HISTORICAL RECONSTRUCTIONS OF MARINE FISHERIES CATCHES: CHALLENGES AND OPPORTUNITIES

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HISTORICAL RECONSTRUCTIONS OF MARINE FISHERIES CATCHES: CHALLENGES AND OPPORTUNITIES

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Editorial: Historical Reconstructions of Marine Fisheries Catches: Challenges and Opportunities

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Keywords: Asia, Africa, Caribbean, Mediterranean, marine fisheries, catch time series

Editorial on the Research Topic

Historical Reconstructions of Marine Fisheries Catches: Challenges and Opportunities

Fishing is conducted to generate a catch, and hence the success or not of a fishery ought to be measured by its catch. Not over a short time: it is too easy to pillage a resource and generate high catches for a short time. The point is to generate reasonably high catches over a longer time period. Few fishing cultures appear to have been able to achieve this. Of the few examples, those that come to mind are: Polynesia with its century old coral-reef based fisheries, and the Pacific Northwest, where salmon-based cultures, including individual villages, have persisted for millennia.

Thus, a long-term perspective is required to evaluate the status of fisheries. The challenge, however, for most fisheries, is that quantitative data from centuries past are difficult or impossible to obtain. Thus, for the catch reconstruction work undertaken by the *Sea Around Us*, 1950 was chosen as a compromise, to balance as early a date as possible, with data availability. The year 1950 was the first year of the decade that followed on the murderous 1940s, marred by a series of conflicts which culminated in the Second World War. Physical and administrative structures were being rebuilt and the United Nations and its "technical organizations" (including the Food and Agriculture Organization, i.e., FAO) started their project of quantifying the world (Ward, 2004), which—among other things—resulted in FAO issuing from 1950 an extremely useful *Yearbook of Fisheries Statistics* (now replaced by a website from which its world fisheries and aquaculture statistics are made available). Thus, 1950 was an appropriate year to choose as a baseline for a reconstruction of catches of the world's marine fisheries.

Also, because the re-industrialization of the fisheries in richer countries had just begun, for example, in Russia (Popov and Zeller) or Bulgaria (Keskin et al.) and of what was later to become developing countries of Africa, the Caribbean, and Asia, were still colonies of European countries—for example, Vanuatu (Léopold et al.) and the Pitcairn Islands (Coghlan et al.). Also, the catches from the early 1950s offered a stark contrast to the later growth of fisheries in the global south, as in Thailand (Derrick et al.), the Turk and Caicos Islands (Ulman et al), or Oman (Khalfallah et al.). This provides the context for the seven contributions in this research topic based on *Sea Around Us* catch reconstructions.

Of the other six contributions, half reach even deeper back into the past, and thus provide deep insights on ecosystem changes in the Mediterranean (Fortibuoni et al.), the small-scale fisheries of Flores, Indonesia (Ramenzoni), and the oyster fishery of Chesapeake Bay, USA (Schulte). The three other contributions, with shorter time horizons, focus instead on important issues, ranging from the effectiveness of monitoring, control, and surveillance in West Africa, where much of the coastal catch is illegally taken by distant water fleets from Asia and Europe (Doumbouya et al.), and the local ecological knowledge (Macusi et al.) and the incomes of small-scale fishers in the Philippines (Anticamara and Go).

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To complete the history of each fishery, these contributions required the assembling of hard-to-obtain older time-series data and filling the gaps using qualitative inferences and reasonable assumptions. As such, these contributions jointly document the impact of the "shifting baseline" concept (Pauly, 1995), which highlighted the accommodation with the biodiversity loss that results from ignoring past evidence of species abundance. Indeed, the one-page contribution in which this argument was presented is nowadays seen as one of the founding documents of "marine historical ecology," a now vibrant (sub-) discipline of ecology (Engelhard et al., 2015).

Marine historical ecology generates, in rigorous fashion, insights about the past exploitation and states of marine ecosystems to inform current management. In the process, practitioners have been able to demonstrate that past population abundance that are projected backward from present abundances and trends often miss the mark, while abundances reconstructed using the various methods of marine historical ecology tend to be much higher than initially assumed, as stunningly illustrated by Rosenberg et al. (2005). This obviously is of utmost importance for public policy, e.g., in debates about rebuilding fish populations that have been impacted by overfishing.

We thus hope that the contributions herein will not only assist in managing the fisheries in question, but will also, either as jointly or individually, encourage the further development of marine historical ecology, and thus help society make informed decisions while managing marine fisheries resources.

AUTHOR CONTRIBUTIONS

MP led the editing of the research topic with help and advice from DP.

