frontiers in Marine Science

ORIGINAL RESEARCH
published: 11 August 2021
doi: 10.3389/fmars.2021.707999

Fishing Effort and Associated Catch per Unit Effort for Small-Scale Fisheries in the Mozambique Channel Region: 1950–2016

Dirk Zeller[1]*, *Gabriel M. S. Vianna*[1], *Matthew Ansell*[1], *Angie Coulter*[2], *Brittany Derrick*[2], *Krista Greer*[2], *Simon-Luc Noël*[2], *Maria L. Deng Palomares*[2], *Audrey Zhu*[2] and *Daniel Pauly*[2]

[1] Sea Around Us – Indian Ocean, School of Biological Sciences and Oceans Institute, University of Western Australia, Crawley, WA, Australia, [2] Sea Around Us, Institute for the Oceans and Fisheries, University of British Columbia, Vancouver, BC, Canada

OPEN ACCESS

Edited by:
Mhd Ikhwanuddin,
University of Malaysia Terengganu,
Malaysia

Reviewed by:
Valeria Mamouridis,
Independent Researcher, Rome, Italy
Appukuttannair Biju Kumar,
University of Kerala, India

***Correspondence:**
Dirk Zeller
dirk.zeller@uwa.edu.au

Specialty section:
This article was submitted to
Marine Fisheries, Aquaculture
and Living Resources,
a section of the journal
Frontiers in Marine Science

Received: 11 May 2021
Accepted: 12 July 2021
Published: 11 August 2021

Citation:
Zeller D, Vianna GMS, Ansell M,
Coulter A, Derrick B, Greer K,
Noël S-L, Palomares MLD, Zhu A and
Pauly D (2021) Fishing Effort
and Associated Catch per Unit Effort
for Small-Scale Fisheries
in the Mozambique Channel Region:
1950–2016.
Front. Mar. Sci. 8:707999.
doi: 10.3389/fmars.2021.707999

The Mozambique Channel region in East Africa has diverse marine ecosystems and serves as a migratory corridor for economically important species. Local and foreign industrial fisheries operate in the Mozambique Channel, but regional small-scale fisheries are the crucially important fisheries that provide food security, livelihoods, and economic opportunities for rural coastal communities. This study reconstructed and investigated trends in the fishing effort and catch per unit effort (CPUE) of small-scale marine fisheries in four Exclusive Economic Zones (EEZ) that constitute the Mozambique Channel, i.e., Union of Comoros, Madagascar, Mayotte, and Mozambique, from 1950 to 2016. Effective fishing effort for small-scale fisheries in the form of fishing capacity in kWdays (i.e., kilowatt days) was derived using the number, length, motorization (engine power) by fishing vessels, as well as an approximate human-powered equivalent for shore-based fishers without vessels, as well as days of fishing per year. Effective small-scale fishing effort in the Mozambique Channel increased by nearly 60 times from just over 386,000 kWdays in 1950 to over 23 million kWdays in 2016. Correspondingly, the overall small-scale CPUE, based on previously and independently reconstructed catch data declined by 91% in the region as a whole, from just under 175 kg·kWday^{-1} in the early 1950s to just over 15 kg·kWday^{-1} in recent years. All four EEZs showed the strongest declines in the small-scale CPUE in the earlier decades, driven by motorization and growth in vessel numbers impacting effective fishing effort. Increased motorization combined with a substantial growth in overall vessel numbers were the drivers of the increasing fishing effort and decreasing CPUE, and clearly suggest that continuing to increase the fishing capacity of small-scale fisheries in the absence of effective and restrictive management actions may exacerbate overexploitation risk.

Keywords: artisanal fisheries, CPUE, fishing capacity, Madagascar, Mayotte, Mozambique, subsistence fisheries, Union of Comoros

INTRODUCTION

The Mozambique Channel region in East Africa separates Madagascar from the African continent (**Figure 1**) and is characterized by high marine biodiversity and a variety of ecosystems, including a large proportion of the Indian Ocean's coral reefs, mangroves, and seagrass beds (Nunes and Ghermandi, 2015). It is also an important corridor for migratory species, such as tuna (Nunes and Ghermandi, 2015). The four countries/territories directly associated with the Mozambique Channel region, namely the Union of Comoros, Madagascar, Mayotte, and Mozambique all heavily depend on small-scale domestic fishing (artisanal and subsistence fishing). For example, the Comoros lacks domestic industrial fisheries and an aquaculture sector (FAO, 2015a); however, between 2005 and 2009, domestic marine fish resources accounted for 60–70% of the animal protein consumed by Comoros islanders (Béné and Heck, 2005; Kurien and López Ríos, 2013; Breuil and Grima, 2014a). For Madagascar, the Food and Agriculture Organization of the United Nations (FAO) reports that the small-scale fishing fleet was responsible for over half of total domestic marine fish catches in 2008 (FAO, 2009). Despite their importance to food security and local livelihoods, small-scale fisheries catches in the region have been widely underreported (Jacquet et al., 2010; Le Manach et al., 2012b; Genay and Merceron, 2017; Anon, 2019c). For example, the reconstructed catch data of the *Sea Around Us*,[1] which complement officially reported data with comprehensive estimates of unreported catches (Zeller et al., 2016), suggest that small-scale catches in Madagascar actually may account for over 80% of the total domestic marine fish catch (Le Manach et al., 2012b), as opposed to the 53% suggested by FAO (2009) based on officially reported data. The underrepresentation of small-scale fisheries is a common issue globally, which contributes to the marginalization in socio-economic and political considerations (Pauly, 2006; Schuhbauer and Sumaila, 2016; Teh et al., 2020) as well as in official statistics (Pauly and Charles, 2015; Zeller et al., 2015; Pauly and Zeller, 2016a), despite more recent efforts to begin addressing this issue (FAO, 2015b).

Since 1950, the coastal populations of the four inhabited countries/territories associated with the Mozambique Channel have increased, and marine catches have correspondingly also grown (Jacquet et al., 2010; Le Manach et al., 2012b; Doherty et al., 2015a,b; Genay and Merceron, 2017). The exceptions are the uninhabited islands of Juan de Nova, Europa, and Bassas da India that are territorial possessions of France, here referred to as the "Mozambique Channel Isl. (France)" (**Figure 1**). These waters are not fished by "domestic" fleets due to the uninhabited nature of the islands, but are accessed by fishers from surrounding areas as well as by distant water fleets (Le Manach and Pauly, 2015). Given the crucial importance of locally sourced seafood for domestic food security and nutrient security for the Mozambique Channel region, demand will likely continue to increase. However, official fisheries statistics describing the small-scale fisheries catches in this region remain limited.

Historically, FAO presumed that small-scale artisanal and subsistence fishers were likely only temporary features during an anticipated transition to industrial fisheries (Panayotou, 1982). Therefore, institutional and political support had been, and often still is, skewed toward large-scale (i.e., industrial) fisheries due to perceived higher direct macroeconomic contributions to national or government income (Zeller and Pauly, 2019). As such, industrial fisheries often have easier access to subsidies, including subsidized development loans (Panayotou, 1982; Harper et al., 2012; Bellmann et al., 2016; Sumaila et al., 2019). More recently, the international community began to recognize the crucial nutrient security and food security, livelihood, and socio-economic importance of small-scale fisheries (FAO, 2015b; Golden et al., 2016; Teh et al., 2020; Vianna et al., 2020), although officially reported statistics as published by the FAO on behalf of countries continue to be hampered by an absence of fishing sector differentiation (Pauly and Charles, 2015). In contrast, such sectoral differentiation is an integral and core feature in the *Sea Around Us* reconstructed catch data for all countries (Pauly and Zeller, 2016a,b), which allows for a more accurate and comprehensive examination of the importance of small-scale sectors at the country, regional and global level (Zeller and Pauly, 2019), including their economic importance (Zeller et al., 2006).

Here, a data reconstruction approach based on Zeller et al. (2016) was used to derive time series estimates of small-scale fishing effort from 1950 to 2016 for each of the four inhabited Mozambique Channel countries/territories. These effort estimates were then combined with independently reconstructed small-scale catch data from the *Sea Around Us* for each of these countries/territories (Pauly and Zeller, 2016a,b) to derive small-scale catch per unit effort (CPUE) estimates for the same time period.

MATERIALS AND METHODS

In this study, small-scale fishing effort for each country/territory was reconstructed using the same general data reconstruction approaches and principles as used earlier and independently by the *Sea Around Us* for catch data reconstruction (Zeller et al., 2016). Data reconstructions essentially aim to complement officially reported data with best estimates of unreported components, using a wide variety of secondary data and information sources combined with carefully vetted and clearly stated, conservative assumptions (Zeller et al., 2016). To ensure independence of the two key datasets being used here (small-scale catches and fishing effort), fishing effort was reconstructed without considering previously reconstructed small-scale catch data in each country (Pauly and Zeller, 2016a,b).

