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A regional analysis of coastal and domestic fishing effort in the wider Caribbean

D.C. Dunn [a,b,*], K. Stewart [b,c], R.H. Bjorkland [b], M. Haughton [d], S. Singh-Renton [d], R. Lewison [b,e], L. Thorne [b], P.N. Halpin [a,b]

[a] Marine Geospatial Ecology Lab, Duke University Marine Laboratory, Nicholas School of the Environment, Duke University, 135 Marine Lab Rd., Beaufort, NC 28516, USA
[b] Project GloBAL, Duke Center for Marine Conservation, Duke University Marine Laboratory, Nicholas School of the Environment, Duke University, Beaufort, NC 28516, USA
[c] Protected Resources Division, NOAA Southwest Fisheries Science Center, 3333 N. Torrey Pines Ct., La Jolla, CA 92037, USA
[d] Caribbean Regional Fisheries Mechanism Secretariat, Corea's Building, Halifax Street, Kingstown, Saint Vincent and the Grenadines
[e] Biology Department, San Diego State University, 5500 Campanile Drive, San Diego, CA 92182, USA

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ABSTRACT

Although regulated fishing effort is relatively well documented for fisheries in developed states, developing countries are dominated by artisanal fisheries that are characterized by large numbers of small boats, fishing in dispersed and remote locations. These factors make quantifying artisanal fishing effort difficult. In this study, we examined the distribution and density of fishing effort across a region dominated by coastal, artisanal fisheries: the wider Caribbean. We used generalized linear regression models to predict missing data needed to compute fishing effort metrics and to explain variance in average boat length of a fishery and the number of small-scale boats in a given country. Clear intra-regional differences between mainland and island fisheries, and between northern and southern Caribbean fisheries, are evident in the results. To map artisanal fisheries based on the minimal data available, we created a free, automated Fishing Effort Envelope Tool (FEET). Through the use of this tool, we mapped all fisheries in the Caribbean to the extent possible given current data. Further, this mapping process also allowed us to identify hotspots of high density coastal fishing and data gaps that may mask areas of even higher fishing pressure. The potential ecological consequences of the scale of artisanal fishing are profound, and have greater implications for developing regions worldwide.

1. Introduction

A review of global production statistics for capture fisheries highlights the importance of the fisheries sector to global economic and food security (FAO, 2009c). While fisheries are unquestionably a vital part of many economies, they also act on marine ecosystems and have serious ecological consequences (Jennings and Kaiser, 1998; Jackson et al., 2001). Resolution of the conflict between economic interests and ecological concerns in fisheries is complicated by the social and political consequences of making management decisions that may affect hundreds of thousands of people. In 2006, 47.5 million people were employed in some capacity as fishers, primarily in developing countries where alternative employment options may be extremely limited (FAO, 2009c). Consumer demand for fish continues to grow and net exports from these developing nations have increased to meet new demand (US$4.6 billion in 1984 to US$20.4 billion in 2004; FAO, 2009c). These and other factors have led to extremely large artisanal fleets in some areas (e.g., the Indian coastal artisanal fishing fleet exceeds 250,000 boats; FAO, 2009b). While some artisanal fishing methods may be highly selective and efficient (e.g., dive fisheries, tuna and swordfish harpooning), some are not (e.g., dynamite and cyanide fishing, fish traps) and may have ecological consequences at least as severe as industrial fisheries (McManus et al., 1997). This problem is exacerbated by the difficulty of monitoring and enforcing management measures on dispersed and distant fishing communities (Chakalall et al., 1998).

Although regulated fishing effort is relatively well described for fisheries in developed states, developing countries are dominated by poorly documented artisanal fisheries. Quantifying fishing effort in artisanal fisheries is difficult because these fisheries are characterized by large numbers of small boats dispersed across potentially very long shorelines, with many located in remote fishing communities. This problem is further compounded by the lack of resources in developing countries (Mohammed, 2003). Ease of access to well-maintained fishing effort datasets for large industrial fleets has led to more frequent analyses of these fisheries (e.g., Lewison and Crowder, 2003; Gilman et al., 2007), with far fewer quantitative

* Corresponding author at: Marine Geospatial Ecology Lab, Duke University Marine Laboratory, Nicholas School of the Environment, Duke University, 135 Marine Lab Rd., Beaufort, NC 28516, USA. Tel.: +1 941 284 8369.
E-mail address: danielcdunn@gmail.com (D.C. Dunn).

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studies of small-scale fisheries (i.e., artisanal and semi-industrial fleets). This has resulted in the marginalization of artisanal fishing and ignorance about its importance and effects. It is, however, vital that fisheries scientists begin to quantify fishing effort in artisanal fisheries. Quantification of fishing effort is needed to regulate fisheries and to prevent overfishing, as it is a basic requirement for studies of catch (or bycatch) per unit effort, stock abundance and fishing mortality (Gelchu and Pauly, 2007). Furthermore, many ecological consequences of fishing are tied to the nature, amount, density, intensity, and location of fishing effort, rather than the more broadly reported amount of catch (McCluskey and Lewison, 2008).

Artisanal fishing effort is, almost by definition, located in the coastal zone (i.e., on the continental shelf or within 50 nautical miles of shore; Chuenpagdee and Pauly, 2008). However, not all fishing that takes place in the coastal zone is artisanal. As such, although we concentrate on analyses of artisanal fisheries in this study, we include a broader analysis of all domestic fishery development levels (i.e., artisanal, semi-industrial, industrial and super-industrial) to better understand the relative proportion of fishing effort by development level and to assess cross-gear impacts. Although most work on coastal fisheries, particularly artisanal fisheries has been performed at the community level (Chuenpagdee et al., 2006), regional analyses are important as they can highlight commonalities among fisheries and allow inferences to be drawn for areas where no data exist. Regional analyses are also vital for a better understanding of the collective importance and effect of fisheries that cannot be understood by examining individual communities or fisheries independently. Lastly, there are many shared fish stocks and physical and biological transboundary linkages within the wider Caribbean that require regional analyses and management approaches (Singh-Renton et al., 2003; Spalding and Kramer, 2004; Chakalall et al., 2007).

