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Small-Scale Fisheries Are Predominant Among Human Factors Influencing Cuban Coral Reefs

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Abstract

Coral reefs provide environmental goods and services that support biodiversity and people but face diverse threats. To assess the human factors that might be influencing the status of Cuban coral reefs, we collected and analyzed data from three sources: observations made on a research cruise that circumnavigated Cuba's waters, expert knowledge, and updated published information. Our results show that small-scale fisheries are predominant among human factors influencing Cuban coral reefs, with more than 97% of the fishing incidents detected in situ during the expedition. Many Cuban reefs are heavily fished, have low levels of contamination, and enjoy high legal protection but experience inadequate enforcement. Tourism occurs on many reefs but could be sustainably increased based on its role in supporting enforcement and compliance and reducing fishing pressure. Densities of marine debris were generally lower in Cuban waters than other Caribbean locations and even lower within protected areas. Many human factors are likely acting synergistically, making management a challenge. This is the first at-sea comprehensive visual survey of human factors in Cuban waters and evaluation of marine debris on Cuba's reefs, establishing a baseline for future assessments. These findings highlight potential human impacts that must be addressed to safeguard the health of Cuba's marine ecosystem.

Keywords: fishing pressure; population; tourism; marine protected areas; marine debris; management measures

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Key Contribution: Cuban coral reefs are affected by human factors, mainly small-scale fisheries. Many of the human factors likely act synergistically, making their management a challenge. However, successful examples of better management and increased coordination between sectors can help build support for new management paradigms.

1. Introduction

Coral reef ecosystems provide an important array of environmental goods and services derived from their many ecosystem functions. They play a critical role in protecting coastlines from erosion, flooding, and storm damage in nutrient cycling and are sources of livelihoods and income from fishing, tourism, and other socioeconomic activities in Cuba and elsewhere [1–4].

Despite their worldwide significance, coral reefs are affected by a combination of global and local stressors, including climate change and human factors, leading to alarming declines in their health and biodiversity [5,6]. Key environmental factors include rising sea surface temperatures, an increase in storm frequency and intensity, and ocean acidification, which compromise coral survival and ecosystem stability [7,8]. Human factors such as overfishing, habitat degradation, pollution, and sedimentation from runoff and airborne deposition exacerbate these effects, creating synergistic interactions that further degrade coral health [8,9]. One example of global and local factors synergistically interacting is the climate and local factors such as overfishing, land-based contamination, diseases, sedimentation, and nutrient loading compiled by França et al. [10]. On the Great Barrier Reef, coral declines are greatest, and coral recovery is slowest on reefs where overfishing has impacted predation and herbivory. In addition, coral reefs near turbid river outflows have a lower likelihood of bleaching mortality due to lower light stress (antagonistic interaction). On the other hand, coral reefs with elevated nutrient levels have reduced coral recovery rates by up to 27% (synergistic interaction).

The loss of coral structure not only threatens the corals themselves but also disrupts the entire marine ecosystem, affecting fish diversity and productivity, which are crucial for small-scale fisheries and community livelihoods [7,8]. Even though it is recognized that human factors affect coral reef health, a vast majority of research has focused mainly on the biophysical factors over the human factors of reef ecosystems, which can limit our understanding of social relationships and wellbeing connected to these ecosystems and potential solutions for reef recovery [2].

Cuban coral reefs are extensively used by fisheries and tourism. They are relatively close to the coasts, making them accessible to people and land-based sources of contamination [11]. Many are protected by hundreds of pieces of legislation and marine protected areas. Fishing, particularly small-scale, is widely practiced on Cuban coral reefs. There are almost 40,000 fishers and 10,000 boats that access the coral reefs and other marine ecosystems from almost 200 sites around Cuba [12]. Ninety percent of those fishers and boats are part of the small-scale fleet [12]. The tourism sector in Cuba is the second largest employer in the country [13]. Ecological tourism accounted for nearly half of Cuba's tourist income, followed by beach tourism at 35% [13]. For both kinds of tourism, marine resources such as coral reefs are used for or impacted by human activities. Contamination reaches coral reefs mainly around large cities such as Havana [14] but also the reefs located around groups of islands like Sabana-Camagüey (i.e., [15]). The major land-based sources of contamination are industries and factories like sugar cane, extraction of metals, extensive agriculture, and cities with high density of human population without appropriate treatment systems for water or waste in general. These pollutants have impacts nationwide, increasing organic materials and driving an already established phase shift from coral-dominated to macroalgae-dominated coral reefs in Cuba [11,16]. There are 39 marine protected areas that include coral reefs in Cuba, protecting almost 28% of the coral reef area of the entire country [17]. The goal of Cuba's National System of Protected Areas is to reach 35% of coral reefs protected.

In Cuba, coral reef studies suggest that human factors such as fishing, tourism, contamination, and population mainly drive the health status of coral reefs [11,18,19]. Most Cuban coral reefs are under high fishing pressure, and, in contrast, few of them are highly protected. Recent studies [11,17] have noted that Cuban coral reefs face pressure from warming waters, storm damage, shore-based contamination, and impacts from tourism. Non-sustainable tourism practices can directly impact coral reefs by damaging or eroding the structure of the reef itself. They can also decrease biodiversity by recreational fishing or can indirectly impact the reef by increasing land-based contaminants from hotels or other facilities, even leading to overfishing by increasing the demand for seafood. Although marine protected areas (MPAs) and other fisheries and environmental regulations are in place to protect coral reefs, enforcement of all kinds of regulations is poor [11,17,20]. However, those studies were carried out at different times or used data obtained by different methodologies and did not include direct observations, limiting the scope of conclusions.

Here, we expand upon and ground-truth these previous studies by quantifying and assessing the human factors that might be influencing the status of Cuban coral reefs from three sources: observations made on a research cruise that circumnavigated Cuba's waters, expert knowledge, and updated published information. We aim to answer three questions: (1) How prevalent are human factors in Cuban coral reefs? (2) How dominant is small-scale fishing in Cuban coral reefs? (3) How are in situ observations of human factors related to the ones obtained by expert elicitation and other sources? We hypothesize that human factors are omnipresent, that small-scale fishing dominates human factors incidence, and that in situ observations properly reflect human factors prevalence in Cuban coral reefs.

