table 1; Figure 2; Figure 3].

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Table 1. Presence of aquatic invasive species in protected areas of the Yucatan peninsula and adjacent marine zone. Protected areas are represented by the following identification keys: Arrecife Alacranes (AA), Arrecife de Puerto Morelos (AP), Arrecifes de Cozumel (AC), Arrecifes de Sian Ka'an (AS), Arrecifes de Xcalak (AX), Arrecifes del Golfo de Mexico-Sur (AG), Bajos del Norte (BN), Bala'an K'aax (BK), Banco Chinchorro (BC), Calakmul (CA), Caribe Mexicano (CM), Costa Isla Mujeres (IM), Dzibilchantun (DZ), Isla Contoy (CN), Isla Cozumel (CZ), Laguna de Terminos (LT), Los Petenes (PE), Manglares de Nichupte (MN), Playa Ria Lagartos (PR), Ria Celestun (RC), Ria Lagartos (RL), Sian Ka'an (SK), Tiburon Ballena (TB), Uaymil (UA), Yum Balam (YB). The invasiveness levels are represented by the following symbols: very high (▲), high (■), medium (●).

Taxonomic Group	Family	Taxon	Protected Areas	Reference number
Macroalgae	Caulerpaceae	*Caulerpa taxifolia* ▲ (M.Vahl) C.Agardh 1817	AA, AG	25, 29, 48
		Caulerpa verticillata ■ J. Agardh, 1847	AA, AP, AC, AS, AX, AG, BC, CM, IM, CN, CZ, PE, MN, PR, RC, RL, SK, YB	25, 28, 29, 34, 35, 37, 38, 40, 41, 44, 45, 48, 54-56
	Ulvaceae	*Ulva Lactuca* ● (Linnaeus, 1753)	AA, AP, AS, AX, BC, IM, CN, RL, SK	25, 26, 28, 29, 32, 34, 35, 44, 45, 56
Plants	Hydrocharitaceae	*Egeria densa* ▲ Planch.	CA, DZ	25, 39, 46
	Pontederiaceae	*Eichhornia crassipes* ▲ (Mart.) Solms	CA, LT, PE, SK, UA	25, 34, 46, 57
Hydrozoans	Cordylophoridae	*Cordylophora caspia* ▲ (Pallas, 1771)	AG	25, 26, 48
	Plumulariidae	*Plumularia setacea* ■ (Linnaeus, 1758)	AA, AG	25, 26, 48
Mollusks	Thiaridae	*Melanoides tuberculata* ▲ (O. F. Müller, 1774)	LT, SK	25, 34, 58
		Tarebia granifera ▲ (Lamarck, 1816)	LT	25, 58, 59
Crustaceans	Penaeidae	*Penaeus monodon* ▲ (Fabricius, 1798)	LT, RC, RL	25, 26, 56, 58, 60-63
	Portunidae	*Charybdis* (*Charybdis*) *helleri* ■ (A. Milne-Edwards, 1867)	LT	25, 64
Fish	Cichlidae	*Oreochromis aureus* ▲ (Steindachner, 1864)	LT, PE	25, 26, 65
		Oreochromis mossambicus ▲ (Peters, 1852)	CA	25, 66
		Oreochromis niloticus ▲ (Linnaeus, 1758)	BK, CA, LT, PE, RC	25, 31, 56, 65-68
		Parachromis managuensis ■ (Günther, 1867)	LT	25, 58, 67, 69
		Parachromis motaguensis ■ (Günther, 1867)		25, 58
	Cyprinidae	*Ctenopharyngodon idella* ▲ (Valenciennes, 1844)		25, 58, 67, 69
		Cyprinus carpio ▲ (Linnaeus, 1758)		25, 58
	Loricariidae	*Pterygoplichthys disjunctivus* ▲ (Weber, 1991)		25, 58, 67, 69-73
		Pterygoplichthys pardalis ■ (Castelnau, 1855)		25, 58, 67, 69-74
	Scorpaenidae	*Pterois miles* ▲	BC	75

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	(Bennett, 1828)		
	Pterois volitans ▲ (Linnaeus, 1758)	AA, AP, AC, AS, AX, AG, BN, BC, CM, IM, CN, CZ, PE, SK, TB, YB	25, 35-38, 40, 41, 47, 48, 72, 76-81

Table 2. Pathways and vectors of the aquatic invasive species [49,50,83]. ▸ Species listed among the 100 worst invasive alien species in the world [82].