Study Area

The Mozambique Channel region (IHO, 1953) lies between the East African coast and the west coast of Madagascar (**Figure 1**). The northern boundary of the channel is marked by the estuary of the River Rovuma in Mozambique (10.46° S and 40.43° E) and the north west point of Grande

[1] www.seaaroundus.org

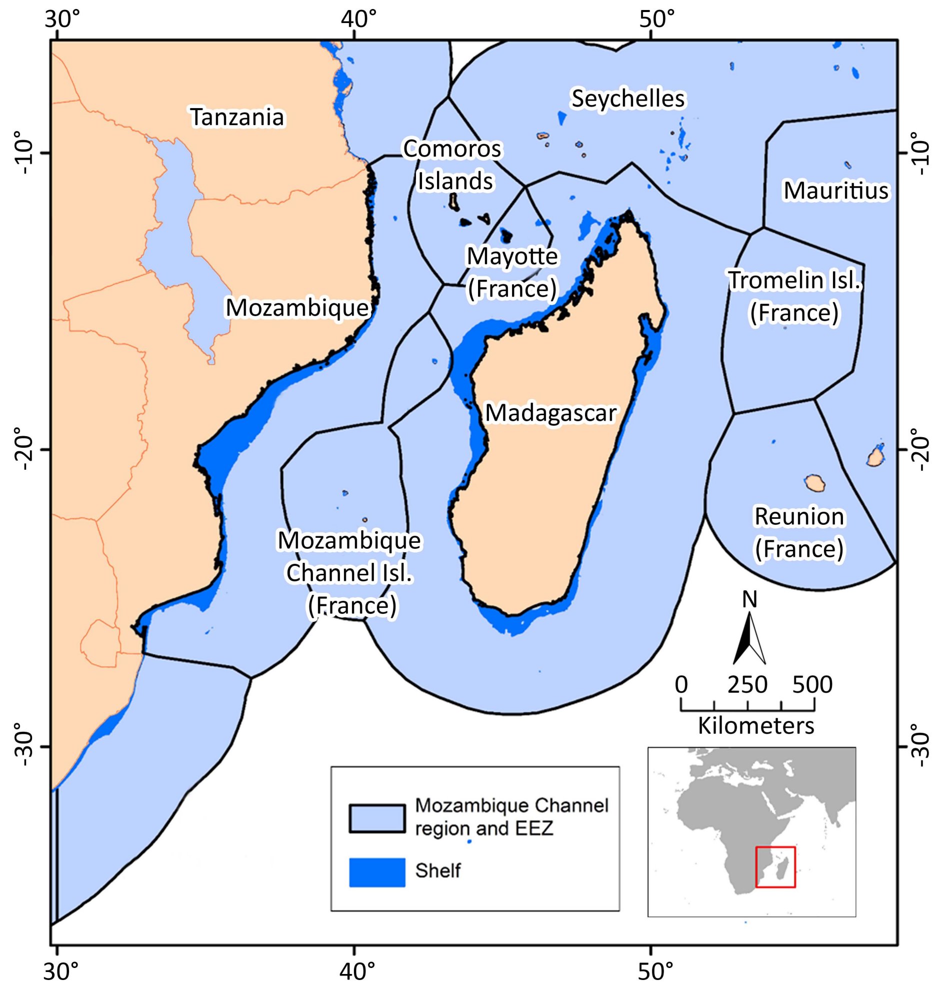

FIGURE 1 | The Mozambique Channel region and the EEZs of the countries or territories considered here: Union of the Comoros, Madagascar, Mayotte, and Mozambique. The uninhabited Mozambique Channel Islands administered by France are indicated as well, but have no domestic, resident small-scale fisheries and thus no resident small-scale effort or catches.

Comore/Ngazidja (the northernmost island of the Comoros Isl. Group; 11.95° S and 49.28° E). The southern boundary of the channel runs from the southern tip of Madagascar to Ponta do Ouro, Mozambique (26.88° S and 32.93° E). Within the channel, there are five Exclusive Economic Zones (EEZs): Union of Comoros Islands, Madagascar, Mayotte, Mozambique, and the minor Mozambique Channel Islands, comprising the uninhabited French dependencies of Juan de Nova, Bassas da India, and Europa Islands (**Figure 1**).

The focus of this study was on small-scale domestic fisheries by resident fishers, and included the EEZs of the Union of Comoros, Madagascar, Mayotte, and Mozambique. The French dependencies here referred to as the Mozambique Channel Islands are uninhabited, and therefore by the definition of small-scale sectors used here (Zeller et al., 2016) have no locally based domestic small-scale fleets, and thus did not contribute to this study. However, their waters are being fished by neighboring countries, including by artisanal and recreational vessels, as well as French and distant-water industrial fleets (Le Manach and Pauly, 2015).

Boat-Based Fishing Effort

Nominal fishing effort (kW), as defined in this study, is the product of total small-scale fleet capacity. A fleet is the number of vessels with a similar capacity, i.e., in the same length class and motorization category, and utilizing the same or similar fishing gears. Engine capacity per fishing vessel (kW) in a given fleet was determined by length and motorization (**Table 1**). Thus, total nominal fishing effort is the product of the engine capacity and the number of boats operating within a fleet segment in a given year. Non-motorized vessels were considered to have equivalent capacity of 0.37 kW·vessel^{-1} for vessels of length class 1 and 0.75 kW·vessel^{-1} for vessels of length class 2 (**Table 1**), based on Greer et al. (2019a).

Effective fishing effort (kWdays) is the product of nominal fishing effort (engine capacity × number of boats within a fleet segment) in kW and the number of days spent fishing per year.

The number of days spent fishing per year (i.e., fishing trip days) for each fleet segment was a major aspect of the research in this project (see country details in **Supplementary Material**). Unfortunately, there was a notable knowledge and data gap in this metric in the literature, thus requiring conservative assumptions to be able to derive likely time series for fishing days. If no specific data were found for a given fleet segment, conservative assumptions, and approximations were used to derive an average number of fishing trip days per year. Due to the generally low technological development of most small-scale vessels in the Mozambique Channel region, we did not apply a "technology creep" factor to our effort estimates (Palomares and Pauly, 2019).

Shore-Based Fishing Effort

Fishing and seafood collecting from shore without the use of a boat, often largely conducted by women, is a regular activity in many parts of the study region and globally (Harper et al., 2013, 2020; Zeller et al., 2015). Given its widespread existence, this fishing component needs to be accounted for in the estimation of overall small-scale fishing effort.

The *nominal fishing effort* or fishing capacity of one shore-based fisher is assumed to be approximately 0.08 kW of engine equivalence per work (fishing) day (Krendel et al., 2007). Thus, shore-based fishing activities were converted to the equivalent nominal fishing effort (kW) by multiplying the number of shore-based fishers by their assumed engine equivalency of 0.08 kW (**Table 1**).

Effective fishing effort (kWdays) was calculated by multiplying the nominal fishing effort for shore-based fishers with the average number of days per year for which fishing from shore occurred. Fishing days for shore-based fishers were determined from country-specific sources wherever available (see country details in **Supplementary Material**). If no specific data were found for a given country, conservative assumptions, and approximations were used to derive an average number of fishing trip days per year. We recognize that shore-based fishers do not necessarily fish all day, i.e., for a full "work day," with regards to the engine equivalency used above. However, as we remained conservative in our estimation of the number of shore-based fishers throughout, we consider our assumption of a full work day engine power equivalency for shore-based fishers to be an acceptable approximation.

TABLE 1 | Assumed and derived engine capacity of motorized and non-motorized fishing vessels by length class for small-scale vessels based on Greer et al. (2019a), as well as engine capacity-equivalency for shore-based fishers.

Length class	Length (m)	Mean length(m)	Capacity (kW)	
			Motorized	Non-motorized
1	<7.9	4.5	9.11	0.37
2	8–15.9	11.3	58.70	0.75
Shore-based	NA	NA	NA	0.08

Length classes over 15.9 m were considered to be industrial vessels and thus not used here.

Country Details

Union of Comoros

Prior to gaining independence in 1975 as the Union of Comoros, the Comoros Archipelago was a French colony. The Comoros Archipelago includes the island of Mayotte, which remains a French colony and is thus examined separately (see **Figure 1** and below). The population of the Union of Comoros is concentrated on three islands: Ngazidja in the northwest, Mwali, located centrally, and Nzwani in the east (**Figure 1**). Comoros declared its 165,000 km^2 EEZ in 1976, and has an *Inshore Fishing Area* of around 1,500 km^2.[2] *Inshore Fishing Areas* are defined as the area that extends from shore to either 50 km offshore or to the 200 m depth contour, whichever comes first (Chuenpagdee et al., 2006). *Inshore Fishing Areas* are thought to represent the majority coastal sea-space along inhabited coastlines within which small-scale fisheries would likely operate (Chuenpagdee et al., 2006; Chuenpagdee, 2011).

Approximately 18% of the population of Comoros was estimated to live below the international poverty line in 2014 (Anon, 2019a). Marine fisheries are crucially important for food security, and exports and imports of fish products are limited, thus most fish are consumed directly in the country (FAO, 2015a). Comoros does not have a truly domestic industrial fleet, or distinct recreational fishing. Fishing is characterized by small-scale artisanal and subsistence activities of local fishers, predominantly using hand lines, gillnets and surface nets.

The detailed estimation methods for the small-scale fishing effort are presented in **Supplementary Material**. There were several data sources stretching back to the mid-1950s for the number of small-scale fishing vessels in the Comoros, with motorization starting in the late 1970s (**Supplementary Table 1**). Several types of vessels are used in the Comoros: the more traditional motorized or non-motorized *pirogues* of up to 7 m length, or the more modern motorized *vedettes* of between 6 and 12 m in length. Data on shore-based fishers was limited, and required assumptions to estimate shore-based fishing activity (**Supplementary Table 2**). Women actively fish and collect seafood (i.e., gleaning) from shore in the Comoros (Hauzer et al., 2013), which we estimated as part of total shore-based effort (**Supplementary Table 2**).

Madagascar

Madagascar represents the eastern boundary of the Mozambique Channel (**Figure 1**), with an EEZ of over 1.2 million km^2 and an *Inshore Fishing Area* (Chuenpagdee et al., 2006) of over 113,000 km^2.[3]

Until its independence in the 1960s, Madagascar was a French colony. Madagascar's political history since then has been marked with multiple regime changes, and the country remained politically unstable (Ploch and Cook, 2012). There is a high rate of poverty, with an estimated 75% of the population living under the international poverty line in 2018 (Anon, 2019b). Although the east is more densely populated, most of the fishing is conducted off the west coast (Le Manach et al., 2012b). In

[2] www.seaaroundus.org/data/#/eez/174
[3] www.seaaroundus.org/data/#/eez/450

Madagascar, marine fishing is an important source of food and exports, particularly in coastal areas where agriculture cannot or is not practised (Le Manach et al., 2012b).