Fishing is a non-random, heterogeneously distributed process. Hence it is imperative to understand not just how much fishing effort exists, but where it is being employed. Salas et al. (2007) cite the use of maps and spatial analysis as an important tool in understanding small-scale fisheries and addressing issues related to meta-populations of fish stocks and connectivity between source and sink populations in the Caribbean. Most mapping of coastal fishing effort has been accomplished by assuming that fisheries are coincident with the area of the continental shelf (i.e., ≥ -200 m depth; Chuenpagdee et al., 2006). However, the continental shelf may contain many different habitat types that support specific fisheries and which have unique factors influencing fishing effort (reef-fish fisheries, shelf break ‘coastal pelagics’ fisheries, trawls on mud bottoms, etc.). Many countries also have specific regulations dictating how close to shore artisanal and industrial fisheries may take place. Furthermore, the spatial distribution of fishing effort is related to the location of fishing communities, and attenuates with distance from the community (Caddy and Carocci, 1999; Corsi, 1999). Thus, it is likely too simplistic to assume an equal distribution of fishing effort across the entire continental shelf. However, the location of every landing site and its associated fishing capacity is rarely known for developing countries. For this study, we created fishing effort envelopes for coastal fisheries within the Caribbean and applied fishing effort across the envelopes based on the distance from shore. These envelopes were employed to construct the first regional assessment of fishing density in the Caribbean. The results demonstrate to managers how fisheries overlap and indicate high priority/high density fishing areas for further research and monitoring. Specifically, we (1) created models to predict missing data; (2) we examined fishing effort and density across the Caribbean to better understand intra-regional differences in fishery characteristics, (3) we identified areas of potentially intense fishing pressure, and (4) we quantitatively compared the amount of fishing effort employed by artisanal, semi-industrial and industrial fisheries.

2. Methods

2.1. Data

Through an in-depth, three-year literature and expert review process, data on fishing effort were collected for every known fishery in each country in the wider Caribbean (see Table S1). Information sought included target species, number of boats, length of boats, type and amount of gear employed, soak-time, sets/day, days/year fished, and depth and distance from shore at fishing locations. The dataset is annotated with information on data sources and metadata on any assumptions or inferences that were made during data processing. Country profiles published by the Food and Agriculture Organization of the United Nations (FAO) provided baseline information, which was updated with more recent information from governmental reports and grey literature when available (FAO, 2009a). Where possible, these data were reviewed and corrected by experts within each country.

One hundred and twenty-three fisheries were identified in the wider Caribbean, including 25 ‘mixed’ fisheries that used multiple gear types, and many fisheries that targeted different species throughout the year. Further subdivision of the 123 fisheries by target species or gear was not feasible due to high levels of biodiversity in the region (i.e., lots of target species), low selectivity within the fisheries, and limited data collection on a national level (Salas et al., 2007). Data compilations for Mexico were not available in time for this publication, and thus were excluded from the analysis. This analysis was specifically directed at understanding domestic coastal fishing and as such, distant water fleets (e.g., United States, Korean and Japanese) were not considered.

2.2. Fishing effort metrics

Detailed information on fishing effort was collected through our initial literature review and expert consultation process. Comprehensive fishing effort data (i.e., kilometer-hours for net fisheries or hook-hours for hook and line fisheries) was unavailable for the vast majority (86%) of fisheries in the wider Caribbean. Piet et al. (2007) offered a framework through which various levels of fishing effort resolution are structured hierarchically by progressively adding more detailed information. With the data available in the Caribbean, we were able to create a fishing effort metric, ‘boat-meters,’ that fell between Piet’s ‘level 1’ (i.e., numbers of vessels) and ‘level 2’ (days at sea; Piet et al., 2007). Boat-meters are defined as the number of boats in the fishery multiplied by the average boat length used in the fishery. While this metric is fairly coarse, it allows for basic comparisons between artisanal, semi-industrial and industrial/super-industrial fisheries to be made, and lays the groundwork for more detailed analyses of fishing effort in the region for the future.

No fixed definition exists for designating the industrial development level of a fishery. It is often a judgment based on the size of the boats used in the fishery, the power of the engine, the type of gear and technology used, and the market for the catch. For this study, development levels (i.e., artisanal, semi-industrial, industrial or super-industrial) were generally taken from either peer-reviewed literature or grey literature. In a small number of cases, the development level was based on expert review of the data and comparison to other fisheries in the region. Fisheries with boat lengths greater than 50 m or horsepower greater than 10,000 hp were considered ‘super-industrial.’