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Reconstructed Russian Fisheries Catches in the Barents Sea: 1950-2014

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The management of marine living resources that straddle country borders has historically been a challenge, particularly in cases where political tensions are high. The jointly managed fisheries resources in the Barents Sea are a notable exception, wherein the Russian Federation (formerly Soviet Union) and Norway have relatively successfully managed fish stocks together since the 1950s, including during the high tensions of the Cold War and the dissolution of the Soviet Union. Using ICES statistics as reported baseline landings, the total catch of the region by the Russian fisheries was reconstructed for the period 1950-2014. Total catch was divided into reported landings, unreported landings, and discards, and assigned to four sectors: industrial, artisanal, recreational, and subsistence. Unreported landings and discards between 1950 and 2014 accounted for ∼12 and 55% of the total catch, respectively, with discards being substantial in the early decades. A majority of the catch was caught using pelagic and bottom trawls, contributing to the high rate of discards. Both discards and landings reached their peak in the 1970s, after which overexploitation contributed to numerous stock declines. Stocks recovered in the 1990s following adoption of legislation and gear regulations limiting discards as part of a joint effort by Norway and Russia to more sustainably manage stocks. The trend of declining Russian Barents Sea catches after the 1980s matches global trends of declining catch, although the present case appears to be mainly due to more successful management interventions. It is assumed that small-scale fisheries removals are minor in the region, but further research to refine estimates of small-scale fishing can improve upon the present study. While this study highlights historical declines in catch due to overexploitation, it does not explore fluctuations in catch caused by environmental variation. In the rapidly warming Arctic region it is of vital importance to understand how stocks may be further affected by climate change in addition to fishing pressure.

Keywords: trawling, discards, cooperation, unreported catches, industrial fisheries, artisanal fisheries, subsistence fisheries

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INTRODUCTION

Natural resources are often casualties in human disagreements and political struggles, and resources in the sea are no exception. International cooperation in fisheries is particularly important as fish are not a stationary resource that respect human-made boundaries. In one of the more unique political arrangements in recent history, Norway and the former Soviet Union (now Russian Federation) have created one of the more successful internationally managed fish stock sharing systems in the world, despite high political tensions and the collapse of the Soviet Union (Gullestad et al., 2014; NMFCA, 2018). In a world with increasing international tensions, Norway and Russia's relatively steady efforts at ongoing cooperation on marine resource use in the Barents Sea through the political thicket of the twentieth century show that perhaps some good can happen if both parties are willing to continue dialogue and cooperation, no matter the circumstances.

The Barents Sea is a relatively shallow sea nestled in the far north of Europe, between the mainland of Norway and north-west Russia, the islands of the Svalbard archipelago to the west, and the Russian islands of Franz-Josef Land and Novaya Zemlya to the east (here defined as ICES areas Ia and Ib; **Figure 1**). Co-management of living resources of the Barents Sea first began in 1923 with the negotiation of seal hunting regulations, some of which are still in effect today, while research cooperation between the two countries began even earlier in the l890s (Alexseev et al., 2011). This relationship began to deepen following the establishment of the International Council for the Exploration of the Sea (ICES) in 1902, which both the USSR and Norway were a part of Alexseev et al. (2011). However, Russian participation with ICES ended in 1914 following the outbreak of WWI, and the working relationship between Norway and the USSR deteriorated until the 1950s. It was in 1958 that the region experienced a rebirth in scientific cooperation and knowledge sharing: scientists from the USSR's Polar Research Institute of Marine Fisheries and Oceanography (PINRO or "ПИНРО") visited Norway's Institute of Marine Research (IMR, or "Havforskningsinstituttet") to participate in the first ever Soviet-Norwegian Fishery Conference (Alexseev et al., 2011). The year 1977 brought new challenges with the declaration of Exclusive Economic Zones (EEZs) by both the USSR and Norway. Previously, much of the Barents Sea was high seas water, and thus in principle open for outside countries to exploit. These EEZ declarations left only a small patch of the Barents Sea at the center with the status of high seas waters (ICES area Ia, **Figure 1**), which effectively left the management of the majority of the Barents Sea in the hands of the two countries. In order to facilitate the declaration of EEZs and subsequent joint management, the Joint Norwegian-Russian Fishery Commission (JNRFC) was established in 1975-76.[1] IMR and PINRO continued conducting joint research surveys and symposia as members of the JNRFC to assess the stocks of important commercial fish, such as herring (*Clupea harengus*), haddock (*Melanogrammus aeglefinus*), and cod (*Gadus morhua*), and provide legal recommendations for quotas and stock management. Norway was therefore one of the first countries to successfully establish economic, scientific, and diplomatic cooperation with the Soviet Union during the Cold War, and this strong working relationship has generally continued into today.