2. Materials and Methods

2.1. Study Area

Cuba is located south of the Tropic of Cancer, bounded by the Caribbean Sea, the Gulf of Mexico, the Straits of Florida, and The Bahamas (Figure 1). The Cuban archipelago consists of the main island, Isle of Youth, and four island groups (Los Colorados, Sabana-Camagüey, Jardines de la Reina, and Los Canarreos) containing more than 4195 islands, islets, and cays [21]. The Cuban shelf is bordered mostly by coral reefs that cover an area of more than 2600 km^2 [22], including patch reefs, reef crests, spur and grooves, and drop-offs [23,24]. Cuba's climate is warm and tropical, seasonally humid, with semi-continental traits and maritime influence [25]. The dynamics of currents in Cuban waters are diverse, influenced by several hydrological and meteorological factors with temporal and spatial variations [21]. Mean flows of the currents off the south and north coasts are westerly [26]. Along western Cuba, circulation is largely driven by two large-scale current systems, the Caribbean Current and the Florida Current [27]. Due to different current systems and countercurrents, numerous mesoscale and smaller eddies can be found, especially in the southeastern part of Cuba [28]. Tidal currents are generally weak around Cuba except for shallow coastal embayments and areas along the northeast coast [29].

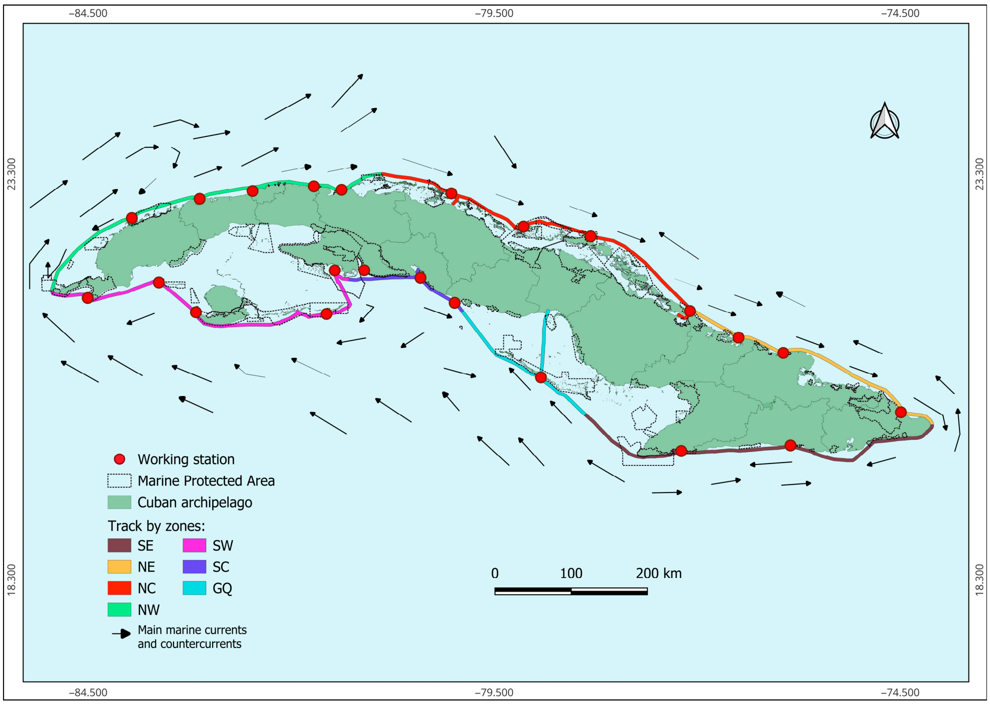

Figure 1. Study area showing at-sea survey tracks during the circumnavigation of Cuba. Continuous lines represent long transect sampling trajectories, with color differences indicating survey zones: SE: Southeastern, NE: Northeastern, NC: North Central, NW: Northwestern, SW: Southwestern, SC: South Central, and GQ: Gardens of the Queen. Red dots mark working stations where short transects were conducted. The survey progressed in a counterclockwise direction. Dashed gray lines indicate protected coastal and marine areas. Coordinates of coral reefs within the zones are in Table S1.

We grouped the survey sites and transects into seven zones (Figure 1, Table S1): Northwestern (from Cabo de San Antonio to Península de Hicacos), North Central (from Península de Hicacos to Bahía de Nuevitas), Northeastern (from Bahía de Nuevitas to Punta de Maisí), Southeastern (from Punta de Maisí to Cayo Cabeza del Este), Gardens of the Queen (from Cayo Cabeza del Este to Península de Ancón), South Central (from Península de Ancón to Golfo de Cazones) and Southwestern (from Golfo de Cazones to Cabo de San Antonio). These zones followed Pina-Amargós et al. [30]. These zones group neighboring reefs and sites into biogeographic units that experience similar oceanographic conditions and human pressures. They are also a more granular version of Cuba's four fisheries management areas, allowing stronger management recommendations and providing a foundation for future studies focused in specific areas around Cuba to build off our findings.

2.2. Data Collection

We measured seven human factors (level of fishing, level of population, level of contamination, distance from the coast, level of tourism, level of protection, and level of enforcement). All these factors are well known to influence marine habitats, and coral reefs in particular. Factors were measured through six qualitative and six quantitative variables (Table 1 and Supplementary Materials S2, Table S2). Variables were assessed from up to three different sources to reduce bias of single sources, depending on availability: in situ observations, expert elicitation, and published sources.

Table 1. Human factors that were considered for the analyses of the study. We followed the methodology used by Pina-Amargós et al. [11] for experts' elicitation and published sources; more details in Supplementary Materials S2. Factor = name of factor, Abb = abbreviation, Ty. Var. = type of variable, Evaluation = source of evaluation and way of measurement.

Factor	Variable	Abb.	Ty. Var.	Evaluation
Level of fishing	Fishing intensity	Pe1	qualitative	Expert elicitation. Rank scale from 1 (very low) to 6 (exceedingly high)
	Fishing effort	Pe2	quantitative	Fisheries database. Number of days of fishing from 2019 to 2023
	In situ observed fishing activity	PeB	quantitative	In situ observations. Number of fishing boats
Level of population	Population 1	Po1	quantitative	Published sources. Number of inhabitants within 30 km around each site
	Population 2	Po2	qualitative	Expert elicitation. Rank scale from 1 (low) to 4 (very high)
Level of contamination	Contamination 1	Co1	qualitative	Expert elicitation. Rank scale from 1 (low) to 4 (very high)
	In situ observed contamination	CoB	quantitative	in situ observations. Items of debris per 100 m^2 on coral reef
Distance from the coast	Distance from the coast	DC	quantitative	Online sources. Distance in km from each site to mainland or inhabited island
Level of tourism	Tourism 1	Tu1	qualitative	Expert elicitation. Rank scale from 1 (low) to 4 (very high)
	Tourism 2	Tu2	quantitative	Published sources. Number of diving shops using the sites
Level of protection	Protection	Pro	qualitative	Published sources. 1 (outside protected area) and 2 (inside protected area with fisheries regulations)
Level of enforcement	Enforcement	En	qualitative	Expert elicitation. Rank scale of patrolling frequency from 1 (very low) to 4 (high)

In situ observation data were collected as part of an expedition that circumnavigated Cuba. The expedition occurred from 19 July to 4 September 2023, for a total of 53 days, covering 1960 nautical miles, allowing 584 h of observations. In situ observations collected data for the evaluation of four factors (fishing, contamination, tourism, and enforcement). Two variables are used for quantitative analysis (fishing incidents and debris in coral reefs; see details below), and the incidents of tourism, contamination, and enforcement are used qualitatively (Table 1 and Supplementary Materials S2, Table S2).