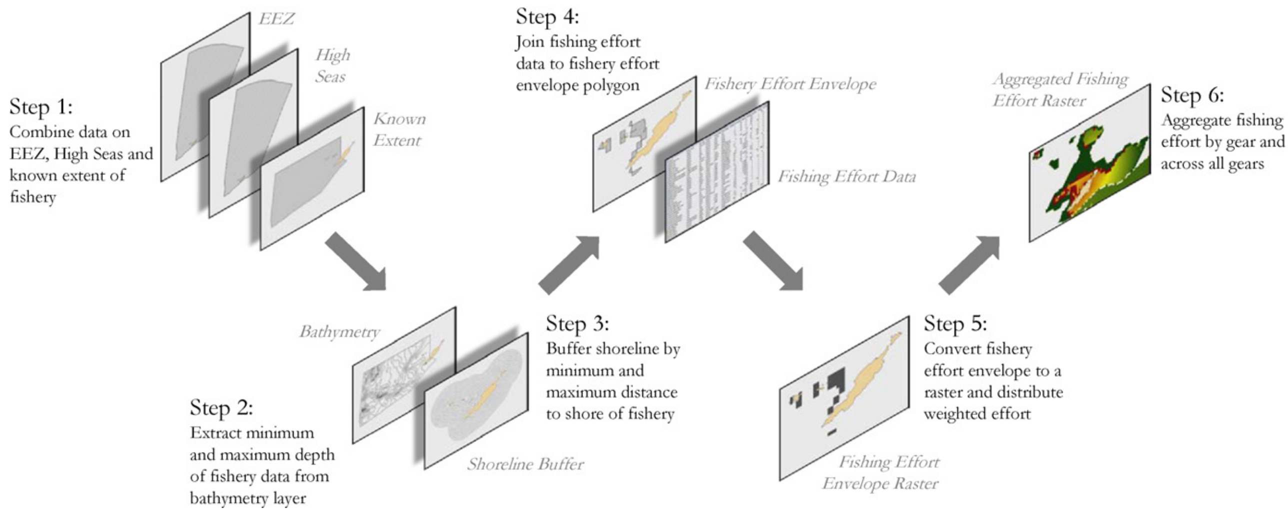

Fig. 1. Graphic representation of the FEET process.

2.3. Empirical models to predict boat length and number of vessels

Data on the number of vessels and average boat lengths for 94.4% and 64.8% of Caribbean fisheries, respectively, were generated through our literature search and expert review process. As previously mentioned, one of the main reasons for examining fishing effort on a regional scale is to allow inferences to be drawn from available data for fisheries for which no data exists. While previous studies based assumptions regarding the quantity of fishing effort on Gross Domestic Product (GDP) or Human Development Index (HDI; Chuenpagdee et al., 2006; United Nations Development Programme, 2007), we believe these methods rely on arbitrary measures and do not adequately account for inter- or intra-regional or gear-specific differences. Instead, we employed multiple linear regressions to create three empirical models to: (1) explain variation in the total number of artisanal boats per country, (2) to predict the number of boats in a given fishery, and (3) to predict average boat length in a given fishery.

The total number of small-scale boats in each country was modeled using HDI, GDP, per capita GDP, population size, length of coastline, area of continental shelf (≥ -200 m depth), whether the fishery was influenced by more productive southern Caribbean waters (see Appendix S1), and sub-region (i.e., insular Caribbean or mainland). The more specific model to predict the number of boats in individual fisheries included the same variables, as well as gear type and development level of the fishery. The predictive model of average boat lengths in individual fisheries was based on all the previous variables as well as a categorical (yes/no) variable to identify Cuban fisheries. The final Cuba variable was included after a preliminary assessment showed differences in boat length averages and standard deviations between Cuban and non-Cuban countries in the insular Caribbean. Although both models of boat numbers contained count data for their response variable, a Poisson distribution was not used because it did not fit the data well. Instead, the number of boats in each model was log-transformed (log 10) into a continuous variable. All continuous predictor variables were also log-transformed (log 10) to standardize their ranges, allowing for easier interpretation and comparison of model coefficients. Both models were run in R using the MASS and bootStepAIC packages (Venables and Ripley, 1999; R Development Core Team, 2004; Rizopoulos, 2008). A bootstrapped forwards and backwards stepwise multiple generalized linear regression was used and model selection was based on Akaike's Information Criterion (AIC; Akaike, 1973). This allowed n datasets to be simulated, taking a sample with replacement from the original dataset, and the model to be refit using the subsampled dataset. The stepAIC function was then called for each refitted model. The boot.stepAIC function does not produce a model object that can be manipulated, so the 'best' formula was rerun as a simple linear regression. From this model, R^2 were reported and missing values in the original dataset were predicted. The US & British Virgin Islands, Aruba and the Netherlands Antilles were removed from the model due to incomplete data. Colombia was removed from the small-scale fishery assessment during model-fitting because it was an outlier.

2.4. Fishing effort envelopes

In many developed fisheries, standardized reporting measures or vessel monitoring systems (VMS) are employed to determine the location of fishing effort. Due to the large number of boats in small-scale fisheries, low catch value per boat, and the dispersed and distant nature of these fisheries from centers of governance, spatially referenced fishing effort data are generally not available. In such circumstances, general details about the physical environment in which the fishery takes place is often the only information available on the location of the fishery. In this study we generated the first estimate of the physical location and density of fishing effort on a regional scale for the wider Caribbean.

We created envelopes around the potential area used by a fishery (i.e., 'fishing effort envelopes') in a 6-step process (Fig. 1) from information collected on the distance from shore and depth of each fishery. To automate this process, a tool was created (the Fishing Effort Envelope Tool; FEET), using Python (2008) and geoprocessing functions from ArcGIS 9.3 (Environmental Systems Research Institute, 2008). In step 1, a mask was created by intersecting the Exclusive Economic Zones (EEZ) and high seas areas used by the fishery, with the maximum possible extent of the fishery as determined through our literature review and discussions with experts. Then (step 2), data on the minimum and maximum depth at which the fishery operated was used to extract areas within the mask from the s2004 global bathymetric dataset (Marks and Smith, 2006). In step 3, minimum and maximum distance to shore data were utilized to buffer the shoreline for each fishery's corresponding territory based on the GSHHS v1.3 global shoreline dataset (Wessel and Smith, 1996). Next (step 4), the mask, bathymetry and shoreline layers were intersected to create a fishing effort envelope. In step 5, the fishing effort data was joined to the fishing effort envelope shapefile and area (km^2) and density (boat-meters/km^2) values were calculated. Finally, the polygon shapefiles were converted into