The small-scale fishing sector consists of fishers on foot as well as "traditional" boat-based fishing in wooden dugout canoes (these can be motorized), with both these components engaging in artisanal as well as subsistence fishing. Locally, the artisanal sector is considered to include motorized boats with engine power up to 50–60 HP, including shrimp trawlers and "catchers," dories and collection vessels for fisheries products such as sea cucumbers (Andrianaivojaona et al., 1992; ASCLME, 2011). Although the FAO/Indian Ocean Commission's *Smartfish* program consider smaller shrimp trawlers to be artisanal (Andrianaivojaona et al., 1992; Mngulwi, 2006; Breuil and Grima, 2014b), the *Sea Around Us* follows the definition of Martín (2012) and classifies all trawler catch as being industrial regardless of vessel size (Zeller et al., 2016). Therefore, shrimp trawlers were not included in the calculation of small-scale fishing effort and CPUE in this study.

The detailed estimation methods for the small-scale fishing effort are presented in **Supplementary Material**. There were several data sources for the number of fishing vessels in Madagascar, stretching back to the mid-1960s, with motorization starting in 1970 (**Supplementary Tables S3, 4**). A substantial number of people in Madagascar fish without boats (Andrianaivojaona et al., 1992; Breuil and Grima, 2014b), and the number of shore-based fishers over time was assumed to correlate to the total Madagascan population (**Supplementary Table 3**). There was very little information on the number of days fished per year by small-scale vessels in Madagascar, with reports from the 1980s suggesting between 150 and 220 days per year (Rey, 1982), while shore-based fishers were thought to fish around 20 days per month in 2009 (Barnes and Rawlinson, 2009) or 240 days per year (**Supplementary Table 5**).

Mayotte

Mayotte, a French territory, is an island located east of the Union of Comoros within the Comoros Archipelago (**Figure 1**). The EEZ of Mayotte, declared in 1978, has an area of nearly 63,000 km^2 and an *Inshore Fishing Area* (Chuenpagdee et al., 2006) of roughly 1,600 km^2.[4] Mayotte is the poorest of France's overseas territories; however, the Gross Domestic Product of the island is higher than that of the other countries in the Mozambique Channel, and it is generally considered to be more developed than its neighbors. As a result, Mayotte is a major destination for illegal immigration (Genay and Merceron, 2017). The large and growing population and resultant food security strain on the marine environment pushed Mayotte in 2010 to declare its entire EEZ as a marine protected area (Anon, 2012). Mayotte's population is dependent on marine fisheries as a primary source of protein, and many of its villages are concentrated along the coast (Guézel et al., 2009).

The detailed estimation methods for the small-scale fishing effort are presented in **Supplementary Material**. As a French territory, data for Mayotte are incorporated in national French statistics; however, these data are not easily disaggregated between Mayotte and other French territories in the Indian Ocean. Reported numbers of small-scale fishing boats exist in five categories: small, medium, and large *pirogues*, and *barques*, as well as small longliners in recent years. These data were available for multiple years between 1962 and 2015 from various sources (**Supplementary Table 6**). Motorization started in the 1970s through the introduction of outboard motors for large pirogues (Jacquemart, 1980), with a small proportion of small and medium pirogues being motorized in subsequent years (**Supplementary Table 7**). There was minimal quantitative information on shore-based fishing in Mayotte, and the number of shore-based fishers was assumed proportionate to the total Mayotte population over time. Accurate estimates of the number of fishing days were not available for all small-scale fleet components in Mayotte, and approximations were required based on similar fleet components in Mayotte or the Mozambique Channel region.

Mozambique

Mozambique is located on the southeast coast of mainland Africa and makes up the western border of the Mozambique Channel. The EEZ of Mozambique, declared in 1976, has an area of over 571,000 km^2 and the *Inshore Fishing Area* (Chuenpagdee et al., 2006) is over 68,000 km^2.[5] Formerly a Portuguese colony, the country gained its independence following a decade-long war from 1964 to 1974. Shortly thereafter, a civil war erupted from 1977 to 1992. Since the first democratic elections in 1994, Mozambique has been relatively stable politically, with economic reform and the resettlement of civil war refugees leading to a high growth rate in both the population and the economy (Bueno et al., 2015). However, the country suffers from wealth inequality (Anon, 2018). Since the mid-2010s the country has faced a growing insurgency by Islamist groups, mainly in the northern region of Cabo Delgado, which has increased the political and socio-economic instability. Small-scale fisheries continue to contribute substantially to food security and livelihoods in coastal communities, while government support is often directed to industrial, cash-revenue generating fisheries (Jacquet and Zeller, 2007; Jacquet et al., 2010). Wooden canoes make up most of the small-scale fleet, and the most widespread gears used are gillnets and beach seines (Oceanic Développement and Mega Pesca Lda, 2014).

The detailed estimation methods for the small-scale fishing effort are presented in **Supplementary Material**. There were data for the number of fishing vessels in Mozambique for multiple years back to the early 1950s (**Supplementary Table 8**), and unlike the other countries/territories in this study, motorization started before 1950 (FAO, 1958). The total number of shore-based fishers were reported for multiple years since 1995, but required adjustments to exclude freshwater statistics from the combined data in 2007 and 2012. Prior to 1995, the number of shore-based fishers was assumed to correlate with the total population back to 1950 (**Supplementary Table 9**). This proportion was adjusted across several time periods to account for increased migration to coastal regions due to the internal conflicts. As described in

[4] www.seaaroundus.org/data/#/eez/175

[5] www.seaaroundus.org/data/#/eez/508

Supplementary Table 10, the average number of days per year spent fishing was approximated based on Hara et al. (2001) and insights from Jacquet and Zeller (2007).

Catch per Unit Effort

Catch per unit of effort is a basic fisheries science measure often used as a first-order evaluation of broad trends in likely relative abundance or relative biomass trends over time of the underlying fish stocks (Skalski et al., 2005; Belhabib et al., 2018). While CPUE has its limitations, it can be useful in long-term trend monitoring of a fishery, particularly where more detailed data and stock assessments do not exist (Stamatopoulos, 2002) and open or semi-open access fisheries predominate, i.e., where restrictive fisheries management actions may be absent or ineffective. Here, the small-scale fisheries catches for each country/territory in the Mozambique Channel region were extracted from the *Sea Around Us* global reconstructed catch database (see text footnote 1) for 1950–2016 (Pauly and Zeller, 2016a,b). These catch data were previously and independently reconstructed for the Union of Comoros (Doherty et al., 2015a), Mayotte (Doherty et al., 2015b), Mozambique (Jacquet and Zeller, 2007; Jacquet et al., 2010), and Madagascar (Le Manach et al., 2011, 2012a,b), and conservatively updated to 2016 (Derrick et al., 2020). CPUE is the quotient of the annual small-scale total catch per country as derived independently through *Sea Around Us* catch reconstructions and the annual effective small-scale fishing effort as reconstructed here.

RESULTS

Fishing Effort

Effective small-scale fishing effort in the entire Mozambique Channel region grew slowly but steadily from around 386,000 kWdays in 1950 to around 2.6 million kWdays in the mid-1970s, increasing more steeply thereafter and reaching approximately 23 million kWdays by 2016 (**Figure 2A** and **Table 2**). Thus, overall small-scale fishing effort in the Mozambique Channel region increased nearly 60-fold since 1950. This increase was dominated by growth in fishing effort in Madagascar since the mid-1980s and in Mozambique since the 1990s, although the other countries/territories also grew in effective effort over the 67-year period considered here (**Figure 2A**).

For the region as a whole, shore-based effective fishing effort was almost equal to boat-based effective fishing effort in the first few years, with boat-based effort growing 96-fold from around 220,000 kWdays in 1950 to approximately 21 million kWdays by 2016 (**Figure 2B** and **Table 2**). This substantial growth in boat-based fishing effort was driven by massive increases in the number of boats, as well as the motorization trend in many of the countries after 1970, especially the Comoros and Mayotte (**Figures 2C–E** and **Table 2**). Only Mozambique maintained a substantial shore-based effort trend over time, although boat-based effort increased strongly after the late 1990s (**Figure 2F**). Importantly, however, both Mozambique and Madagascar seem to be experiencing an increase in shore-based fishing effort in the most recent years (**Figures 2D,F**).

Catch per Unit Effort

The previously and independently reconstructed small-scale marine catches for the Mozambique Channel countries/territories displayed an overall fivefold increase over the 1950–2016 time period, growing from approximately 67,000 tonnes in 1950 to over 350,000 tonnes in 2016 (**Figure 3A**). Small-scale catches in the Mozambique Channel region were dominated by Mozambique and Madagascar (**Figure 3A**), which was to be expected, given their substantially larger populations, long coastlines and large coastal fishing areas. Small-scale catches in the Comoros Islands increased slowly from around 1,000 tonnes in 1950 to just over 4,000 tonnes in 1978, before increasingly strongly through the 1980s and early 1990s. Growth in catches slowed through the 1990s, and catches plateaued around 18,500 tonnes year^{-1} in the mid-2010s (**Figure 3B**). The catches of small-scale fisheries in Madagascar grew near linearly from around 14,000 tonnes in 1950 to 136,000 tonnes in 2016 (**Figure 3C**). Catches in Mayotte increased from 237 tonnes in 1950 to just over 2,600 tonnes in 1995 (**Figure 3D**). Thereafter, catches entered a period of strong fluctuations throughout the late 1990s and early 2000s, before increasing again strongly to over 3,100 tonnes by 2016 (**Figure 3D**). Mozambique's small-scale catches were strongly influenced by the civil war driven coastal migrations during the 1960–1990 period (Blythe et al., 2013), with catches first increasing from around 51,500 tonnes in 1950 to an initial peak of just under 147,500 tonnes in 1979 (**Figure 3E**). Thereafter, catches declined to approximately 79,700 tonnes in 2005, before increasing again during the 2000s and especially since 2013 to a new all-time peak of just over 192,500 tonnes in 2016 (**Figure 3E**).

Overall, the small-scale CPUE estimates for the entire Mozambique Channel region, as derived from the combination of the previously reconstructed catches and presently reconstructed fishing effort data suggested a decline of 91% between 1950 and 2016, from around 174 kg·kWday^{-1} in 1950 to just over 15 kg·kWday^{-1} by 2016 (**Figure 4A**). The strongest decline in CPUE was observed during the 1950s, after which the rate of decline slowed until the mid-1980s; thereafter, the CPUE continued to decline at a slower rate (**Figure 4A**).