We recorded in situ observations data during the expedition about fishing, enforcement (patrolling), tourism, contamination (oil slicks on transects and marine debris on coral reefs only), and other socioeconomic activities at sea (Table 1 and Supplementary Materials S2, Table S2). We quantified the number of human activities, from now on human incidents, by transect and then by zone. The survey included two types of transects: long, during extended vessel movements along zones, at 9 knots average speed; and short, during movements using a tender for surveying coral reefs and sharks, at 20 knots average speed (Figure 1). A zone includes the long and short transects placed within its boundaries. Due to differences in transect length, speed, weather conditions, and time of navigation, which affect detection probability, we followed a protocol to minimize bias. Two observers with binoculars and cameras annotated all human incidents detected within 500 m on both sides of the vessel/tender during the transects, ensuring that there was no double counting or missing any incidence. The vessel captains and the tender's skipper assisted in the observations using both visual checks and radar. All observations were made during day-light navigation, avoiding visibility range bias. We classified human incidents related to fisheries (e.g., fishing vessel by type (small-scale boat, large-scale state boat), shore-based fishing, set nets, speargun fishers) as in situ observed fishing activity (PeB), the quantitative variable selected for the statistical analysis. In the case of fishing vessel type, the differentiation between small-scale fishing boats and large-scale fishing boats was made based on the mandatory classification each boat must display on the hull. In Cuba, every boat has a specific classification corresponding to the authorized activity and ownership.

It is widely recognized that the differentiation between small-scale fishing and large-scale fishing is context dependent and must be classified in accordance with each country's peculiarities. This study defined both fishing types in the Cuban context. Cuba has two main fisheries sectors: state (commercial) and private (commercial and recreational). The private sector has over 10 times more fishers and more boats (36,200+ fishers and 8600+ boats) than the state sector (~3300 fishers and ~800 boats) (more details in Supplementary Materials S1). For this study, all private fishing was considered small-scale fishing activity. This classification aligns with the Food and Agricultural Organization description of small-scale fisheries [31]: fisheries involving fishing households, using relatively small amounts of capital and energy, relatively small fishing vessels (less than 15 m), making short fishing trips close to shore, mainly for local consumption. We also considered small-scale fishing to include the incidents involving citizens fishing from the shore, close to the coast, using floating devices like rafts, car tires, very small boats (not registered), and autonomous speargun fishers. We considered Cuban state fisheries large-scale because they are part of companies, use larger amounts of capital and energy, with larger fishing vessels than the private fleet (15 to 20 m) employing larger gillnets and longlines, make longer fishing trips both close to and far from the shore, and the catch is used for local consumption and exportation.

We also assessed contamination during the expedition through in situ observations of debris on coral reefs (CoB). Two observers carried out visual counts of debris on coral reef drop-offs and spur and grooves in 64 sites of 23 coral reefs (Figure 1, Table 1 and Supplementary Materials S1, Table S1). At each site, six belt transects of 15 m × 1 m were surveyed, searching for lost fishing gear and other marine debris following Miller et al. [32,33]. The type of marine debris and numbers of sessile invertebrates damaged through abrasion or entanglement [34] were recorded. This quantitative variable (CoB) was included for statistical analyses.

Expert elicitation data were collected following the methodology used by Pina-Amargós et al. [11] for the evaluation of five factors (fishing, population, contamination, tourism, and enforcement) and 10 variables (Table 1 and Supplementary Materials S2, Table S2). We estimated variables per site considering the period 2019–2023, since the environment responds to these variables on the scale of months to years. Nineteen experts, who participated in the expedition, evaluated the qualitative variables. Each of the sites was evaluated by eight experts on average, with at least four of them being nationwide experts with previous experience using the scores presented by Pina-Amargós et al. [11] and being part of this previous research. Final scores were determined collaboratively by the experts in two rounds of evaluation, following the Delphi methods [35].

Published sources provided information on four factors (fishing, population, protection, and distance from the coast) and four variables (Table 1 and Supplementary Materials S2, Table S2). Fishing effort data by fishing zone were collected from fisheries databases of the Center for Fisheries Research. The mean population value was obtained from the World

Population web page [36]. Protection was obtained from the 2023 shapefile of Marine Protected Areas from the Cuban National Center of Protected Areas. Distance to coast was calculated using the distance from each site to mainland, a permanently inhabited island, or an island with tourism infrastructure, and selecting the minimum distance as a proxy of human pressure. Computing the minimum distance of each site included the distance function of the Geopandas library from Python (version 3.6).

The temporal representativeness of the data is guaranteed by several factors. In the scale of years, two of the three variables describing fishing were measured in the 2019–2023 timeframe (fishing intensity and fishing effort), and the third fishing variable, in situ observed fishing activity, was analyzed to assess its usefulness compared to variables derived from the literature and expert validation (see Data Analysis and Results). The same applied for contamination and its two variables: contamination and in situ observed contamination. The rest of the variables data were the most updated in the available literature or measured in the 2019–2023 timeframe. In the scale of months, for fisheries, there is no published data about landing seasonality but in any given month of the year, there are about 20 species of the most important commercial fisheries families or groups of fish that reproduce [37]. These are the families Clupeidae, Carangidae, Lutjanidae, Gerridae, Haemulidae, Mugilidae, Scombridae, Xiphidae, and sharks and rays. These families and groups accounted for 62% of fish species landings in Cuba [38]. Since reproduction times are when fishers mostly target fish in Cuban waters [38], it is expected to have similar landings across all months. In the scale of months, for tourism, July and August were "intermediate months" in terms of the number of tourists (average 7.5% of the total of 2023). "Low months" were May, June, September, and October, which averaged 6.4%, and "high months", November through April, averaged 9.9% [13]. Most tourists in Cuba (international and domestic) target coastal areas, with direct and indirect impact on the marine realm. With the exception of the marine debris damaging sessile invertebrates through abrasion or entanglement, data does not represent human factor impacts but instead human factor prevalence and magnitude in the Cuban coral reefs.