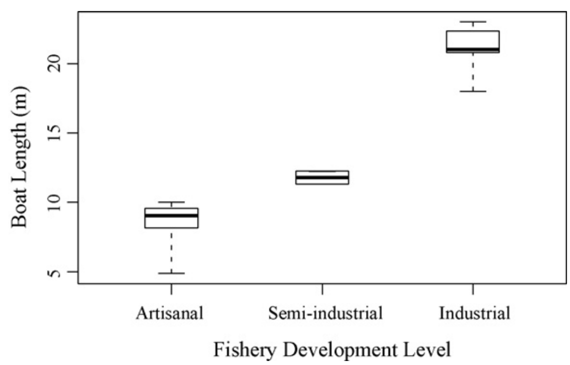

Fig. 2. Average boat lengths by gear type were significantly different for fisheries related to mainland and island countries in the wider Caribbean.

1 km gridcell rasters and effort was calculated for each cell based on an inverse distance weighting from the coastline. Total effort distributed across the raster was equal to the number of boat-meters calculated for each fishery. This process was repeated for every fishery for which some spatial data were available. Fishing effort envelopes were then aggregated into gear-specific regional rasters and one regional total fishing effort raster. Where possible, maps of the fishing effort envelopes were reviewed by fisheries experts within each country. Revisions to the fishing effort envelopes were made according to this expert input.

3. Results

Across the wider Caribbean, average boat lengths for artisanal, semi-industrial and industrial fisheries were 8.9 m (SD = 3.9, $n = 59$), 13.5 m (SD = 4.6, $n = 6$) and 20.4 m (SD = 3.3, $n = 14$), respectively. Average boat lengths for artisanal fisheries between the two sub-regions were found to be significantly different (i.e., between insular and mainland countries; $p = 0.0047$; Fig. 2). Significant differences were also found between Cuba and other insular Caribbean countries ($p = 0.0098$). These regional trends were incorporated into our models of total numbers of boats in small-scale fisheries and numbers of boats and boat lengths in each fishery by including sub-region (i.e., mainland/island) and Cuba (yes/no) as categorical variables in the multiple linear regression models.

3.1. Regression model results

The explanatory model of the total number of small-scale (i.e., artisanal and semi-industrial) boats in a country performed adequately (Multiple $R^2 = 0.73$, Adjusted $R^2 = 0.68$). Four variables were kept in the final stepwise regression model: per capita GDP, GDP, and two categorical variables identifying island fisheries and those in the southern Caribbean (Table 1). Per capita GDP had a strong negative effect, while GDP had a lesser positive effect on the number of boats. The sub-region (i.e., island vs. mainland) where the fishery was located and whether it was in the southern Caribbean both had a positive influence on the number of small-scale boats. Although a prior model that included population size had resulted in a better fit (Multiple $R^2 = 0.77$, Adjusted $R^2 = 0.72$), population and GDP are highly correlated in Caribbean countries (Pearson's correlation statistic = 0.89), and thus population was removed from the model.

Table 1
Stepwise multiple linear regression model of the number of small-scale boats per country.

Coefficients	Estimate	Std. error	*t* value	Pr(>|*t*|)	
(Intercept)	13.82159	1.44756	9.548	<0.001	***
factor(South)yes	0.62173	0.33901	1.834	0.07909	.
factor(Island)yes	1.59445	0.39413	4.046	<0.001	***
log(PerCapGDP)	−1.06346	0.17958	−5.922	<0.001	***
log(GDP_PPP)	0.51825	0.07906	6.555	<0.001	***

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1.
Residual standard error: 0.8226 on 24 degrees of freedom.
Multiple R^2: 0.726, Adjusted R^2: 0.6803.
F-statistic: 15.9 on 4 and 24 df, *p*-value: <0.001.

Table 2
Stepwise multiple linear regression model of the number boat lengths by fishery.

Coefficients	Estimate	Std. error	*t* value	Pr(>|*t*|)	
(Intercept)	9.404	0.6531	14.398	<0.001	***
FishDevLvlindustrial	11.499	0.7215	15.938	<0.001	***
FishDevLvlsemi-industrial	4.499	1.0979	4.098	<0.001	***
Islandyes	−4.327	0.7705	−5.615	<0.001	***
Southyes	0.787	0.5717	1.376	0.174	
Log_PCGDP	6.098	2.7935	2.183	0.033	*
Cubayes	11.419	1.2391	9.215	<0.001	***

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1.
Residual standard error: 1.998 on 63 degrees of freedom.
Multiple R^2: 0.8979, Adjusted R^2: 0.8882.
F-statistic: 92.38 on 6 and 63 df, *p*-value: <0.001.

The predictive regression model of the average boat length in any fishery performed very well (Multiple $R^2 = 0.90$, Adjusted $R^2 = 0.89$). The final model included fishery development level, sub-region, per capita GDP, whether it was a Cuban fishery, and whether the fishery occurred in the southern Caribbean (Table 2). A higher fishery development level increased the average boat length. Although higher per capita GDP also increased boat length, the larger standard error (SE) for this coefficient suggests that its inclusion in the final model may lead to higher SE in the predicted averages. The categorical variable for island fisheries indicated that they had a negative effect on boat length. Conversely, the categorical variable describing which fisheries were Cuban had a strong positive influence on average boat length. No adequate model was found to predict the number of boats in a given fishery. Through these empirical models we were able to fill data gaps in 27% of all fisheries in the Caribbean (44 fisheries). Thus we were able to compare fishing effort for 94.3% (116 of 123) of Caribbean fisheries.