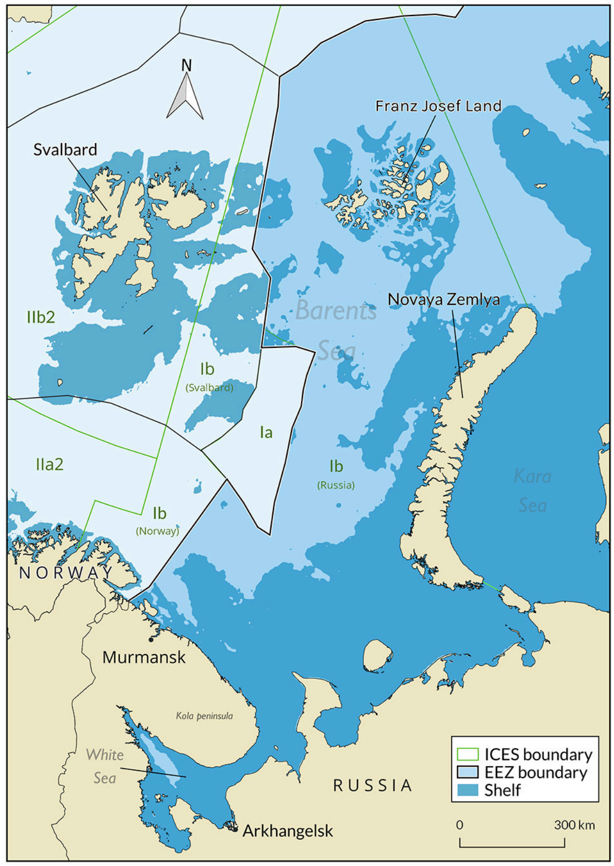

FIGURE 1 | Map of the Barents Sea region, including the Exclusive Economic Zones (EEZ) and shelf areas (to 200 m depth) of the Russian Federation and neighboring Norway. ICES statistical areas fall within the green boundaries. We define the Barents Sea here as corresponding to ICES areas Ia and Ib. The White Sea falls between the Kola peninsula and Arkhangelsk.

The Barents Sea and adjacent White Sea (off Arkhangelsk, **Figure 1**) were among the first areas of the world to develop large-scale commercial fishing. Over 200 fish species are found in the Barents Sea, and ∼21 species are commercially targeted by Russian fisheries (Wienerroither et al., 2011). Russian commercial fishing activities in the Barents Sea have existed since the fifteenth century, but were primarily coastal and artisanal in nature, with oar powered vessels and hand lines until the arrival of the first Russian steam trawler in 1906 (Benko and Ponomarenko, 1972; Grekov and Pavlenko, 2011). Prior to the Russian Revolution, trawling pressure came primarily from English and German trawler fleets, which outnumbered Russian trawlers four hundred to one until the 1920s (Shevelev et al., 2011). It was not until WWII that both the Russian trawl fishery and research capacity in fish stocks grew. Two main

[1] http://www.jointfish.com/.

fleets operated in the Barents region: the Arkhangelsk fleet and the Murmansk fleet (**Figure 1**). By 1913, the Arkhangelsk fleet had four steam trawlers in operation and by 1920 full-scale development of the Russian trawler fleet was underway. In 1916, the Soviet Union built the city of Murmansk to serve as an industrial and fisheries center and the Murmansk fleet was born (Grekov and Pavlenko, 2011; Shevelev et al., 2011). This, along with improvements in technology, e.g., in 1931 the first diesel operated trawler was introduced, resulted in growth of the fishing fleet from 17 industrial fishing vessels in 1927 to 562 trawlers in Murmansk alone by 1955 (Grekov and Pavlenko, 2011). From 1950 until 1980, the bottom trawl was the predominant fishing gear in the Russian Barents Sea fishery. Trawling only declined with the decline of Atlantic cod (*G. morhua*) and haddock (*M. aeglefinus*) stocks in the 1980s (Matishov et al., 2004) and the weakening of the Soviet economy, which meant cheaper, less fuel-intensive fishing techniques such as longline had to be employed (Grekov and Pavlenko, 2011). As a result of the collapse of the Soviet Union in the early 1990s, much of the Soviet distant-water fleet returned to focus on waters closer to home, including the Barents Sea (Grekov and Pavlenko, 2011; Shevelev et al., 2011). However, overall declines in Barents Sea fish stocks meant that despite the increasing fishing effort in the region there was no corresponding increase in catch (Grekov and Pavlenko, 2011; Shevelev et al., 2011; Greer, 2014). By 1996, Shevelev et al. (2011) note that "the Russian fishing industry was no longer profitable"; by 2001, fishing effort in the region had peaked and thereafter began declining (Greer, 2014); and by 2005, ∼280 trawl vessels worked the North Atlantic, less than half the number that did so in the 1950s (Grekov and Pavlenko, 2011; Shevelev et al., 2011). While the overall number of trawl vessels has declined, Russian Barents Sea fisheries are still dominated by bottom and pelagic trawls (Wienerroither et al., 2011; ICES, 2015a).