Taxon	Pathways and vectors
Caulerpa taxifolia ▶	Fishing nets, boat anchors, fishing equipment, pets trade, intentional release, improperly disposed waste from aquaria, internet sales
Caulerpa verticillata	Fisheries, boat anchors, trade for use in aquaria, intentional release
Ulva Lactuca	Ship ballast water and sediment, intentional release
Egeria densa	Trade for use in aquaria, improperly disposed waste from aquaria, it spreads by moving waters that carry whole plants or stem fragments to new locations
Eichhornia crassipes ▶	Internet sales, popular ornamental plant for ponds, canoes and boats, unwanted plant material is discarded into creeks, rivers and dams
Cordylophora caspia	Aquaculture stock, ship hulls, ballast water, floating plant material, commercial oysters, dumping aquaria
Plumularia setacea	Fisheries, aquaculture, ballast water, dry ballast, biofouling, packing material
Melanoides tuberculata	Trade in aquarium plants and fish, aquaculture, ornamental purposes, flooding, internet sales
Tarebia granifera	Trade for use in aquaria, improperly disposed waste from aquaria
Penaeus monodon	Aquaculture, breeding and propagation, ship ballast water and sediment, research
Charybdis (Charybdis) helleri	Interconnected waterways, ship ballast water and sediment, hull fouling
Oreochromis aureus	Aquaculture, escape from confinement or garden escape, intentional release, live food trade, pet trade
Oreochromis mossambicus ▶	Sport fishing, aquaculture, escape from confinement or garden escape, weed and midge control, research, intentional release, food for game fishes
Oreochromis niloticus	Fisheries, aquaculture, live food trade, escape from confinement or garden escape, intentional release
Parachromis managuensis	Trade for use in aquaria, aquaculture, escape from confinement or garden escape
Parachromis motaguensis	
Ctenopharyngodon idella	Weed control, aquaculture, sport fishing
Cyprinus carpio ▶	Fisheries, aquaculture, intentional release, sport fishing, interconnected waterways, ornamental purposes, pet trade, escape from confinement or garden escape
Pterygoplichthys disjunctivus	Escapes from aquaculture farms, aquarium trade, intentional release, live food trade
Pterygoplichthys pardalis	
Pterois miles	Pet trade, intentional release, ship ballast water and sediment (eggs and larvae), hurricanes
Pterois volitans	

References of information according to Table 1.

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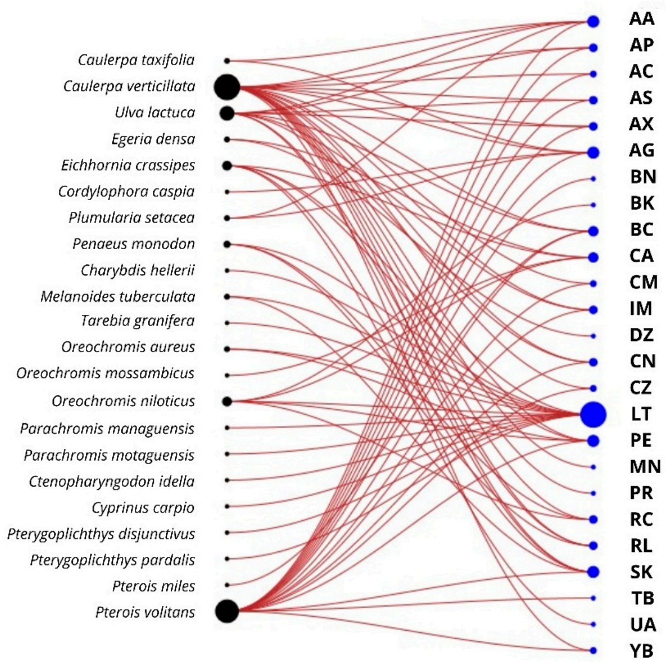

Figure 2. Presence-absence relationship of aquatic invasive species in the protected areas of the Yucatan peninsula and adjacent marine zone. The bigger the circle, the greater the presence. Identification keys for protected areas according to Table 1.