3.2. Analysis of fishing effort

The output from the boat length regression model was used to fill an important data gap and perform an analysis of total fishing effort in the region. Known and predicted fishing effort (in boat-meters) were aggregated and summed across the region. Artisanal and industrial fisheries respectively accounted for 87% and 11% of fishing effort (boat-meters) in the region, while semi-industrial and super-industrial fisheries only accounted for 1% each (Fig. 3a). Mixed fisheries predominated in the region making up 62% of boat-meters across all fisheries, while longline fisheries accounted for 9% of all effort. Gillnet, trawl, trap and hook and line fisheries each accounted for 5–7% of fishing effort, and dive, and hook and line fisheries made up 1–3% individually (Fig. 3b). However, when we looked at the two sub-regions separately we found important differences in the breakdown of fisheries by development level. Mainland fishing effort was 77% artisanal and 19% industrial by boat-meter, while insular Caribbean fishing effort was more highly dominated by artisanal fisheries (i.e., 95% artisanal, 4% industrial, 1% semi-industrial; Fig. 4a and b).

Fishing effort density ranged from 0.002 to 118.5 boat-meters/km^2 for individual fisheries (Appendix S1). Twenty-seven fisheries had density levels higher than 1 boat-meter/km^2. Only one of those was an industrial fishery. Eight fisheries exhibited density

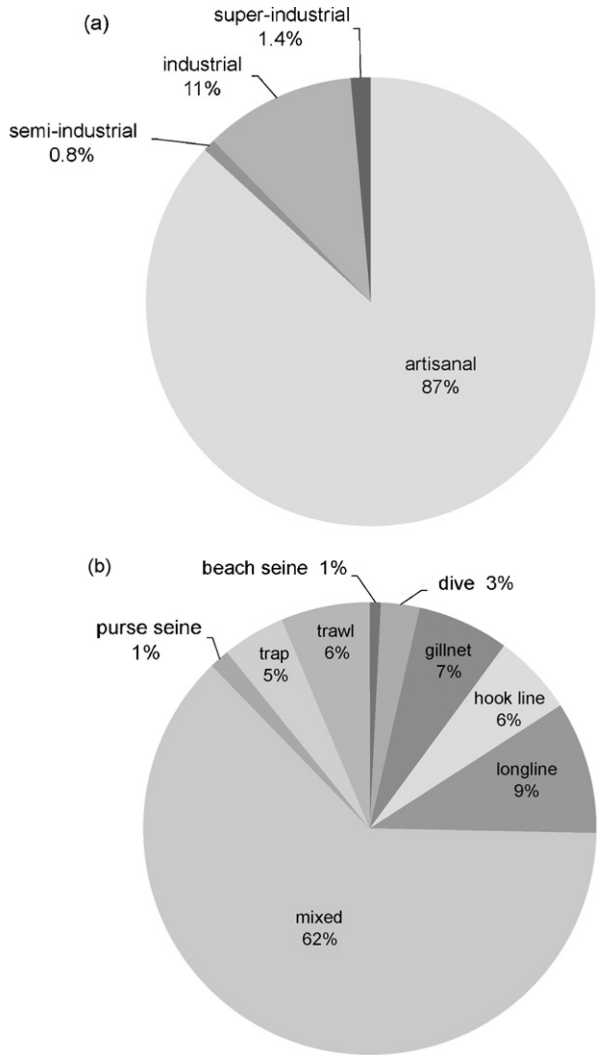

Fig. 3. Percentage of fisheries in the wider Caribbean by: (a) boat-meters by development level and (b) boat-meters by gear type.

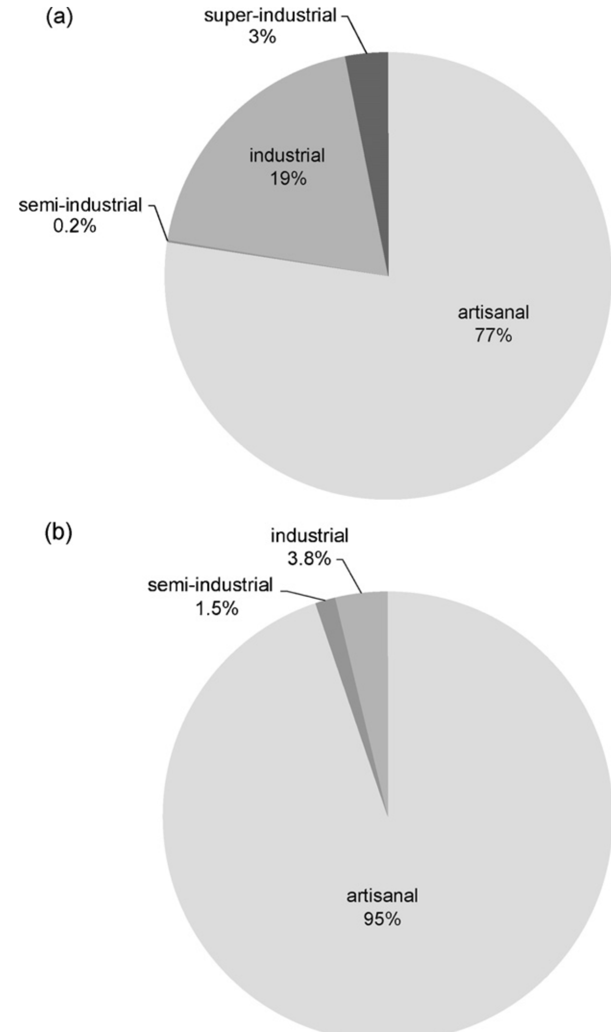

Fig. 4. Percentage of fishing effort by development level in: (a) Caribbean mainland countries and (b) Caribbean island countries.

levels greater than their average boat length, equating to a density greater than 1 boat/km^2. No correlation between gear type and density level was found. Based on inverse distance weighting from shore, aggregate fishing effort density for the wider Caribbean region ranged from 0 to 216.8 boat-meters/km^2. Maps of the density of fishing effort by individual gear types as well as by all gear types were generated for the wider Caribbean (Fig. 5; for individual gear maps see Appendix S2).