The objective of this study was to reconstruct total Russian fisheries catches (or fisheries removals allocated to Russia during the Soviet Union period) in the Barents Sea region for the period 1950-2014 using the catch reconstruction approach of Zeller et al. (2016), and builds upon and updates a previous preliminary reconstruction of Barents Sea catches by Jovanović et al. (2015). The catch reconstruction approach, first described in Bhathal (2005), develops comprehensive time-series estimates of catches missing from the reported catch baselines (i.e., unreported catches, as well as estimates of discards), and thus provides a more comprehensive picture of total removals from the marine environment. Historical time series data on total fisheries removals are crucial to fisheries management and policy, as they provide a core baseline dataset that can assist in the assessment of the populations upon which fisheries depends (Caddy and Gulland, 1983; Pauly, 2016). Furthermore, they embed any discussions on future fisheries development, management, and policy in the appropriate historical data context. While ICES stock assessment working groups have access to datasets that "outsiders" do not, and do consider some data on discards and unreported catches, these data are rarely made publicly available in sufficient detail due to confidentiality and political reasons, despite these fishes being a public resource (Zeller and Pauly, 2004). As actual total fisheries catches are generally higher than the reported data would suggest (Pauly and Zeller, 2016), we expect that the present study can assist public understanding and policy development for sustainable fisheries decisions by providing a more comprehensive historical baseline of likely total removals of fish from the Barents Sea by Russian fisheries since 1950.

METHODS

The International Council for the Exploration of the Sea (ICES) maintains a publicly accessible database presenting reported landings by country, taxon, ICES statistical area, and year for the period 1950-present[2] (ICES, 2017b). This database does not contain data on discards and other unreported catch. There are also some years with gaps in the data, such as the 1950-1954 gap during which the Soviet Union was not a member of ICES, and gap years where catch was likely not reported for certain species despite substantial catch being reported in years previously and subsequently. After slight adjustments to the ICES catch statistics to account for these gaps and disaggregation of Russian catch from the Soviet Union, we refer to these data as "ICES baseline landings" (see **Supplementary Material** for gap adjustments and USSR disaggregation). As the aim of this study was to determine total catch, six different unreported components of catch were identified, estimated and added to these ICES baseline landings: (1) unreported stock assessment landings (addressing discrepancies between ICES working group catch and ICES reported catch), (2) unreported illegal landings (mainly the result of organized crime and/or poaching), (3) unreported artisanal landings, (4) discards, (5) recreational catch, and (6) subsistence catch. Note that international reporting requests (e.g., FAO) specifically include non-commercial (e.g., recreational) landings, but explicitly exclude discards (Pauly and Zeller, 2016). We consider this anachronistic in an era of ecosystem consideration in fisheries (Pauly and Zeller, 2016).

Reported Landings

Taxonomic Disaggregation

Within the ICES baseline landings data, several years included catch statistics with very coarse taxonomic resolution, i.e., "Finfishes nei," "Flatfishes nei," and "*Anarhichas*" (wolffishes). These broad "nei" (or "not elsewhere included") categories are often reported to a finer taxonomic resolution in national statistics, suggesting that "nei" categories may be an artifact of the statistical reporting or harmonization process at ICES (Pauly and Zeller, 2015). These uninformative taxonomic groupings were taxonomically disaggregated based on best-available information and conservative assumptions about which species should be included in these categories (**Table 1**). "Finfishes nei" was disaggregated into the top 10 species caught proportionally by weight, excluding major commercially targetted species (i.e., not cod, capelin, or haddock). Non-major species were chosen under the assumption that they are less likely to be identified to the species or genus level in records, while valuable or

[2]http://www.ices.dk/marine-data/dataset-collections/Pages/Fish-catch-and-stock-assessment.aspx.