2.3. Data Analysis

For a general characterization of the zones by human factors, we standardized each value by dividing the mean value per zone by the maximum value of each factor. Standardized human factors were presented in five categories: very high, high, medium, low and very low. We assessed the relationship between all factor pairs using the Spearman rank correlation coefficient for rank-scale factors and Pearson's correlation coefficient for quantitative factors. In both cases, Holm's correction for multiple tests was applied. We also applied linear models using in situ observed fishing activity (PeB) and in situ observed contamination (CoB) as response variables, with fishing intensity on a rank scale (Pe1), fishing effort (Pe2), and contamination on a rank scale (Co1) as covariates, to evaluate the usefulness of in situ observations compared to variables derived from the literature and expert validation. Because the rank-scale variables could not be assumed to have equidistant levels, they were treated as ordered categorical predictors. This approach allowed for appropriate handling of the ordinal nature of the data, avoiding the incorrect assumption of equal intervals between ranks, which could otherwise lead to misleading interpretations. In situ observed fishing activity and contamination were log-transformed to meet the assumptions of linear regression with count response variables. We used the coefficient of determination (R^2) as a measure of the effect size. We opted for simple linear regression with log-transformed response variables over more complex generalized linear or mixed-effect models due to our relatively small sample size. This approach is more practical and interpretable when describing general patterns and relationships in a small dataset; we acknowledge that generalized linear models with Poisson or negative binomial distributions would be more robust for formal hypothesis testing.

We used Permutational Multivariate Analysis of Variance (PERMANOVA), as developed by Anderson [39], to evaluate how the set of human-related factors varied across zones, protection status, distance to the coast, and enforcement intensity. For this analysis, distance to the coast was classified into three categories: Near (<2 km), Intermediate (2–10 km), and Distant (≥10 km). The distance matrix among sites was calculated using Gower distance, which is appropriate for mixed data types that include both quantitative and ordinal variables. The test was based on 9999 permutations, and the effect size was measured using the R^2 statistic. To aid interpretation of the PERMANOVA results, we applied non-metric multidimensional scaling (NMDS) to represent the Gower distance matrix. The resulting 2D ordination plot was labeled according to each of the four categorical factors. All statistical analyses were performed in R [40], using a significance threshold of $p < 0.05$.

3. Results

3.1. Human Factors Influencing Cuban Coral Reefs

We found that the reefs studied are an average of about 5 km from the coastline of the main island, with 76% of them less than 2 km from the coastline. Only two reefs are farther than 10 km from the coastline: Gardens of the Queen (~50 km) and San Felipe (~20 km).

Most surveyed reefs are close to densely populated areas (average of 258,866 inhabitants within a 30 km radius). Notably, 21% of the sites exceed this average, especially the three near La Habana reefs, which have a population of over 2 million inhabitants. Only 27% of the sites surveyed have no nearby permanent inhabitants.

The three variables related to fishing pressure (observed, intensity, and effort) revealed that fishing, and particularly small-scale fishing, dominated the human factors influencing Cuban coral reefs. A total of 569 human incidents were observed during the in situ visual surveys, with over 90% related to fishing incidents, and most of them small-scale fishing incidents (97%). The fishing activities observed included boats with fishing gear (i.e., long lines, nets, and rods), finfish trawlers, set nets, spearfishing, handline fishers, turtle nets, and body parts of turtles. Some of this fishing gear (i.e., turtle nets, set nets) is illegal, representing 7% of the fishing incidents (Supplementary Materials S3, Table S3). Only about 6% of the incidents were related to tourism activities; in order of frequency, the activities observed were marine boat tours, snorkeling, scuba diving, and recreational fishing.

A high prevalence of fishing activity was observed closer to Cuban cities with higher populations (Figure 2, Table S3), like in the South Central zone, Rancho Luna, Cienfuegos (74 incidents, 7.25 h^{-1}) and in the Northwestern zone, La Habana (73 incidents, 3.65 h^{-1}). In general, 9 of the 23 reefs surveyed (39%) had above the average prevalence of fishing activities for the country (18 incidents). The Northwestern zone of Cuba was observed to have the most intense fishing activity, with an average of 36 incidents and 3.16 h^{-1} during the sampling period. Within the Northwestern zone, all of the 5 reefs surveyed were observed to have higher than average prevalence of fishing activity. Other zones were observed to have lower levels of fishing activities, with the South Central zone with 31 incidents and the Northeastern zone with 21 incidents. In both the South Central (one reef) and Northeastern zones (two reefs), a smaller portion of the reefs were observed to have higher than average prevalence of fishing activity. The lowest prevalence of fishing activity was observed in the Southwestern and Gardens of the Queen zones, with 2, 0.21 h^{-1} and 0 average incidents, respectively. All of the reefs in the previously mentioned two zones are within protected areas (Figure 2).