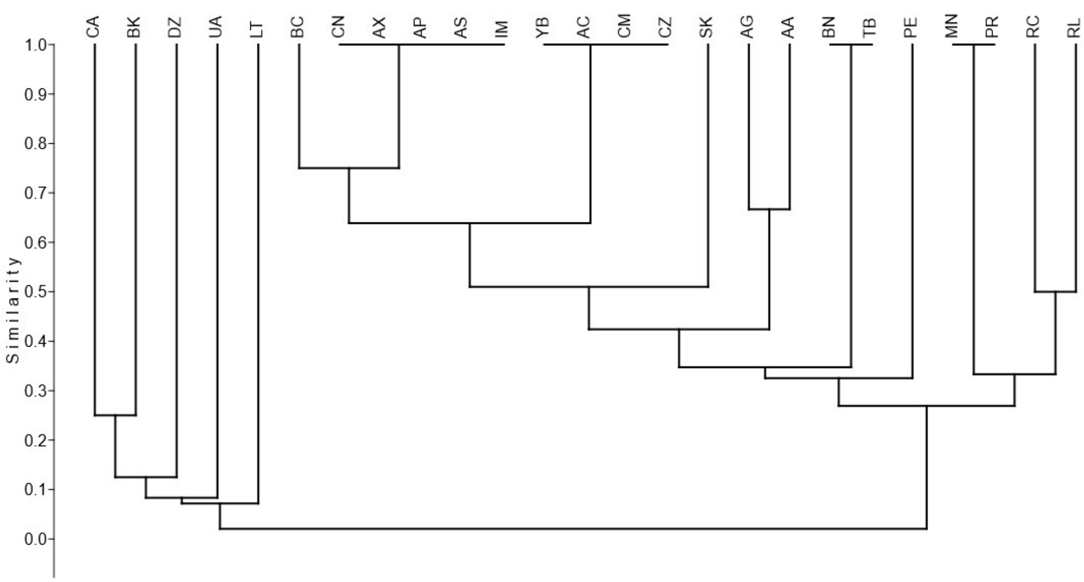

Figure 3. Dendrogram of similarity of aquatic invasive species in protected areas of the Yucatan peninsula and adjacent marine zone. Identification keys for protected areas according to Table 1.

4. Discussion

The arrival of alien species is unsure; yet possible modes as to how the species will have arrived can form some basis for practical management [84], taking as a reference the pathways and methods of propagation of species that arrived in the past [85,86]. A single pathway may not be responsible for an introduction, as a relay of different pathways and their vectors could be involved [86]. The introduction pathways identified in Table 2 show that, for both inland aquatic and marine species, intentional releases, ballast water and biofouling are the most significant means by which alien species reach ecosystems, therefore, management the pathways through which alien species arrive and spread is important to reduce the threat of biological invasions [85,87,88].

In this article we take an important step towards establishing a baseline on the presence of aquatic invasive species in protected areas in the Yucatan Peninsula and adjacent marine zone. Updating species lists and distribution data is crucial for successful long-term management [17]. Specifically, the information generated in protected areas on invasive species must be given the same importance as the information generated for species at risk, since, depending on the level of knowledge available, the best decisions can be made for the restoration and conservation of ecosystems.