The small-scale fisheries CPUE in the Comoros Islands initially experienced an increase, from 19.3 kg·kWday^{-1} in 1950 to the time series maximum of 27 kg·kWday^{-1} in 1962, after which the CPUE declined strongly to a low of 6.3 kg·kWday^{-1} in 1989 (**Figure 4B**). The CPUE recovered slightly in the early 1990s before starting a steady decline to the all-time low of 4.3 kg·kWday^{-1} by 2016. Overall, the small-scale CPUE in the Comoros Islands declined by approximately 78% between 1950 and 2016 (**Figure 4B**). The CPUE for the small-scale fisheries on Madagascar stayed relatively constant at a high level of around 110 kg·kWday^{-1} during the 1950s and 1960s, reaching a time series maximum of 117 kg·kWday^{-1} in 1969 (**Figure 4C**). Starting in 1970, the CPUE began a strong decline to around 32 kg·kWday^{-1} in the late 1980s, after which the decline tapered off somewhat, before leveling out at around

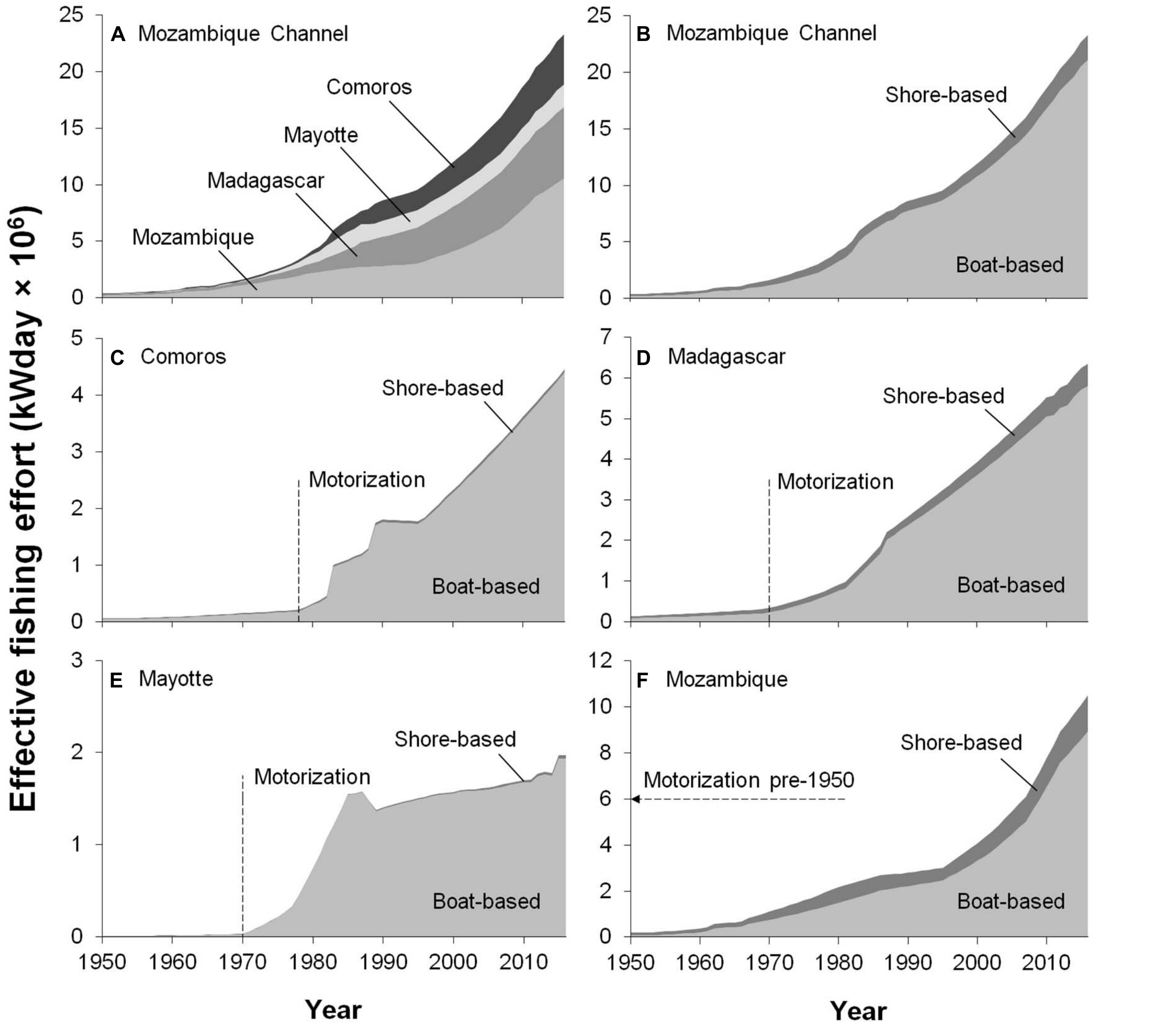

FIGURE 2 | Annual effective fishing effort (kWday × 10^6) between 1950 and 2016 for small-scale fisheries in **(A)** the Mozambique Channel region by country; **(B)** the Mozambique Channel region by boat- versus shore-based fisheries; **(C)** Comoros; **(D)** Madagascar; **(E)** Mayotte; and **(F)** Mozambique. Start year of motorization is indicated.

TABLE 2 | Effective fishing effort (kWdays) of the four Mozambique Channel entities and the entire Mozambique Channel region examined for 1950 and 2016.

Area	Shore-based effective fishing effort (kWdays × 10^6)		Boat-based effective fishing effort (kWdays × 10^6)		Total effective fishing effort (kWdays × 10^6)	
	1950	2016	1950	2016	1950	2016
Comoros	0.010 (6%)	0.06 (3%)	0.05 (22%)	4.40 (21%)	0.06 (15%)	4.46 (19%)
Madagascar	0.045 (27%)	0.56 (25%)	0.08 (39%)	5.79 (28%)	0.13 (34%)	6.35 (27%)
Mayotte	0.001 (1%)	0.03 (1%)	0.01 (3%)	1.94 (9%)	0.01 (2%)	1.97 (8%)
Mozambique	0.111 (66%)	1.57 (71%)	0.08 (36%)	8.93 (42%)	0.19 (49%)	10.51 (45%)
Region	0.17	2.22	0.22	21.07	0.39	23.29

Percentage values indicate the contribution to the total regional effective fishing effort of each component in each year.

22 kg·kWday^{-1} by 2016 (**Figure 4C**). The overall decline of small-scale CPUE on Madagascar was 80% over the 60+ year time period considered here. The CPUE of Mayotte's small-scale fisheries declined starting in 1950 from 30 kg·kWday^{-1} through the 1950s before tapering off in the late 1960s at around 21 kg·kWdays^{-1} (**Figure 4D**). The introduction of motorization

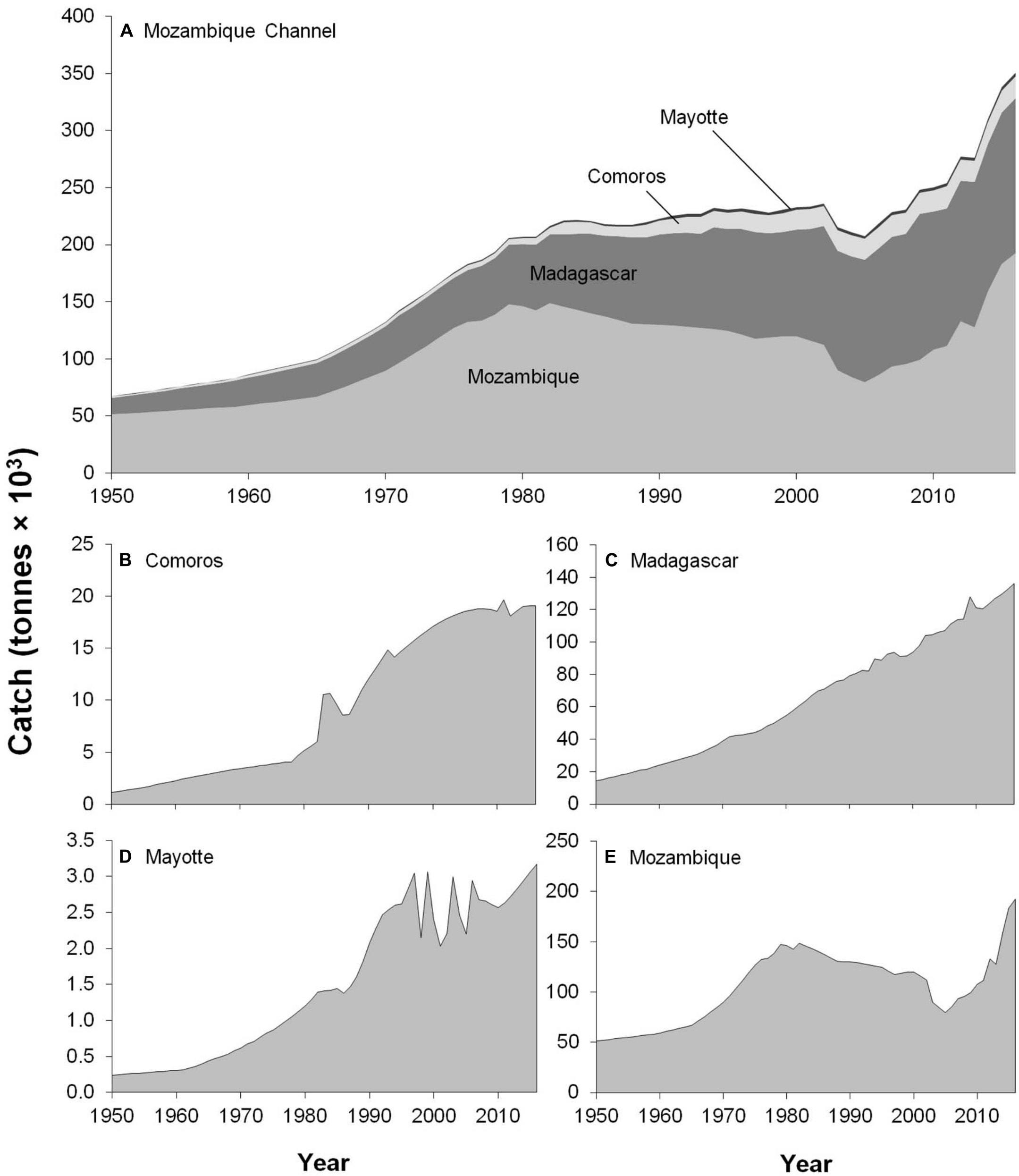

FIGURE 3 | Previously and independently reconstructed catches (tonnes × 10^3) for small-scale fisheries from 1950 to 2016 for **(A)** the Mozambique Channel region by country; **(B)** Comoros; **(C)** Madagascar; **(D)** Mayotte; and **(E)** Mozambique.