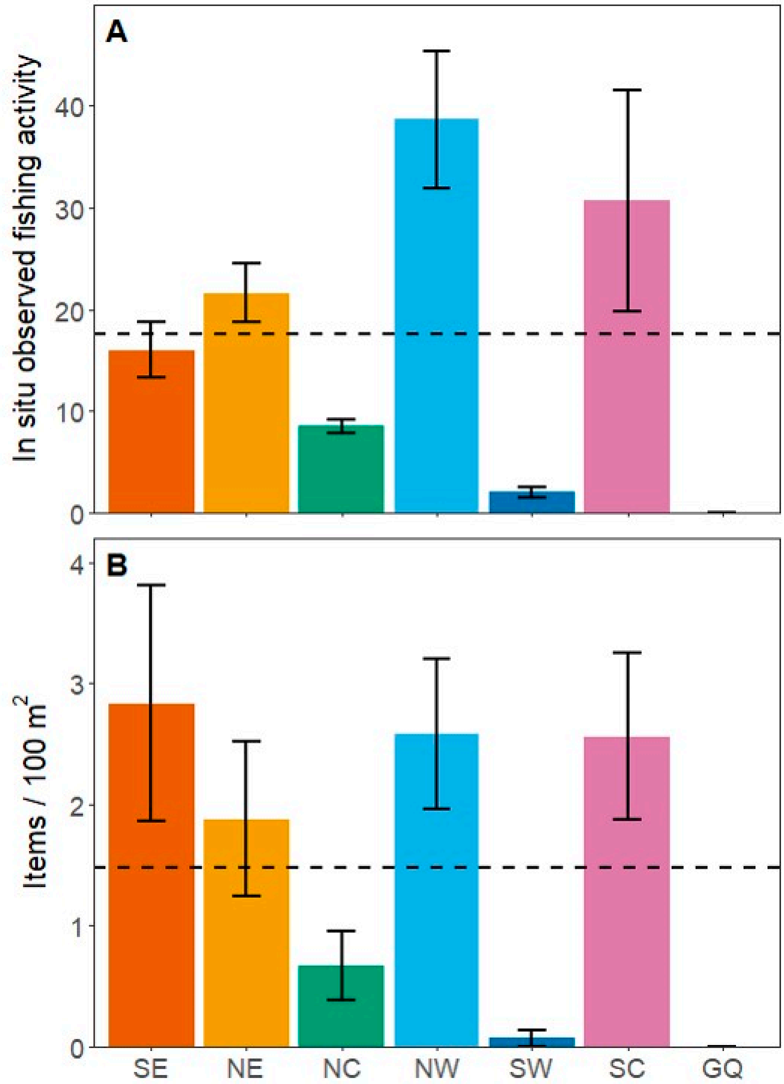

Figure 2. Mean values by zone with standard errors for in situ indicators of human impact on the studied reefs. (**A**) In situ observed fishing activity (PeB); (**B**) Number of marine debris items per 100 m^2 (CoB). The dashed horizontal lines indicate the mean for all values of each variable. Zones are SE: Southeastern, NE: Northeastern, NC: North Central, NW: Northwestern, SW: Southwestern, SC: South Central, and GQ: Gardens of the Queen.

Experts considered that 58% of the sites were very high or extremely high fishing sites with heavy small-scale fishing pressure. Only 11% of the sites were considered to be exposed to infrequent fishing. The average fishing effort of the studied zones was 127 days at sea, with two zones above 200 days at sea, the Southeastern and North Central (Figure 3).

An average of two diving shops use each reef site, although 20% (13 sites) are not used for scuba diving. About 53% of the sites were visited yearly by thousands of dive visitors (most of them not experienced divers), while about 45% received hundreds of dive visitors (most of them experienced divers and water sport practitioners) (Figure 3).

Although 58% of sites were within protected areas, evidence at sea of enforcement of fisheries and environmental regulations was very scarce, including inside the protected areas. Experts considered that more than 60% of the surveyed sites were patrolled less than once per month. Only 16% of the protected sites studied were considered to have daily patrolling at sea (Figure 3).

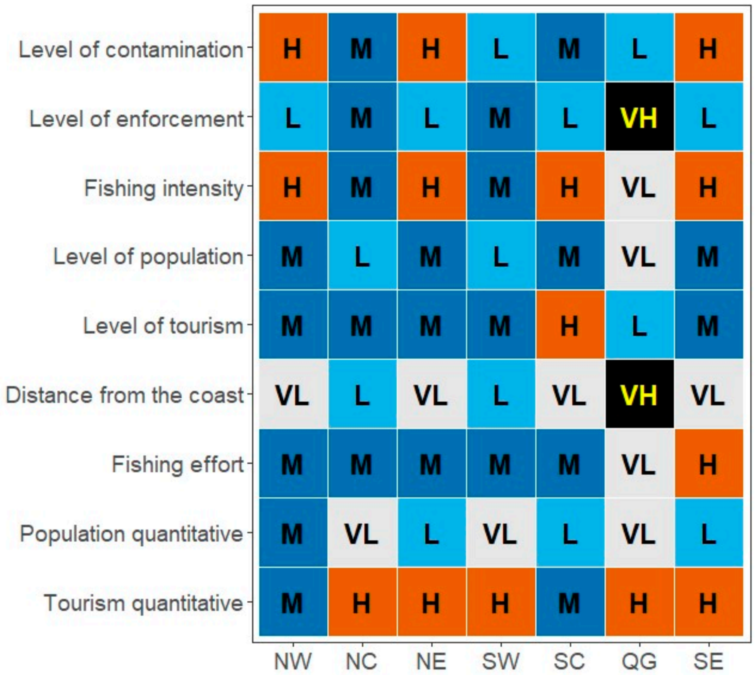

Figure 3. Heatmap of the zones based on human factors. Each value was standardized by dividing the mean value for each zone by the maximum value of the corresponding factor. Very High (VH, black), High (H, orange), Medium (M, dark blue), Low (L, light blue), and Very Low (VL, gray). Zones are SE: Southeastern, NE: Northeastern, NC: North Central, NW: Northwestern, SW: Southwestern, SC: South Central, and GQ: Gardens of the Queen.

In the case of contamination, results showed that 33% of the reef sites are exposed to very low contamination, and 12% are exposed to very high contamination (Figure 3). Oil at sea was observed only once near Santiago de Cuba.

A total of 97 debris items were encountered within 396 belt transects covering 5940 m^2 of coral reef habitat. Marine debris was found at 37 of the 64 sites (56%). Nearly 52% of the debris encountered consisted of lost fishing gear such as gillnets (25%), monofilament line (16%), rope (8%), and wire leaders, lead sinkers, and small anchors accounting for the rest (3%). The remaining debris consisted of plastic items like bottles and bags (28%) and other items (20%) such as cans, pieces of metal, concrete, and cardboard. Around 32% of the debris items were impacting the coral reef sessile creatures by abrasion or entanglement, mostly stony corals, followed by octocorals.

The average density of marine debris in the country was 1.7 items per 100 m^2, from a maximum of seven items per 100 m^2 in three surveyed sites (in NW, La Habana; SC, Cienfuegos; and SE, Santiago de Cuba) to a minimum of 0 items per 100 m^2 in 44% of the surveyed sites. Generally, densities of marine debris were lower in marine protected areas (1.1 items per 100 m^2) compared to non-protected coral reefs (2.04 items per 100 m^2). Most of the sites with the highest marine debris densities were close to highly populated cities (Figure 2) like La Habana (5.6 items average per 100 m^2), Rancho Luna (5.2 items average per 100 m^2), and Santiago de Cuba (4.8 items average per 100 m^2). The zones with the highest marine debris densities (3 items average per 100 m^2) were the Northwestern, with 4 reefs surveyed above the country average (1.7 items per 100 m^2), and the South Central and the Northeastern, each with two reefs with observed above-average presence of marine debris. The Southeastern and North Central zones were observed to have an average of two and one items per 100 m^2 presence of marine debris, respectively. The zones with the lowest marine debris densities observed were the Southwestern and Gardens of the Queen, with 0.1 and 0 items on average per 100 m^2, respectively (Figure 2).

3.2. Relationship Between Human Factors

For the qualitative variables derived from expert elicitations, we identified three positive relationships and two negative relationships of high significance. Fishing intensity was positively and highly correlated with contamination and population size (Figure 4A); at the same time, population was positively and highly correlated with contamination, while tourism was positively correlated with enforcement (Figure 4A). A negative relationship was observed between both fishing intensity and protection and fishing intensity and enforcement (Figure 4A). A negative relationship between contamination and protection and between contamination and enforcement was detected as well. The other factors showed low and no significant relationship. An observation that is noteworthy is that the main "negative" factors—fishing intensity, contamination and population (Pe1, Co1, Po1)—are positively and highly correlated with each other, but at the same time are negatively and highly correlated with "positive" factors, i.e., protection and enforcement (Pro, En).