Although the region's protected areas present diverse ecosystems, protection categories, extension and problems, the Laguna de Terminos Flora and Fauna Protection Area (Figure 1) stand out due to the 13 aquatic invasive species distributed there, 70% of which have a very high invasive risk. The species that represent the greatest risk in this protected area are invasive fish: *Pterygoplichthys disjunctivus* and *P. pardalis*, which have been widely studied for their effects on the trophic chains of freshwater ecosystems [58,69–71,73], these effects are characterized by alterations in the structure of the fish community, positioning them as dominant species in estuarine systems, as occurs in the Palizada-Del Este area [2014]; adaptive capacity to brackish environments competing for space with native fish, as has been documented at the mouth of the Chumpan River [70]; incidence on siltation and erosion processes [73], and destruction of fishing gear, causing a decrease in the catch of commercially important species [58,73].

In the marine environment, the lionfish (*Pterois volitans*) represents the species with the largest geographical range, since it is found in all the protected areas of the northern Yucatan Peninsula and the Mexican Caribbean. *Pterois volitans* is a threat to the marine ecosystems, mainly for coral reefs [77–81,89] because individuals reproduce fast [77,81], reach high population densities [77,79], consume a wide range of native fish and invertebrate species [78–80,89] and can potentially compete for shelter with native species [89]. In addition, lionfish have economic risks because its diet habits not only include juveniles of commercially important species such as lobsters, but because it also competes with snappers (Lutjanidae) and grouper (Serranidae) for food and habitat [79].

The similarity analysis determined that the groups: Bajos del Norte-Tiburon Ballena, Arrecifes de Cozumel-Caribe Mexicano-Isla Cozumel-Yum Balam, and Arrecife Puerto Morelos-Arrecifes de Sian Ka'an-Arrecifes de Xcalak-Costa Isla Mujeres-Isla Contoy (Figure 3) present the same species composition in each group; all areas are marine, and *Pterois volitans* is present in all these areas. Banco Chinchorro has a similarity of 0.75 (Figure 3) with the group Arrecife Puerto Morelos-Arrecifes de Sian Ka'an-Arrecifes de Xcalak-Costa Isla Mujeres-Isla Contoy, the difference is that Banco Chinchorro has an additional species: *Pterois miles*, which was the only species that had a single record in a protected area [75] (Guzmán-Méndez et al. 2017). In the Arrecife Alacranes-Arrecifes del Golfo de Mexico-Sur group, it is noteworthy that they are adjacent areas (Figure 1, Figure 3), and that together they conserve a marine surface of 4,443,433 ha [24]. The Ria Celestun-Ria Lagartos cluster (Figure 3) stands out because both biosphere reserves share characteristics of shape, extension, ecosystems and problems [56], although they are located at opposite ends of the coastal zone of the state of Yucatan (Figure 1). Similarity results can guide management measures for invasive species, since, by sharing species, protected area managers must implement coordinated actions at a regional level, mainly in marine areas with high connectivity. The key elements to achieve this coordination could be trained personnel, standardized control and notification methods per species or taxonomic group, systematic monitoring, early detection, rapid response and long-term maintenance programs [17].

5. Conclusions

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It is urgent to coordinate management strategies for aquatic invasive species in protected areas, since they are key sites for the conservation of a wide variety of ecosystems and biodiversity, and they maintain fundamental ecological characteristics for greater biotic resistance to biological invasions. Early detection and rapid response will be decisive to avoid the effects that some species have already shown to have on aquatic ecosystems and the economy of the communities in the region. The lionfish (*Pterois volitans*) invasion has been shown to have significant repercussions not only on the structure and functioning of coral reef systems, but also on the tourism and fishing sector [77-81; 89]. The sailfin catfishes (*Pterygoplichthys disjunctivus* and *P. pardalis*), have significantly altered the food webs of inland aquatic ecosystems, caused the reduction of biomass of commercially important species and damaged the fishing gear of local fishermen [58,69–71,73].

Systematic monitoring will significantly strengthen prevention strategies and generate information on new or established species, including their distribution, abundance, and impacts, which will provide information to redirect economic resources towards management, control or eradication. The information generated in this work can be useful for decision makers in the protected areas of the Yucatan Peninsula and the adjacent marine zone, as it provides an update on the presence of aquatic invasive species, introduction pathways and their level of invasion.

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Conflicts of Interest: The authors have declared that no competing interests exist.

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