in Mayotte's fleets after 1970 led to a very rapid and massive decline in the derived CPUE in the early-1970s, before reaching a very low level of around 1.5 kg·kWday^{-1} in the early 1980s (**Figure 4D**). The CPUE fluctuated slightly around this level ever since, resulting in an overall CPUE decline of 95% since 1950 (**Figure 4D**). The CPUE of the small-scale fisheries in Mozambique declined strongly and rapidly from very high levels of 272 kg·kWday^{-1} in 1950 to just over 100 kg·kWday^{-1} by the early 1960s (**Figure 4E**). It continued to decline more gradually over the remainder of the time period to reach very low levels of around 13 kg·kWday^{-1} by the early-2010s, before increasing again very modestly to 18 kg·kWday^{-1} by 2016 (**Figure 4E**). Overall, this resulted in a decline in CPUE of 93% since 1950 (**Figure 4E**).

DISCUSSION

A considerable variety of different and non-standardized measures of fishing effort are used around the world, which makes global comparisons difficult. Fortunately, a standardized measure of effort using the power input in fisheries, i.e., kWday,

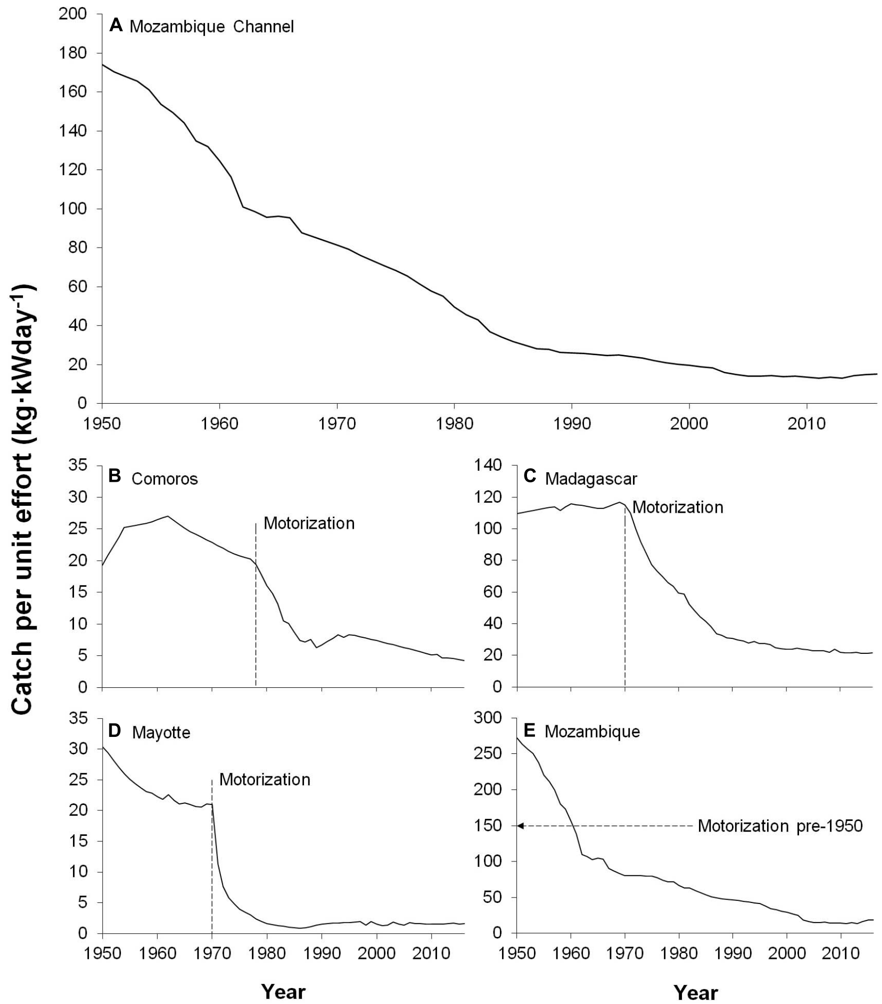

FIGURE 4 | The catch per unit effort (CPUE) for small-scale fisheries (kg·kWday^{-1}) from 1950 to 2016 for **(A)** the complete Mozambique Channel region; **(B)** Comoros; **(C)** Madagascar; **(D)** Mayotte; and **(E)** Mozambique. Start year of motorization is indicated.

is now available globally (Parker et al., 2018; Greer et al., 2019a,b), enabling international comparisons. This finally permits direct comparisons between fisheries, gear-types, regions countries, and globally to be undertaken in a standardized fashion. Here, we used a data reconstruction approach (Zeller et al., 2016) to refine and update the preliminary fishing effort data of Greer et al. (2019a) for small-scale fisheries from 1950 to 2016 in the four inhabited countries or territories that make up the Mozambique Channel region off East Africa (**Figure 1**). Furthermore, we combined the small-scale fishing effort time series data derived here with previously and independently estimated small-scale catch data for these countries/territories (Jacquet and Zeller, 2007; Jacquet et al., 2010; Le Manach et al., 2011, 2012b; Doherty et al., 2015a,b,c), obtained using the catch data reconstruction approach of Zeller et al. (2016), to develop CPUE time series for the small-scale fisheries in the Mozambique Channel region from 1950 to 2016.

Overall, our results illustrated consistent and strong increases in fishing effort over the 67-year period considered here. This growth in effort was driven not only by increasing motorization, but also by considerable increases in the number of small-scale fishing boats being used. Crucially, the combined catch and fishing effort data clearly demonstrated consistent and strong declines in the CPUE of small-scale fisheries in every country or territory examined, with CPUE declining by 91% across the region. The geographically smaller entities of Comoros and Mayotte had CPUE declines of 78 and 95%, respectively, while CPUE declines of 80 and 93% were observed for Madagascar and Mozambique, respectively. Declining CPUE time series trends, especially in the absence of effective effort-controlling fisheries management, generally suggest declining relative abundances of the underlying fished stocks (Hoggarth, 2006). Thus, the pattern of CPUE observed here suggests a strongly declining fisheries resource base for the small-scale fisheries in these countries/territories over the last 60+ years, impacting a crucial food security sector in this region of Africa. This trend is in general agreement with a recent assessment of the biomass patterns of exploited stocks for the tropical Indian Ocean region, which suggested general declines in stock biomass of around 60–70% from levels in 1950 (Palomares et al., 2020). Furthermore, the overall levels of catches, including industrial and foreign fishing, in the Agulhas Current Large Marine Ecosystem, which includes the Mozambique Channel entities considered here, have been declining steadily since peaking in the late 1960s (**Figure 3** in Zeller et al., 2020).

Effective fishing effort was calculated here using four core fishing capacity parameters: (1) the number of boats, (2) the length of boats, (3) the engine power (kW) of boats, with non-motorized boats being assigned an approximate human-power equivalent, and (4) the number of days boats fish in a year (fishing days). Shore-based small-scale fishing without boats was also included in the fishing effort estimation, using the number of shore-based fishers, shore-based fishing days and a human-power equivalent. This ensured comprehensive coverage of all small-scale fishing in each country and territory. Estimating broad-scale fishing effort based on indirect methods such as used here relies on assumptions that, no matter how carefully and conservatively made, are inherently uncertain, which has generated some debate in regards to the potential accuracy of the data (Greer et al., 2019b; Ziegler et al., 2019). However, our extensive use of a range of available fishing capacity parameters sourced at the fisheries- and country-level may provide some advantages over more generalized estimation techniques, and is thought to provide a reasonable representation of the fishing effort trends in the region over time.

The increase in small-scale fishing effort we documented here was the combined result of growth in both the number of boats as well as motorization of fleets. The introduction and popularization of motorization of traditional vessels, and the introduction of newer, larger powered vessels were important factors driving fishing effort trends. Mayotte, for example, had the lowest effective fishing effort in 1950, with no motorized fishing vessels. With the introduction of motorization after 1970, effective fishing effort steeply increased over the subsequent decade as fleets rapidly motorized. In contrast, the small-scale fishing fleets in Madagascar were the largest in terms of number of boats, and although its effective fishing effort is still increasing due to continuing growth in the number of non-motorized vessels, the very low proportion of vessels that are motorized (0.03% in 2016) limits the fishing power and fishing capacity of its large small-scale fleet.

Clearly, the four parameters used here to estimate effective fishing effort do not necessarily capture all aspects of vessel and fishing capacity. Most fishing effort models, including the one we used here, do not implicitly account for the impacts of technological advances on effort measures over time (i.e., technology creep), such as the introduction and spread of synthetic material in fishing gear, sonar, GPS, refrigeration or fish aggregating devices (Palomares and Pauly, 2019). Technology creep is pronounced in industrial fishing fleets over time, and is likely to have increased the fishing capacity of industrial vessels in the region, further contributing to overfishing and general decline in stock biomass in the Mozambique Channel. However, the available literature suggests that the small-scale fleets in the Mozambique Channel region may not have implemented many of these capacity-enhancing technologies at this point, other than motorization and the use of synthetic fishing gear materials. For example, in the Comoros and Mozambique, refrigeration is restricted to only a few boats (Chacate and Mutombene, 2013; Breuil and Grima, 2014a), and Madagascar's fleet is largely non-motorized and thus unlikely to have widespread refrigeration. Such technological advances do result in effective effort growth of fleets over time even when the number and size of vessels remains the same, and would need to be accounted for in long time series comparisons (Palomares and Pauly, 2019; Scherrer and Galbraith, 2020). Due to the general absence, for the time being, of major technological advances in the small-scale fleets considered here, other than motorization and synthetic materials, the present study did not include any adjustment factors for technology creep (Palomares and Pauly, 2019; Scherrer and Galbraith, 2020).