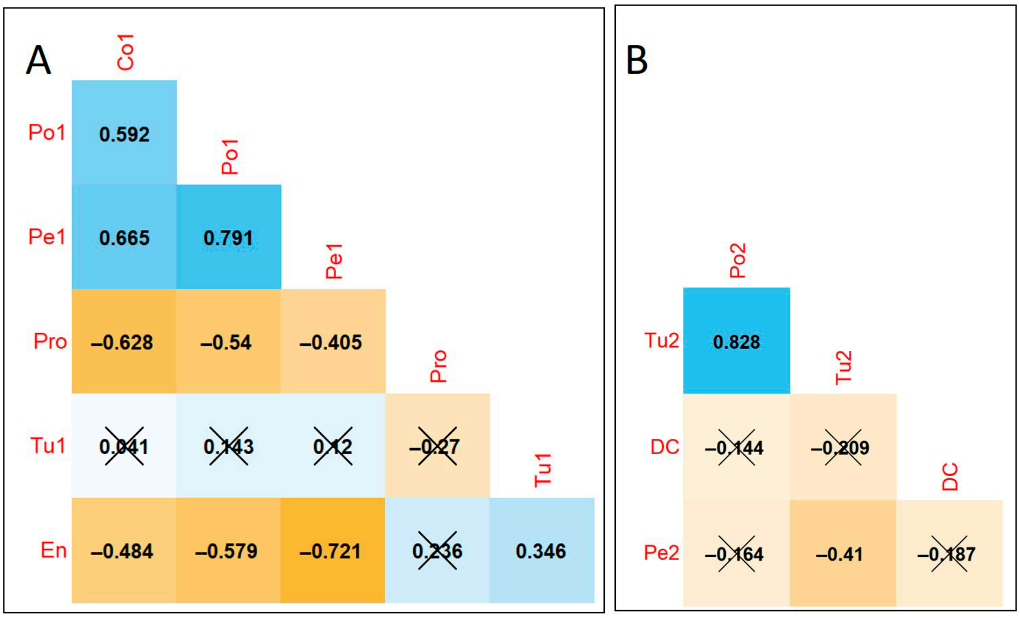

Figure 4. Correlograms showing pairwise Spearman rank correlations among human factors. (**A**) Qualitative factors (rank scale): Po1: Population; Pe1: Level of fishing; Pro: Protection; Tu1: Tourism; En: Enforcement. (**B**) Quantitative factors: Tu2: Tourism; DC: Distance from the coast; Pe2: Level of fishing. Color intensity and hue represent the strength and direction of the correlation (blue: positive; orange: negative). Non-significant correlations after Holm's correction ($\alpha = 0.05$) are indicated by a cross. See Table 1 for detailed descriptions of the human factors.

In the case of the relationship between quantitative human factors, only tourism was positively and highly correlated with population and negatively correlated with fishing effort (Figure 4B). The other factors showed low and no significant relationship.

The relationship between in situ observed fishing activity and fishing intensity derived from expert elicitation was positive and highly significant, with a high coefficient of determination ($R^2 = 0.71$, $p < 0.0001$; Figure 5A). In contrast, the relationship between fishing effort and in situ observed fishing activity showed a very low coefficient of determination and was not statistically significant ($R^2 = 0.02$, $p = 0.1284$; Figure 5B). The association between expert-evaluated contamination and in situ observed contamination was also highly significant but exhibited a relatively low coefficient of determination ($R^2 = 0.35$, $p < 0.0001$; Figure 5C).

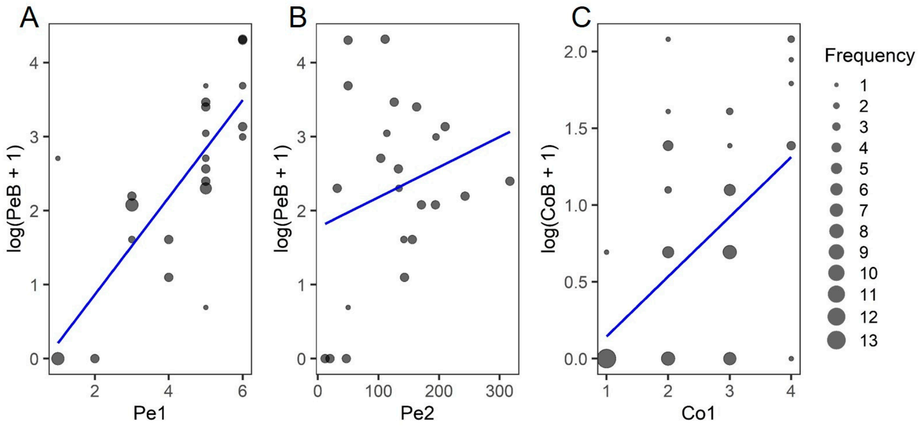

Figure 5. Relationships between in situ observations and factors derived from expert validation or literature sources, as determined by linear models. (**A**) Relationship between in situ observed fishing activity (log-transformed; PeB) and fishing intensity classified on a rank scale (Pe1). (**B**) Relationship between in situ observed fishing activity (log-transformed; PeB) and fishing effort (Pe2). (**C**) Relationship between in situ observed contamination (log-transformed; CoB) and contamination classified on a rank scale (Co1). Black dots represent observed values, and blue lines represent the fitted linear models.

Results of Permutational Multivariate Analysis of Variance (PERMANOVA) for the multivariate indicators of human impact across 64 reef sites indicated significant differences by zone ($F = 12.83$, $R^2 = 0.57$, $p = 0.0001$), protection ($F = 41.06$, $R^2 = 0.39$, $p = 0.0001$), distance to the coast ($F = 13.16$, $R^2 = 0.29$, $p = 0.0001$), and level of enforcement ($F = 14.63$, $R^2 = 0.41$, $p = 0.0001$). NMDS ordination plots (stress value = 0.12) showed that geographical position did not clearly explain the ordination of sites by zone, with geographically adjacent zones appearing to have very dissimilar human impacts (e.g., Southeastern and Gardens of the Queen) and geographically distant zones having more similar assemblages (Southwestern and Northcentral, Northeastern and Northwestern; Figure 6A).