4. Discussion

4.1. Mainland vs. island fisheries

Clear differences in fishing were observed between mainland and island fisheries. As expected, there were differences in average boat length across gear types and among fishery development levels. There was also a large discrepancy between the percentages of fishing effort exerted by each development level between island and mainland fisheries (Fig. 4a and b). As GDP and per capita GDP were significant explanatory variables of the number of small-scale boats per country, it seems logical to assume they might have some bearing on the difference in the ratio of artisanal to industrial fishing effort. Gross Domestic Product had a positive coefficient in the model. This is likely related to the correlation between population size and GDP, as a larger population intuitively indicates more fishers and more boats. Average GDP for mainland countries in 2006 was US$111.042 billion, while that of island countries (not including overseas territories) was only US$6.907 billion (International Monetary Fund, 2009). However, GDP for many mainland countries was less than or equal to the island average. Further, mainland countries with GDP less than or equal to the island average showed no significant difference in the ratio of artisanal to industrial fishing or average boat lengths from other mainland countries. Thus GDP would appear to have little explanatory power with regard to the difference in the ratio of artisanal to industrial fishing between the islands and the mainland.

Per capita GDP had a negative influence on the total number of small-scale boats. This is logically explained when we consider that higher per capita GDP indicates a more highly developed country and economy, which would likely include more developed fisheries. More industrial fisheries (i.e., more technically developed fisheries) are generally characterized by fewer but larger boats with greater fishing effort capacity. However, per capita GDP for insular Caribbean countries is on average more than twice that of mainland countries (US$7986 and US$3603 respectively; IMF, 2009). Thus, the use of per capita GDP to explain the differences in the ratio of artisanal to industrial fishing is illogical, as it suggests an inverse relationship between the development level of a country and the development level of its fisheries.

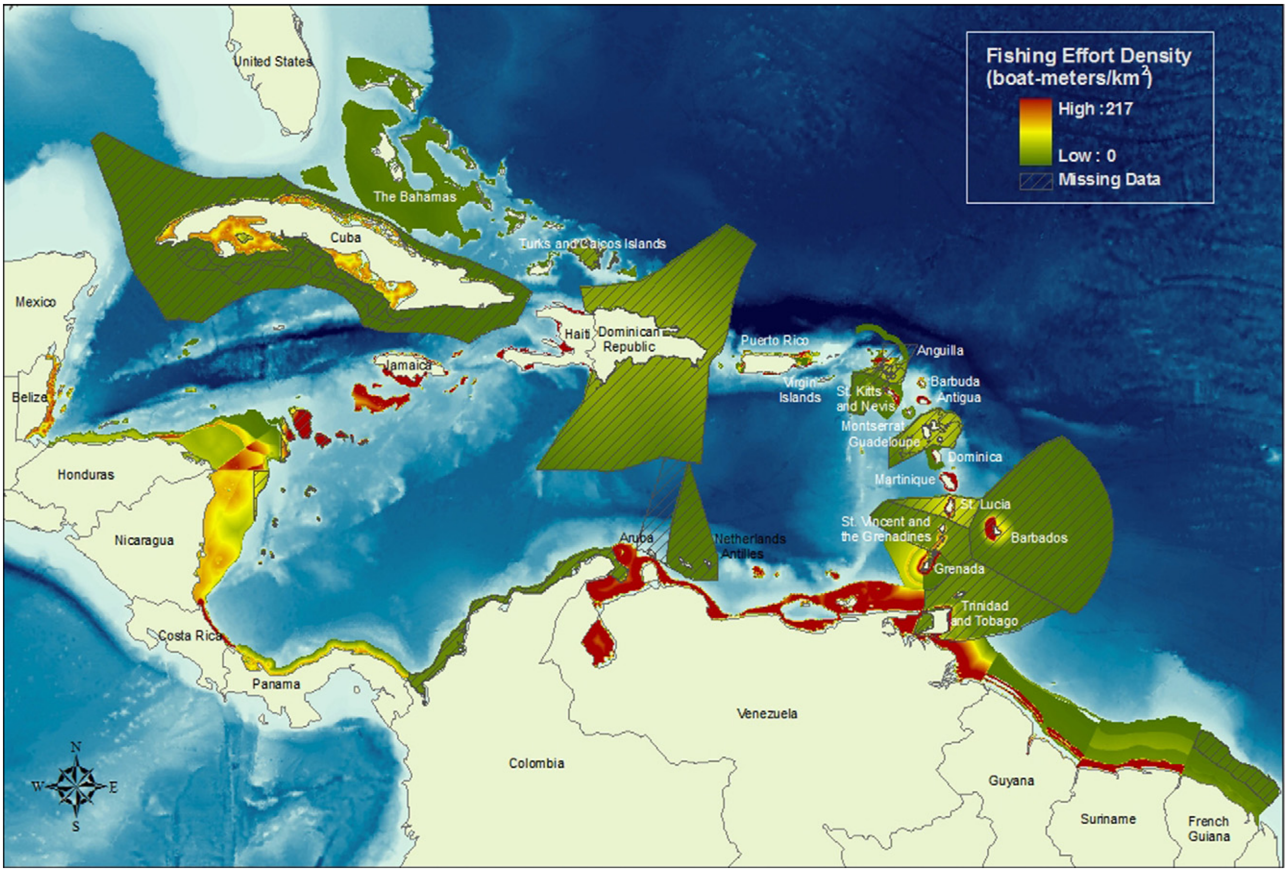

Fig. 5. Aggregated coastal fishing effort in boat-meters across all gears and development levels in the wider Caribbean.