A limitation of the approach used by us is the assumption of equal capacity and predictive ability of vessel length to estimate effective fishing effort *between gears*; this may not always be reflective of reality. For example, while vessel characteristics such as length and engine power alone may predict effective fishing effort well for some gears, e.g., for industrial trawlers (which were not evaluated here), effective fishing effort for vessels using, e.g., longlines is more often dependent on the length and number of longlines deployed and the number of hooks used per line rather than vessel length or engine power alone (Bell et al., 2017). Furthermore, for estimating overall effort for longline fishing, one will need to include the effective effort (in kWday) of the vessels which caught the bait used by the longline vessels, which is most likely proportional to the number of hooks used overall across all sets. Until recently, it was deemed not viable to estimate cumulative effective fishing effort of all gears and fleets across all countries, as standardized global conversions between different traditional measures of effective fishing effort were lacking. Fortunately, this has now been addressed *via* the standardization of fishing effort as kWday, as shown here and in other recent examples (Piroddi et al., 2015; Belhabib et al., 2018; Greer et al., 2019a,b). Fundamentally, in order to catch fish, one needs an input of energy. Prior to motorization, this energy was derived through human power (e.g., oars) or wind-power, which in our study was approximated through a human-power equivalent. Since motorization, most of this energy is derived from fuel, which has become the most expensive input in fishing. Therefore, using kWday as the key fishing effort measure for all gears is reasonable, and also provides an immediate indication of the fishing cost. Expressing the returns (i.e., CPUE) in $kg{\cdot}kWday^{-1}$ allows easy and standardized comparison and visualization across gears, fleets, countries, and time periods. The direct connection between this measure of effort and fuel use, and hence fuel cost as well as CO_2 emissions, also allows fishing effort and CPUE to be readily re-expressed in economic and climate impact terms, such as $kg{\cdot}\$^{-1}$ of fuel cost and tCO_2 per unit effort or unit catch.

Here, data from boats using various different gear types were used to estimate effort from length and engine power, and as such the kW per vessel predicted by length is thought to represent the average vessel capacity. Because small-scale fisheries often may switch between various fishing gears, and motorized small-scale vessels most commonly use outboard motors with lower engine power (kW) than other types of motorization, the impact of gear type on average vessel capacity is not expected to greatly impact our results.

Infrequent and incomplete data on boat types and lengths were commonplace in our study, and fishers who do not use vessels, particularly women (Harper et al., 2013, 2017, 2020), are often not considered at all in many countries' data and information sources (Hauzer et al., 2013). Women fishers are frequently underrepresented in fisheries statistics and policy (Harper et al., 2013, 2017, 2020). Many traditional perspectives of what constitute "fisheries" and "fishers" tend to exclude or downplay small-scale activities such as collection of seafood from shore (gleaning) from the definition of fishing, when in reality there is a long tradition of women and children collecting seafood from shores in Mozambique Channel coastal communities (e.g., Hauzer et al., 2013) and elsewhere (Harper et al., 2013, 2020). We have accounted for the contributions of shore-based fishers in this study as best as possible based on available information. This is particularly important as shore-based fishing may represent the major source of protein and micro-nutrients to the poorest sectors of coastal communities (Golden et al., 2016; Hicks et al., 2019; Pauly, 2019), which may not have access to boats or elaborate fishing gear. A greater emphasis should be given by governments' fisheries departments and by the scientific community to the recording, estimating and inclusion of all small-scale fisheries in studies and data to evaluate the impact, the food security and nutrient security as well as livelihood importance of these fisheries as a whole (Vianna et al., 2020).

This study focused on the small-scale fisheries in the Mozambique Channel region of East Africa only, and did not account for recreational or large-scale, industrial fisheries, whether domestic or foreign. Resource overlap between the small- and large-scale sectors is nearly global in its occurrence and constitutes a growing source of conflict in many regions (Le Manach et al., 2012b; Belhabib et al., 2014). Small-scale and industrial fishers both often target similar species, e.g., tuna and tuna-like species in the Comoros (Breuil and Grima, 2014a), or shrimp in Madagascar (Cripps, 2009), as well as likely elsewhere. Such resource competition, if not strictly controlled and managed, will continue to increase the political and socio-economic marginalization of small-scale sectors (Pauly, 2006).

African countries are also particularly vulnerable to illegal and unregulated foreign fishing (Kurien and López Ríos, 2013). The waters of Comoros, Mozambique, and Madagascar have all been targeted by Asian tuna longline fleets with and without prior access agreements (Anon, 1995; Cox, 2012; Breuil and Grima, 2014a,b). When agreements do exist for foreign fleets, monitoring, compliance and enforcement is difficult and generally very limited or widely absent, and the catch is often not landed or processed in the host country (UNCTAD, 2017). For example, tuna caught by European Union vessels in Comoros waters are not landed in the Comoros, nor are there fully trained onboard observers from the Comoros aboard these vessels, despite it having been shown that full observer coverage is necessary for equitable resource use (Zeller et al., 2011). Thus, the foreign tuna fisheries in the Comoros does not create any employment or livelihood support for the local population, despite the agreement between the European Union and Comoros being fair and transparent, and the access fees collected promoting modernization of the domestic fishing sector (UNCTAD, 2017). On the other hand, while European Union fishing quotas in Madagascar had increased by 30% between 1986 and 2010, the fees paid by the European Union to Madagascar had decreased by 20% (Le Manach et al., 2013). Governments in this region have historically lacked the organizational structures and resources to engage effectively in fisheries governance (Cox, 2012), in part due to decades of political instability. Considering the often-overlooked importance of small-scale fisheries to domestic livelihoods and food security in coastal communities, the countries and territories in the Mozambique Channel region may want to carefully consider the interaction between domestic and foreign fisheries when renewing or establishing future fishing agreements.

Given the considerable increases in effective fishing effort observed here for small-scale fisheries in the Mozambique Channel region, it is not surprising that the CPUE has been declining substantially for decades now. The findings of this study are consistent with previous suggestions by Watson et al. (2013) who, based on a shorter time series (1950–2006), suggested that CPUE had been declining globally since 1950, including in the Indian Ocean. Declining CPUE trends in the absence of effective effort restrictions generally are indicators of declining relative abundance of fished stocks (Hoggarth, 2006). Given the country-level focus in the present study, it is challenging to draw specific conclusions on the status of any particular stock or species, but the overall declining CPUE in all EEZs points to serious concerns about the status of the fish stocks underlying and supporting small-scale fisheries in the Mozambique Channel region, as it does elsewhere in the western Indian Ocean (Christ et al., 2020). We suggest that this decline in CPUE should be viewed as a serious warning sign of decreased abundance and biomass of the exploited fish populations. Thus, local governments should consider implementing policies to promote recovery of fish populations, i.e., stock rebuilding, to abundance levels that readily support maximum sustainable yields (Pauly and Froese, 2020). This will require minimizing or restricting further growth in fishing effort until the biomass and abundance of local stocks can recover. Enforcing gear restrictions (e.g., larger mesh and hook sizes) and permanent no-take zones would assist in rebuilding fish populations. Such effort and spatial access restrictions should also apply to foreign fleets due to the limited direct local benefits provided and possible interaction and conflict with domestic small-scale fisheries. Given the importance of small-scale fisheries in the Mozambique Channel, the adoption and enforcement of such policies could result in considerable improvements in food and nutrient security as well as the socio-economic condition of coastal communities in the region.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

AUTHOR CONTRIBUTIONS

DZ developed and formalized the fisheries data reconstruction approach and conceptualized, drafted, revised, and edited the manuscript. DZ, MP, and DP conceptualized the development of the fishing effort data reconstruction, developed the methodological approach, and conceptualized, edited, and revised the manuscript. MA assembled catch data and reconstructed effort data, synthesized CPUE data, prepared the figures and **Supplementary Material**, and drafted, revised, and edited the manuscript. KG advised on effort reconstruction methods. AC, BD, GV, and S-LN contributed to the effort data reconstruction, assembled catch data, and edited the manuscript. AZ collected and reconstructed fishing effort data and edited the manuscript. All authors contributed to the article and approved the submitted version.

FUNDING

All *Sea Around Us* and *Sea Around Us – Indian Ocean* research is supported by the Oak Foundation, the Marisla Foundation, the Paul M. Angell Family Foundation, the David and Lucile Packard Foundation, the Minderoo Foundation, and Bloomberg Philanthropies *via* Rare.

ACKNOWLEDGMENTS

This is a contribution of the *Sea Around Us – Indian Ocean* and the *Sea Around Us*, at the University of Western Australia and the University of British Columbia, respectively. We thank numerous colleagues and all current and former *Sea Around Us* staff, students and volunteers for assistance over the years in assembling the gradually evolving catch and effort datasets. We thank Elaine Chu for preparing **Figure 1**. All errors that remain in the presented data are ours, and we appreciate errors and oversights, as well as new data sources being pointed out to us for correction.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2021.707999/full#supplementary-material

REFERENCES

Andrianaivojaona, C., Dasylva, G., and Kasprzyk, Z. (1992). *Pêches et Aquaculture á Madagascar. Bilan Diagnostic*. Antananarivo: PNUD.

Anon (1995). *Report of the 6th Expert Consultation of Indian Ocean Tunas. 25-29 September 1995*. Colombo: Indo-Pacific Tuna Development and Management Programme.

Anon (2012). *Parc Naturel Marin de Mayotte [Online]*. Available online at: http://www.aires-marines.fr/L-Agence/Organisation/Parcs-naturels-marins/mayotte (accessed March 9, 2019).

Anon (2018). *Mozambique Economic Update: Less Poverty, but More Inequality [Online]*. Available online at: https://www.worldbank.org/en/country/mozambique/publication/mozambique-economic-update-less-poverty-but-more-inequality (accessed April 18, 2019).