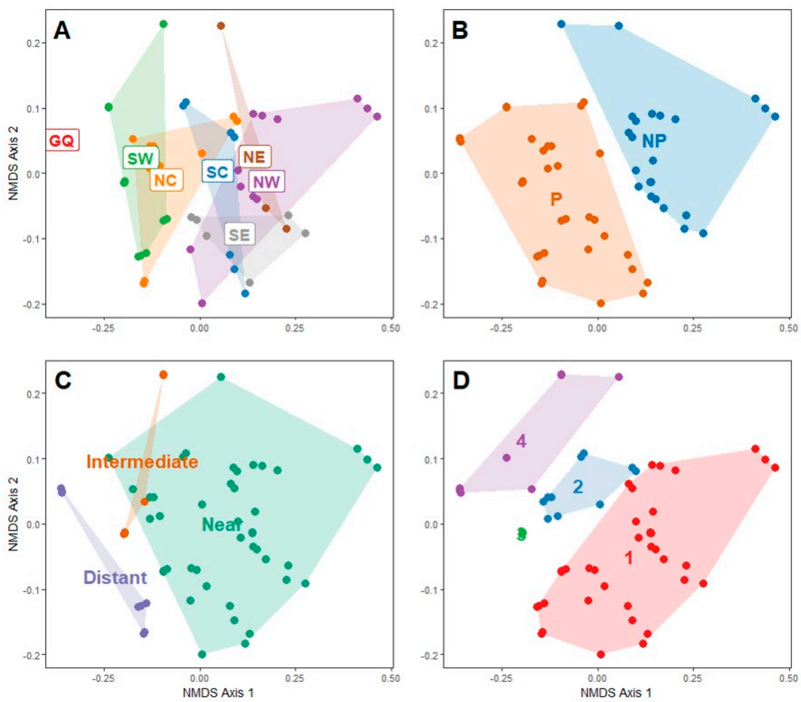

Figure 6. Non-metric multidimensional scaling (NMDS) ordination plot (stress = 0.12) based on all measured variables across 64 sampling sites. Each point represents a site, and the four panels show

the same ordination, with sites grouped according to different categorical factors. (**A**) Zones (GQ: Gardens of the Queen, SE: Southeastern, NE: Northeastern, NC: North Central, NW: Northwestern, SW: Southwestern, and SC: South Central). (**B**) Protection status (protected, P, and non-protected, NP). (**C**) Distance to the coast (Near, <2 km; Intermediate, 2–10 km; and Distant, ≥10 km). (**D**) Enforcement level (from 1, low, to 4, high). Colored points and polygons highlight the spatial arrangement of sites within each category, providing visual insight into how community structure varies across zones, protection status, spatial gradients, and enforcement intensity. Labels at the polygons' centroids indicate the levels of each factor.

By contrast, the multivariate indicators of human impact were more similar at sites with comparable levels of enforcement and protection, and both showed a strong gradient in assemblage composition (Figure 6B,D). In the case of distance to the coast, there was no strong separation between intermediate and near-to-the-coast sites, but most of the sites surveyed were near to the coast (Figure 6C).

4. Discussion

This study represents the first comprehensive at-sea visual survey of human activities in Cuban waters and the first nationwide evaluation of marine debris on coral reef ecosystems. It serves as a vital contribution to establishing a baseline for future assessments of the impact of human activity on marine biodiversity and conservation as a way of continuing to establish a sound scientific basis for management [41,42].

Our data reveal that human factors are omnipresent in the Cuban marine realm and that small-scale fishing is the most prevalent human activity in the Cuban marine environment in general and coral reefs in particular. This is consistent with international studies that estimate that small-scale fishing is responsible for more than half of all landings in the entire world, providing food security for millions of people, and employing more than 90% of all wild-catch fishers worldwide [43].

We demonstrated that human factors across surveyed sites are not homogenously distributed around the seven biogeographic zones around the Cuban archipelago. Most reefs are very accessible, and those closer to highly populated areas have a high level of fishing, mainly small-scale, like in the Southeastern zone. On the other hand, some reefs are farther from the coastline, with very low or no permanent inhabitants, with very low contamination, exposed to infrequent fishing due to some category of protection and frequent patrolling. Those few reefs are located in the Southwestern zone, like Guanahacabibes (not far from the coastline), Cayo Largo and Golfo de Cazones, and the Gardens of the Queen zone. In the rest of the Cuban reefs surveyed, only one site in Cayo Francés in the North Central zone and one site in Vita in the Northeastern zone are exposed to infrequent fishing due to some frequent patrolling. What is common for all these sites is not the legal protection but the enforcement in place with daily or weekly patrolling frequency, supported or entirely conducted by tourism operations. This is especially true in the Vita site, which is not under legal protection, but local tourism activity is a deterrent to fishing within diving and snorkeling sites. The rest of the sites inside protected areas have a low or very low patrolling frequency, an aspect that was reflected during the expedition, with only a few places where park rangers, fishing inspectors, or other authorities were observed at sea. The negative relationship between fishing intensity and protection and fishing intensity and enforcement on one hand, and the negative relationship between population and protection and between population and enforcement on the other hand, might be explained by this finding. Some of these results have been discussed before in other studies [11,17,20,44].

Fishing effort is a variable widely used for describing fishing pressure, but in our case study, this needs to be used with caution since it does not include small-scale fisheries, whose level can be very high. That is the case of the Northwestern zone (La Habana and Varadero reefs) and the South Central zone (Rancho Luna reef), which show very low fishing effort reported by the state-operated fleets but experts consider to have extremely high fishing intensity exerted by the small-scale fleet. In situ observed fishing activity recorded during the expedition helped to support expert elicitation, showing that La Habana, Varadero, and Cienfuegos have the largest numbers of fishing incidents, much larger than sites with the highest historical state fishing effort, like Santiago de Cuba and Pilón in the Southeastern zone and Cayo Coco in the North Central zone. Most of these incidents were related to the small-scale fishing fleet. Other studies had previously stressed that fishing intensity in the Northwestern zone [19,44–46] and fishing activities, in general, are some of the most prevalent human activities in Cuban waters [11,30,38,47].

During the surveys, we observed a low number of incidents related to tourism activities in coastal and reef zones, consistent with the decrease in all tourism (all indicators) since 2019, especially international visitors to the country [13]. Previously, marine tourism like scuba diving, snorkeling, and recreational fishing used to occur frequently, taking advantage of the ecological services that coral reefs provide, especially in marine protected areas [4,48,49]. Nonetheless, tourism operators are helping with enforcement within protected areas, as was discussed before, and endorsed by the positive relationship between tourism and enforcement and the negative relationship between tourism and fishing effort. This is the first time the negative relationship between tourism and fishing effort has been described in Cuba. The role of tourism in specific sites had been emphasized in previous studies in the country [11,17] and abroad, where tourism employees are more willing to protect the resources that provide income for them and their families and find ways to support enforcement [50,51].