A better explanation stems from the numerous obstacles to the development of fisheries faced by Caribbean island nations and territories. There is significant disparity in the availability of natural resources and production facilities for fishing supplies between island and mainland countries. Limited boat-construction capacity for mid-sized (>12 m) or fiberglass fishing vessels within the insular Caribbean restricts development and forces fishers to import such boats from outside the region (Mahon and McConney, 2004). Similarly, fishing gear itself is also generally imported, as demand has not reached the critical mass necessary to support manufacturing facilities in most countries (Mahon and McConney, 2004). The cost of importing larger vessels and gear (including prohibitive importation taxes) likely prevents further development of artisanal fisheries in the insular Caribbean.

Cuba represented an anomaly within the insular Caribbean. Atypically high standard deviations in the average boat lengths of all island fisheries were the result of greater than average boat length values for all fisheries in Cuba. Further investigation is needed to better understand why these fisheries, although still considered artisanal by the Cuban government, may be more developed than others in the region. The island's size and greater natural resources for shipbuilding may have contributed to the current discrepancy. Restrictions on emigration and boat ownership may also contribute to the larger boat sizes.

4.2. Further model interpretation

The model of the number of small-scale boats per country was positively influenced by whether the fishery was in the southern Caribbean. This is likely due to the higher productivity of the southern waters (Richards and Bohnsack, 1990) supporting more fishers. The high productivity of this region and the larger shelf area affect the types of fisheries and thus the size of the boats used. It is likely that catch value, stemming from these factors, has driven increases in exports, thus further incentivizing capacity expansion within these fisheries. We recommend that catch value, export value and productivity variables be included in any future attempts to model fishing effort.

The regression model that was fit to predict average boat lengths in a given fishery performed very well. As expected, increases in boat length were associated with each higher development level (i.e., artisanal vs. semi-industrial vs. industrial). The model also confirmed that island fisheries had a negative effect on the size of boats (see mainland vs. island discussion above), and that Cuba had anomalously large boats. Also, as expected, the more productive southern Caribbean waters had a positive influence on boat length. The last variable kept in the final model, per capita GDP, had a strong positive effect on predicted boat lengths. As mentioned previously, this result is fairly intuitive as countries with higher per capita GDP (i.e., more developed countries) would likely also have more highly developed fisheries, leading to increased boat lengths.

4.3. Fishing effort densities in the wider Caribbean

The density of fishing within coastal areas of the wider Caribbean varies greatly (0–217 boat-meters/km^2; Fig. 5). The estimated densities are directly influenced by the accuracy of the spatial data obtained for each fishery; the more accurate the data, the more intense the fishing appears to be. For instance, the Montserrat artisanal finfish beach seine fishery is defined as being within 1.6 km of shore. The three 6-meter boats in this fishery thus operate in a 2 km^2 area, resulting in a high density of 8.6 boat-meters/km^2. This is a far different scenario than the 3731 6-meter boats that operate in the artisanal mixed-gear lobster, pelagic and finfish fishery in the Dominican Republic. Little spatial data is available on where this fishery operates and thus we could only delimit it by the countries' EEZ, an area of 255,018 km^2. The result is a deceptively low density of fishing (0.09 boat-meters/km^2). As such, it is necessary to differentiate between those fisheries that have good spatial data and those that do not when drawing conclusions. For this reason, we have broken out the results of this analysis into three sections: high density, high resolution fisheries (i.e., well defined spatially); high density, medium resolution fisheries, and high density, low resolution fisheries (i.e., no spatial data).

Dominica, Puerto Rico, Trinidad and Tobago, Grenada, St. Kitts and Nevis, Antigua and Barbuda, and St. Lucia all have high density, high resolution fisheries. The impact these fisheries should be examined more closely to ensure overfishing in these confined areas is not occurring. Haiti, Martinique, Suriname, and Guyana all have at least one high density, medium resolution fishery. These fisheries are relatively well defined, but still span large areas (>1000 km^2) and have high densities of fishing effort. As such their impacts are likely far greater than the high density, high resolution fisheries and they warrant more immediate attention to mitigate potential ecological impacts. Venezuela, Nicaragua, the Dominican Republic, Jamaica, and Cuba all have high density, low resolution fisheries that require further spatial data collection to better define the extents of the fisheries operating within their EEZs. These are the largest artisanal fisheries in the Caribbean (generally >2500 boats), yet we seem to know the least about them. It is imperative that we begin to collect fishing effort and spatial data on these fisheries to begin to understand their true extent and impact.

Venezuela, Trinidad and Tobago, Suriname, and Guyana all have multiple high density fisheries. Overlap of these fisheries results in poorly understood cumulative impacts on the ecosystem. We encourage fishery managers within the region to use the maps in this study to identify priority areas of overlapping fishing effort (e.g., waters in Guyana ~18 m depth and ~30 km from shore where three fisheries may be operating).