Anon (2019a). *The World Bank in Comoros - Overview [Online]. The World Bank*. Available online at: https://www.worldbank.org/en/country/comoros/overview (accessed March 5, 2019).

Anon (2019b). *The World Bank in Madagascar - Madagascar Overview [Online]. The World Bank*. Available online at: http://www.worldbank.org/en/country/madagascar/overview#2 (accessed March 9, 2019).

Anon (2019c). *World Development Indicators [Online]. The World Bank*. Available online at: http://datatopics.worldbank.org/world-development-indicators/ (accessed March 17, 2017.)

ASCLME (2011). Coastal livelihoods in the Republic of Madagascar. Agulhas and Somali Current Large Marine Ecosystems Project (ASCLME). Nairobi: Nairobi Convention.

Barnes, D. K. A., and Rawlinson, K. A. (2009). Traditional coastal invertebrate fisheries in south-western Madagascar. *J. Mar. Biol. Assoc. U.K.* 89, 1589–1596. doi: 10.1017/s0025315409000113

Belhabib, D., Greer, K., and Pauly, D. (2018). Trends in industrial and artisanal catch per effort in West African fisheries. *Conserv. Lett.* 11:e12360. doi: 10.1111/conl.12360

Belhabib, D., Koutob, V., Sall, A., Lam, V. W. Y., and Pauly, D. (2014). Fisheries catch misreporting and its implications: the case of Senegal. *Fish. Res.* 151, 1–11. doi: 10.1016/j.fishres.2013.12.006

Bell, J. D., Watson, R. A., and Ye, Y. (2017). Global fishing capacity and fishing effort from 1950 to 2012. *Fish Fish.* 18, 489–505. doi: 10.1111/faf.12187

Bellmann, C., Tipping, A., and Sumaila, U. (2016). Global trade in fish and fishery products: an overview. *Mar. Policy* 69, 181–188. doi: 10.1016/j.marpol.2015.12.019

Béné, C., and Heck, S. (2005). Fish and food security in Africa. *Naga World Fish Center Q.* 28:6.

Blythe, J. L., Murray, G., and Flaherty, M. S. (2013). Historical perspectives and recent trends in the coastal Mozambican fishery. *Ecol. Soc.* 18:65. doi: 10.5751/ES-05759-180465

Breuil, C., and Grima, D. (2014a). *Fisheries in the ESA-IO Region: Profile and Trends. Baseline Report Comoros*. Ebene: SmartFish Programme of the Indian Ocean Commission.

Breuil, C., and Grima, D. (2014b). *Fisheries in the ESA-IO Region: Profile and Trends. Baseline report Madagascar*. Ebene: SmartFish Programme of the Indian Ocean Commission.

Bueno, N., Plagemann, J., and Strasheim, J. (2015). Provincial autonomy: the territorial dimension of peace in Mozambique. *GIGA Focus* 10, 1–8.

Chacate, O. E., and Mutombene, R. (2013). *Mozambique National Report to the Scientific Committee of the Indian Ocean Tuna Commission, 2013*. Luanda: Instituto Nacional de Investigação Pesqueira.

Christ, H. J., White, R., Hood, L., Vianna, G. M. S., and Zeller, D. (2020). A baseline for the Blue Economy: catch and effort history in the Republic of Seychelles' domestic fisheries. *Front. Mar. Sci.* 7:269. doi: 10.3389/fmars.2020.00269

Chuenpagdee, R. (ed.) (2011). *World Small-Scale Fisheries: Contemporary Visions*. Delft: Eburon Academic Publishers.

Chuenpagdee, R., Liguori, L., Palomares, M. D., and Pauly, D. (2006). *Bottom-Up, Global Estimates of Small-Scale Marine Fisheries Catches*. Vancouver: University of British Columbia.

Cox, J. (2012). *Assessment Report on Small-Scale Fisheries in Africa*. Cape Town: Masifundise Development Trust.

Cripps, G. (2009). *Understanding Migration Amongst the Traditional Fishers of West Madagascar*. London: Blue Ventures Conservation Report for ReCoMaP.

Derrick, B., Khalfallah, M., Relano, V., Zeller, D., and Pauly, D. (eds) (2020). *Updating to 2018 the 1950-2010 Marine Catch Reconstructions of the Sea Around US: Part I - Africa, Antarctica, Europe and the North Atlantic*. Vancouver: University of British Columbia

Doherty, B., Hauzer, M., and Le Manach, F. (2015a). "Reconstructing catches for the Union of Comoros: uniting historical sources of catch data for Ngazidja, Ndzuwani and Mwali from 1950-2010," in *Fisheries Catch Reconstructions in the*

Western Indian Ocean, 1950-2010, eds F. Le Manach and D. Pauly (Vancouver: University of British Columbia), 1–11.

Doherty, B., Herfaut, J., Le Manach, F., Harper, S., and Zeller, D. (2015b). "Reconstructing domestic marine fisheries in Mayotte from 1950–2010," in *Fisheries Catch Reconstructions in the Western Indian Ocean, 1950-2010*, eds F. Le Manach and D. Pauly (Vancouver: University of British Columbia), 53–65.

Doherty, B., McBride, M. M., Brito, A. J., Le Manach, F., Sousa, L., Chauca, I., et al. (2015c). "Marine fisheries in Mozambique: catches updated to 2010 and taxonomic disaggregation," in *Fisheries Catch Reconstructions in the Western Indian Ocean, 1950-2010*, eds F. Le Manach and D. Pauly (Vancouver: University of British Columbia), 67–81.

FAO (1958). *Yearbook of Fishery Statistics Volume 9: Production and Fishing Craft*. (Rome: FAO), 357.

FAO (2009). *Fishery and Aquaculture Country Profiles: The Republic of Madagascar*. Rome: FAO.

FAO (2015a). *Fishery and Aquaculture Country Profiles: The Union of Comoros. FAO Fisheries and Aquaculture Department*. Rome: Food and Agriculture Organization of the United Nations.

FAO (2015b). *Voluntary Guidelines for Securing Sustainable Small-Scale Fisheries in the Context of Food Security and Poverty Eradication*. Rome: Food and Agriculture Organization of the United Nations.

Genay, V., and Merceron, S. (2017). *La Population Augumente plus Rapidement Qu'avarant*. Mamoudzou: Insee - Service régional de Mayotte.

Golden, C. D., Allison, E., Cheung, W. W. L., Dey, M., Halpern, B., McCauley, D. J., et al. (2016). Nutrition: fall in fish catch threatens human health. *Nature* 534, 317–320. doi: 10.1038/534317a

Greer, K., Zeller, D., Woroniak, J., Coulter, A., Winchester, M., Palomares, M. L. D., et al. (2019a). Global trends in carbon dioxide (CO2) emissions from fuel combustion in marine fisheries from 1950-2016. *Mar. Policy* 107:103382. doi: 10.1016/j.marpol.2018.12.001

Greer, K., Zeller, D., Woroniak, J., Coulter, A., Winchester, M., Palomares, M. L. D., et al. (2019b). Reply to Ziegler et al. "Adding perspectives to: global trends in carbon dioxide (CO2) emissions from fuel combustion in marine fisheries from 1950-2016" and addressing concerns of using fishing effort to predict carbon dioxide emissions. *Mar. Policy* 107:103491. doi: 10.1016/j.marpol.2019.03.004

Guézel, R., Quartararo, A., Aboutoihi, L., Saindou, K., Salaün, P., Ybrahim, B., et al. (2009). *Richesses de Mayotte — Parc Naturel Marin de Mayotte — Les Hommes et L'océan — Mission d'étude Pour la Création d'un Parc Naturel Marin à Mayotte*. Mamoudzou: Agence des aires marines protégées.

Hara, W., Deru, J., and Pitamber, S. (2001). *Appraisal Report. Artisanal Fisheries Development Project - Mozambique*. Abidjan: African Development Fund.

Harper, S., Adshade, M., Lam, V. W. Y., Pauly, D., and Sumaila, U. R. (2020). Valuing invisible catches: estimating the global contribution by women to small-scale marine capture fisheries production. *PLoS One* 15:e0228912. doi: 10.1371/journal.pone.0228912

Harper, S., Bevacqua, D., Chudnow, R., Giorgi, S., Guillonneau, V., Le Manach, F., et al. (2012). Fuelling the fisheries subsidy debate: agreements, loopholes and implications. *Fish. Res.* 113, 143–146. doi: 10.1016/j.fishres.2011.10.007

Harper, S., Grubb, C., Stiles, M., and Sumaila, U. R. (2017). Contributions by women to fisheries economies: insights from five maritime countries. *Coast. Manage.* 45, 91–106. doi: 10.1080/08920753.2017.1278143

Harper, S., Zeller, D., Hauzer, M., Pauly, D., and Sumaila, U. R. (2013). Women and fisheries: contribution to food security and local economies. *Mar. Policy* 39, 56–63. doi: 10.1016/j.marpol.2012.10.018

Hauzer, M., Dearden, P., and Murray, G. (2013). The fisherwomen of Ngazidja island, Comoros: fisheries livelihoods, impacts, and implications for management. *Fish. Res.* 140, 28–35. doi: 10.1016/j.fishres.2012.12.001

Hicks, C. C., Cohen, P. J., Graham, N. A. J., Nash, K. L., Allison, E. H., D'Lima, C., et al. (2019). Harnessing global fisheries to tackle micronutrient deficiencies. *Nature* 574, 95–98. doi: 10.1038/s41586-019-1592-6

Hoggarth, D. D. (2006). *Stock Assessment for Fishery Management: A Framework Guide to the Stock Assessment Tools of the Fisheries Management and Science Programme*. Rome: FAO.

IHO (1953). *Limits of oceans and seas - Special publication N. 23*. Monegasque: International Hydrographic Organization.

Jacquemart, P. (1980). *Les Problèmes de la Pêche à Mayotte. Doctorat Vétérinaire, École Nationale Vétérinaire d'Alfort*. Créteil: Faculté de Médecine de Créteil.