In the case of contamination, sites that have higher levels of contamination are some of the same sites mentioned before, which are close to highly populated zones that are also heavily fished. Those sites are in La Habana and Varadero in the Northwestern zone, Santiago de Cuba in the Southeastern zone and Baracoa in the Northeastern zone. This is consistent with statistical relationships obtained between fishing intensity, contamination, and population size. In situ observed contamination in coral reefs recorded during the expedition shows similar results to the ones obtained from expert elicitation. Rancho Luna is the exception, which was evaluated by experts as likely to feature low levels of contamination but was observed to have high levels during the expedition, although marine debris is only a portion of the contaminants that affect the marine environment. High levels of contamination have been detected in reefs around La Habana [19,45,46].

There is no comprehensive baseline for marine debris in Cuban coral reef ecosystems from which to make comparisons. Our results show that marine debris is a problem in Cuban waters, as it is worldwide, but the average for the country (1.7 items per 100 m^2) is lower than that reported for the Florida Keys (three items per 100 m^2) [33], the Asia–Pacific region, and considerably lower within protected areas. The highest densities found by our study are four times lower than the maximum in the Florida Keys (33 items per 100 m^2; [34]) and three times lower than the maximum in the Asia–Pacific region (focused on plastics), specifically found in Indonesia (25.6 items per 100 $\pm$ 12.2 m^2, [52]). The lowest densities found by our study were under the minimum in the Asia–Pacific region (focused on plastics), found in Australia (0.4 items per 100 $\pm$ 0.3 m^2) [52]. Marine debris in oceans and seas also creates esthetic problems, considerably increases costs of cleaning or restoration, and can cause irreversible impacts on marine organisms and habitats [53].

The composition of the marine debris in Cuban waters, with more than half consisting of lost fishing gear, is also consistent with the high influence of fishing, mainly small-scale, on Cuban coral reefs. Although, this level is below what has been found in the Florida

Keys, where 87% of all debris is lost fishing gear [34]. However, when considering plastic items in general, the values are similar to other studies that have found that plastics are between 60 and 80% of the total marine debris in the world's oceans [54–56]. Generally speaking, sites with the highest levels of marine debris densities in Cuba coincide with greater exposure to contamination based on expert elicitation, except for Rancho Luna. This new evidence of marine debris in Cuban waters, especially plastics, requires follow-up and better waste management systems, as well as some measures for the elimination of this waste when possible. These actions are necessary since marine debris may not only be impacting sessile marine organisms directly but also indirectly since other studies have found widespread effects. Plastic waste can promote microbial colonization by pathogens, increasing the likelihood of disease from 4% to 89% when corals are in contact with plastic, especially in the case of reef-building corals [38]. Additionally, it has been estimated that ingestion or entanglement of plastic marine debris adversely affects 267 species globally, including 86% of sea turtles, 44% of seabirds, and 43% of marine mammals [53]. Fishes and crustaceans are also one of the largest groups affected by this phenomenon as well, given risks from both ingestion and entanglement in derelict fishing gear [53].

Statistical results reflect that in situ observed fishing activity and in situ observed contamination are good predictors of the influence of human activities on Cuban coral reef ecosystems. At the same time, fishing variables were the ones with the most correlations, stressing the relevance of fishing as a human factor in the Cuban marine realm as well. If high-quality quantitative data of human stressors are not available, are difficult or excessively costly to obtain, and not many experts are available, direct field observations of fishing pressure and contamination can be used as a proxy of human impacts. Additionally, the multivariate PERMANOVA results indicating clear groupings by protection and enforcement level could be interpreted as an encouraging sign that protected area designations, when paired with adequate enforcement, are effective across multiple human impacts.

In general, the intrinsic biases of the methodologies used—including subjectivity in expert scoring, detection of incident probability bias, plus the economic limitations (e.g., gas, electricity power, financial resources) of Cuba at the moment of the expedition—suggest that this information should be used with caution. In this regard, this study represents a rapid assessment of general patterns and relationships in a data-limited scenario. Nonetheless, the protocols followed to minimize errors and bias and the correspondence obtained between expert elicitation and in situ observed fishing activity and marine debris are positive indications of the accuracy of the results.

5. Conclusions

In general, our study reveals that many Cuban reefs are heavily fished, particularly by a small-scale fleet, have low levels of contamination, and enjoy high legal protection. However, the enforcement of environmental and fisheries regulations is inadequate. Tourism is occurring in many Cuban coral reefs but could be increased and expanded sustainably based on its role in supporting enforcement and compliance and reducing fishing pressure. Densities of marine debris were generally lower in Cuban waters than in other locations in the region and even lower within protected areas. Many human factors likely act synergistically, making their management a challenge. However, existing successful examples of better management and increased coordination between tourism and fishing sectors in Cuba can help build support for new management paradigms. Based on this study, we recommend designing and implementing research to assess the impacts of human factors on Cuban coral reefs.

Supplementary Materials: The following supporting information can be downloaded https://www.mdpi.com/article/10.3390/fishes10090463/s1, Table S1: Details of zones, reefs, sites, and survey dates (month/day/year); Table S2: Selected group of natural and human factors known to influence coral reef biota and measurable qualitatively and/or quantitatively. Table S3: Details of Fishing incidences (In situ observed fishing activity) by zones (Zo) and Reefs (Re). PeB.h-1: Fishing incidences per hour of navigation (observation). IPeB: Ilegal fishing incidence (N: turtle net, TR: body parts of turtles, SN: set net, SF: spearfishing, FT: finfish trawlers, L: Longline), in parenthesis () the number of illegal incidences per each type. Legal provisions refer to the regulations that make a specific activity o gear illegal. SE: Southeastern, NE: Northeastern, NC: North Central, NW: Northwestern, SW: Southwestern, SC: South Central, and GQ: Gardens of the Queen. Reefs: GQ: Gardens of the Queen, PILO: Pilón. SACU: Santiago de Cuba, BARA: Baracoa, VITA: Puerto de Vita, PUPA: Puerto Padre, SLCW: Santa Lucía Camagüey, CACO: Cayo Coco, CAFR: Cayo Francés, ISSA: Isabela de Sagua, VARA: Varadero, PUES: Puerto Escondido, HABA: La Habana, BAHO: Bahía Honda, SLPR: Santa Lucía Pinar del Río, MLGO: María la Gorda, SAFE: San Felipe, PUFR: Punta Francés, CLDS: Cayo Largo del Sur, GOCA: Golfo de Cazones, GIRO: Girón, RALU: Rancho Luna Cienfuegos, ANCO: Ancón.

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Conflicts of Interest: Author Yandy Rodríguez Cueto was employed by the company ProsperIA, Ciudad de México. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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