The effect of different types of fishing gear is not uniform (Dayton et al., 1995). It is therefore important to not only look at the overall density of fishing effort, but to understand the density of fishing effort by gear. High density levels of trawl fishing in Trinidad and Tobago and Guyana are of concern due to the destructive impact of this gear on benthic environments (Watling and Norse, 1998; National Research Council, 2002). The low selectivity and high mortality rates for bycatch in bottom-set gillnets represent another threat to coastal ecosystems (Jefferson and Curry, 1994; Zydelis et al., 2009). High density gillnet use in Trinidad and Tobago, Guyana, Suriname, Barbados and Puerto Rico could have serious impacts for non-target species and coastal marine megafauna. The lack of specific information on the gear types used in 'mixed' fisheries should not be assumed to mean that these fisheries necessarily have a lower impact on the marine ecosystem. Thus, we recommend further study of mixed fisheries in Dominica, Haiti, Martinique, St. Kitts and Nevis and Suriname due to high densities of fishing effort in these fisheries. It is also important to note that destructive gears may be used in these fisheries, even though they are not represented in the individual gear maps (see Appendix S2). Thus any discussion of the distribution of destructive gears must include the possibility that these gears are being used in mixed fisheries. For this reason, better data is needed for all mixed fisheries so that we can fully understand their impacts.

4.4. The real scale of small-scale fisheries

Although much attention has been focused on the effects of modern industrialized fishing on fish stocks, habitats and ecosystems, small-scale fisheries have thus far not received the same attention. The general perception has been that the efficiency with which industrial fisheries are able to catch target species, and the vast quantities of gear deployed by industrial boats, represent far greater threats to ecosystem dynamics and fish stock levels than diffuse fisheries with many small boats that hold orders of magnitude less gear. However, few studies have sought to quantify small-scale fishing on regional or even country-wide scales. Thus it has been extremely difficult to make comparisons between fishing effort exerted by different fishery development levels. In this study, we offer the first regional assessment of the magnitude of fishing by fishery development level for the wider Caribbean.

The insular Caribbean is dominated nearly 9:1 by artisanal fisheries (by boat-meter). However, the ratio of the amount of gear deployed to boat length may be significantly smaller for artisanal boats than industrial vessels. Thus, the actual ratio of artisanal to industrial fishing effort is likely to be less than 9:1. Regardless, artisanal fleets represent a major component of, if not the vast majority of, fishing effort in the Caribbean. It is important to note, that the potential ecological effects of artisanal fisheries are significantly increased by the smaller area in which these fisheries generally operate (i.e., the continental shelf or territorial seas; see distance to shore data in Appendix S1; FAO, 2009). These coastal areas are also more directly subject to many other environmental pressures (e.g., pollution, eutrophication, development, recreational sports), and thus may be more vulnerable to the ecological consequences of fishing. Tropical artisanal fisheries likely pose a substantial risk to marine megafauna that have life-history stages associated with coastal habitats (e.g., sea turtles, manatees, dugongs). The lack of selectivity in the gear used, the absence of bycatch mitigation measures, and the difficulty of monitoring these fisheries may be resulting in undesirable bycatch levels in some areas (D'Agrosa et al., 2000; Peckham et al., 2007). There are, however, a number of mitigating factors that require further investigation before we can fully understand the ecological ramifications of artisanal fishing. Specifically, further research should be done on the ecological impact to trophic dynamics of non-selective gears and near-zero discard-rates (as nearly all fish that are caught are kept). Finally, the same limited extent of most artisanal fishing that makes it a risk to coastal marine megafauna may also prevent this effort from being applied in open ocean areas and limit the risk to sensitive deep-water habitats, and endangered marine mammals and sea birds that forage or migrate through those areas.

4.5. Future directions

If the ratio of artisanal to industrial boat-meters in the insular Caribbean fisheries is similar to those in other developing regions (e.g., Equatorial Africa, South and Southeast Asia), then we must begin to consider the possibility that global artisanal fishing effort is at least equal to that employed by industrial fisheries. As such, more quantitative regional studies on fishing effort in developing areas are needed to determine the true global ratio of fishing effort employed by different development levels. Given our lack of knowledge regarding the ecological effects of artisanal fishing, the ramifications of this scenario are almost entirely unknown. Thus, it is imperative that further research be conducted on the effect of non-selective, low discard, multi-gear fisheries on tropical food webs and benthic complexity. Overlaying the fishing effort envelopes created in this study on maps of habitat types (e.g., hardbottom, sand, seagrass beds) would also help us to begin to understand the ecological effects of these fisheries. These habitats have been catalogued (e.g., Wabnitz et al., 2008) and are available online (e.g., World Resources Institute; http://www.wri.org). Habitats and areas not previously mapped may be predicted at regional scales (Dunn and Halpin, 2009), allowing for rapid assessments to be done. The distribution of fishing effort could also be further refined by taking into account persistent oceanographic and weather conditions. To ensure our analysis can be easily repeated in other regions, the Fishing Effort Envelope Tool is in the process of being implemented as a component of the Marine Geospatial Ecology Tools (Roberts et al., 2008), an open-source geoprocessing toolbox available online (http://mgel.env.duke.edu/tools).

It is essential that we dedicate far more resources to improving data collection and monitoring in developing regions to overcome the data gaps exposed in this study and to move beyond models of fishing effort to known quantities. A first step toward achieving a higher resolution understanding of artisanal fishing effort in the Caribbean would be to gather data on the amount of gear deployed (e.g., number of hooks, or number and length/depth of nets) by coastal artisanal fisheries. The fishing effort values presented in this study have no temporal component. As the lengths of fishing seasons vary greatly, the addition of time into the fishing effort metric would greatly improve the accuracy of estimates of the density of fishing effort. A parallel effort must be put forward to ensure that we improve estimates of illegal, unregulated or unreported (IUU) fishing effort so that it can be included in total estimates of fishing effort. Consideration of shore-based and subsistence fishing, and of populations that have traditionally been marginalized and unaccounted for in country or regional statistics (e.g., women and children), is also necessary in any comprehensive estimate of fishing effort (Chuenpagdee et al., 2006). Only by addressing all of these issues can we fully understand the impact of the distribution and intensity of fishing across the wider Caribbean.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.fishres.2009.10.010.

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