Jacquet, J. L., and Zeller, D. (2007). "National conflict and fisheries: reconstructing marine fisheries catches for Mozambique," in *Reconstruction of Marine Fisheries Catches for Key Countries and Regions (1950-2005) Fisheries Centre Research Reports 15(2)*, eds D. Zeller and D. Pauly (Vancouver: University of British Columbia), 35–47.

Jacquet, J., Fox, H., Motta, H., Ngusaru, A., and Zeller, D. (2010). Few data but many fish: marine small-scale fisheries catches for Mozambique and Tanzania. *Afr. J. Mar. Sci.* 32, 197–206. doi: 10.2989/1814232x.2010.501559

Krendel, E. S., Ramakumar, R., Butterfield, C. P., Farber, E. A., Phair, K. A., Menkes, S. B., et al. (2007). "Power generation," in *Marks' Standard Handbook for Mechanical Engineers*, 10th Edn, eds E. A. Avallone and T. Baumeister (New York, NY: Mc-Graw Hill), 9–4.

Kurien, J., and López Ríos, J. (2013). *Flavouring Fish into Food Security. Report/Rapport: SF-FAO/2013/14*. Ebene: FAO.

Le Manach, F., and Pauly, D. (eds) (2015). *First Estimate of Unreported Catch in the French Îles Éparses, 1950–2010*. (Vancouver: University of British Columbia), 27-35.

Le Manach, F., Andriamahefazafy, M., Harper, S., Harris, A., Hosch, G., Lange, G.-M., et al. (2013). Who gets what? Developing a more equitable framework for EU fishing agreements. *Mar. Policy* 38, 257–266. doi: 10.1016/j.marpol.2012.06.001

Le Manach, F., Gough, C., Harris, A., Humber, F., Harper, S., and Zeller, D. (2012a). Erratum to "Unreported fishing, hungry people and political turmoil: the recipe for a food security crisis in Madagascar" [Marine *Policy* 36(1) (2012) 218-225]. *Mar. Policy* 36:564. doi: 10.1016/j.marpol.2011.08.008

Le Manach, F., Gough, C., Harris, A., Humber, F., Harper, S., and Zeller, D. (2012b). Unreported fishing, hungry people and political turmoil: the recipe for a food security crisis in Madagascar? *Mar. Policy* 36, 218–225. doi: 10.1016/j.marpol.2011.05.007

Le Manach, F., Gough, C., Humber, F., Harper, S., and Zeller, D. (2011). "Reconstruction of total marine fisheries catches for Madagascar (1950-2008)," in *Fisheries Catch Reconstructions: Islands, Part II*, eds S. Harper and D. Zeller (Vancouver: University of British Columbia), 21–37

Martín, J. (2012). *The Small-Scale Coastal Fleet in the Reform of the Common Fisheries Policy. IP/B/PECH/NT/2012_08*. Brussels: European Parliament.

Mngulwi, B. S. M. (2006). "Review of the state of world capture fisheries management: indian Ocean," in *Country Review. Tanzania Mainland*, ed. C. De Young (Rome: FAO), 458.

Nunes, P. A. L. D., and Ghermandi, A. (2015). *Understanding and Valuing the Marine Ecosystem Services of the Northern Mozambique Channel*. Gland: WWF International.

Oceanic Développement and Mega Pesca Lda (2014). *Ex-Post and Ex-Ante Evaluations of the Protocol to the Fisheries Partnership Agreement between the EU and the Republic of Mozambique*. Concarneau: Oceanic Développement.

Palomares, M. L. D., and Pauly, D. (2019). On the creeping increase of vessels' fishing power. *Ecol. Soc.* 24:31. doi: 10.5751/ES-11136-240331

Palomares, M. L. D., Froese, R., Derrick, B., Meeuwig, J. J., Nöel, S.-L., Tsui, G., et al. (2020). Fishery biomass trends of exploited fish populations in marine ecoregions, climatic zones and ocean basins. *Estuar. Coast. Shelf Sci.* 243:106896. doi: 10.1016/j.ecss.2020.106896

Panayotou, T. (1982). *Management Concepts for Small-Scale Fisheries: Economic and Social Aspects*. Bangkok: FAO.

Parker, R. W. R., Blanchard, J. L., Gardner, C., Green, B. S., Hartmann, K., Tyedmers, P. H., et al. (2018). Fuel use and greenhouse gas emissions of world fisheries. *Nat. Clim. Change* 8, 333–337. doi: 10.1038/s41558-018-0117-x

Pauly, D. (2006). Major trends in small-scale marine fisheries, with emphasis on developing countries, and some implications for the social sciences. *Marit. Stud.* 4, 7–22.

Pauly, D. (2019). Micronutrient richness of global fish catches. *Nature* 574, 41–42. doi: 10.1038/d41586-019-02810-2

Pauly, D., and Charles, A. (2015). Counting on small-scale fisheries. *Science* 347, 242–243. doi: 10.1126/science.347.6219.242-b

Pauly, D., and Froese, R. (2020). MSY needs no epitaph—but it was abused. *ICES J. Mar. Sci.* 2020:fsaa224. doi: 10.1093/icesjms/fsaa224

Pauly, D., and Zeller, D. (2016a). Catch reconstructions reveal that global marine fisheries catches are higher than reported and declining. *Nat. Commun.* 7:10244. doi: 10.1038/ncomms10244

Pauly, D., and Zeller, D. (eds) (2016b). *Global Atlas of Marine Fisheries: A Critical Appraisal of Catches and Ecosystem Impacts*. Washington, DC: Island Press.

Piroddi, C., Gristina, M., Zylich, K., Greer, K., Ulman, A., Zeller, D., et al. (2015). Reconstruction of Italy's marine fisheries removals and fishing capacity, 1950-2010. *Fish. Res.* 172, 137–147. doi: 10.1016/j.fishres.2015.06.028

Ploch, L., and Cook, N. (2012). *Madagascar's Political Crisis*. Washington, DC: Congressional Research Service.

Rey, R. C. (1982). *La Peche Maritime a Madagascar, 1–75 Document OISO, RAF/79/065*. Mahé: FAO.

Scherrer, K. J. N., and Galbraith, E. D. (2020). The risk of underestimating long-term fisheries creep. *Ecol. Soc.* 25:18. doi: 10.5751/ES-11389-250118

Schuhbauer, A., and Sumaila, U. R. (2016). Economic viability and small-scale fisheries—A review. *Ecol. Econ.* 124, 69–75. doi: 10.1016/j.ecolecon.2016.01.018

Skalski, J. R., Ryding, K. E., and Millspaugh, J. J. (2005). "Analysis of population indices," in *Wildlife Demography: Analysis of Sex, Age, and Count Data*, eds J. R. Skalski, K. E. Ryding, and J. J. Millspaugh (Cambridge, MA: Academic Press), 359–433. doi: 10.1016/b978-012088773-6/50009-2

Stamatopoulos, C. (2002). *Sample-Based Fishery Surveys: A Technical Handbook*. Rome: FAO.

Sumaila, U. R., Ebrahim, N., Schuhbauer, A., Skerritt, D., Li, Y., Kim, H. S., et al. (2019). Updated estimates and analysis of global fisheries subsidies. *Mar. Policy* 109:103695. doi: 10.1016/j.marpol.2019.103695

Teh, L. C. L., Teh, L. S. L., Abe, K., Ishimura, G., and Roman, R. (2020). Small-scale fisheries in developed countries: Looking beyond developing country narratives through Japan's perspective. *Mar. Policy* 122:104274. doi: 10.1016/j.marpol.2020.104274

UNCTAD (2017). *Fishery Exports and the Economic Development of Least Developed Countries?: Bangladesh, Cambodia, The Comoros, Mozambique, Myanmar and Uganda*. New York, NY: United Nations Conference on Trade and Development.

Vianna, G. M., Zeller, D., and Pauly, D. (2020). Fisheries and policy implications for human nutrition. *Curr. Environ. Health Rep.* 7, 161–169. doi: 10.1007/s40572-020-00286-1

Watson, R. A., Cheung, W. W. L., Anticamara, J. A., Sumaila, R. U., Zeller, D., and Pauly, D. (2013). Global marine yield halved as fishing intensity redoubles. *Fish Fish.* 14, 493–503. doi: 10.1111/j.1467-2979.2012.00483.x

Zeller, D., and Pauly, D. (2019). Viewpoint: back to the Future for fisheries, where will we choose to go? *Glob. Sustain.* 2:e11. doi: 10.1017/sus.2019.8

Zeller, D., Booth, S., and Pauly, D. (2006). Fisheries contribution to the gross domestic product: underestimating small-scale fisheries in the Pacific. *Mar. Resour. Econ.* 21, 355–374. doi: 10.1086/mre.21.4.42629521

Zeller, D., Harper, S., Zylich, K., and Pauly, D. (2015). Synthesis of underreported small-scale fisheries catch in Pacific island waters. *Coral Reefs* 34, 25–39. doi: 10.1007/s00338-014-1219-1

Zeller, D., Hood, L., Palomares, M. L. D., Sumaila, U. R., Khalfallah, M., Belhabib, D., et al. (2020). Comparative fishery yields of African large marine ecosystems. *Environ. Dev.* 36:100543. doi: 10.1016/j.envdev.2020.100543

Zeller, D., Palomares, M., Tavakolie, A., Ang, M., Belhabib, D., Cheung, W., et al. (2016). Still catching attention: Sea Around Us reconstructed global catch data, their spatial expression and public accessibility. *Mar. Policy* 70, 145–152. doi: 10.1016/j.marpol.2016.04.046

Zeller, D., Rossing, P., Harper, S., Persson, L., Booth, S., and Pauly, D. (2011). The Baltic Sea: estimates of total fisheries removals 1950–2007. *Fish. Res.* 108, 356–363. doi: 10.1016/j.fishres.2010.10.024

Ziegler, F., Eigaard, O. R., Parker, R. W. R., Tyedmers, P. H., Hognes, E. S., and Jafarzadeh, S. (2019). Adding perspectives to: "Global trends in carbon dioxide (CO2) emissions from fuel combustion in marine fisheries from 1950 - 2016". *Mar. Policy* 107:103488. doi: 10.1016/j.marpol.2019.03.001

Conflict of Interest: The 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.

Publisher's Note: All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.