TABLE 1 | Taxonomic disaggregation of highly uninformative pooled taxonomic groups ("nei" = not elsewhere included) in the reported catch data for Russia and the former USSR.

Pooled group	Disaggregated species	Disaggregation (%)
Finfishes nei	*Boreogadus saida*	64.0
	Sebastes spp.	11.0
	Anarhichas lupus	9.0
	Eleginus nawaga	4.0
	Anarhichas minor	3.8
	Anarhichas denticulatus	3.2
	Pollachius virens	2.5
	Salmo salar	1.0
	Coregonus spp.	1.0
	Osmerus eperlanus	0.5
Flatfishes nei	*Pleuronectes platessa*	55.0
	Hippoglossoides platessoides	20.0
	Hippoglossus hippoglossus	12.0
	Platichthys flesus	11.0
	Glyptocephalus cynoglossus	2.0
Anarhichas spp.	*Anarhichas lupus*	89.0
	Anarhichas minor	6.0
	Anarhichas denticulatus	5.0

commercially important species with dedicated ICES stock assessment groups likely are. "Flatfishes nei" and "*Anarhichas*" were both disaggregated proportionally by weight of landed flatfish and wolffish species, respectively.

Spatial Disaggregation

Russian statistics for the Barents Sea have only been reported as ICES statistical area I, without subarea reference (**Figure 1**). In order to assign them to more spatially explicit locations, catch was split into each subarea: Ia (High Seas), Ib (Russian EEZ), or Ib (Norwegian EEZ, including Svalbard; **Figure 1**). Catch was split proportionally by surface area (**Table 2**). In doing so, most catch was allocated to Russia's EEZ, as that is the largest area, followed by Norwegian waters, followed by High Seas (Ia). As Norway and Russia have numerous bilateral fishing agreements, Russian fishing is indeed occurring in Norwegian waters (Nakken, 1998; FAO, 2007; ICES, 2015a). Very little information could be found on more spatially explicit fishing locations that could be applied to all data, as catch statistics are generally reported in broad geographical regions by national authorities and by ICES.

Assignment to Commercial Fisheries Sectors: Industrial vs. Artisanal

Generally, Russian fishing activities in the Barents Sea can be divided into three main groups by fishing gear: trawl, purse seine, and longline. According to an examination of the cod fishing fleet in the Barents Sea in 2004 (WWF, 2005), ∼150 trawlers under 15 m and 200 trawlers over 15 m were active. While nearly half of the fleet is small and could be considered artisanal in nature, we considered all fishing gears that are actively moved

TABLE 2 | Surface areas of individual ICES subareas in the Barents Sea, including EEZ division as derived by the *Sea Around Us* (Zeller et al., 2016). The Norwegian EEZ includes Svalbard waters.

Subarea	"Owner"	Area (km^2)	Area (%)
Ia	High Seas	68,154	4.19
Ib	Norwegian EEZ	360,751	22.17
Ib	Russian EEZ	1,198,336	73.64

through the water or across the seafloor while using engine power as industrial gear (or "large-scale") irrespective of vessel size, as defined in Martín (2012). Furthermore, given the heavy focus on offshore fishing by relatively large vessels throughout the Barents Sea, we considered the purse seiners and longliners as industrial as well. We therefore considered all landings reported to ICES as part of the industrial sector. Catches by artisanal (i.e., small-scale commercial) fleets were estimated as unreported catches as described below.

Unreported Catch

Six main components of unreported catch were estimated and added to the ICES reported baseline: (1) unreported stock assessment landings from ICES Working group reports, (2) unreported illegal landings (e.g., poaching), (3) unreported artisanal landings, (4) discards, (5) recreational landings, and (6) subsistence landings. The nature of unreported landings differed between the former USSR and the Russian Federation.

Unreported Stock Assessment Landings

Official ICES catch statistics are not corrected for unreported catches that may be included in ICES stock assessment working group reports (ICES, 2017a). We considered discrepancies between ICES publicly reported statistics and ICES Working Group reports used for stock assessment as "unreported stock assessment landings." Unreported landings were added for nine species using data from several ICES Working Group reports (ICES, 2001; 2015a; 2015b; 2015b; 2016). Unreported stock assessment landings added an average of 10% to the total reported landings.

Unreported Illegal Landings

Unreported illegal landings, such as obtained through poaching, reflect estimates of entirely unreported landings across the fishery and are criminal in nature. Unreported illegal landings, oftentimes to avoid state control (during the Soviet era) or as a result of organized criminal activity (poaching), occurred throughout nearly the entirety of the study period (O'Hearn, 1980; WWF, 2005; FAO, 2007; Burnett et al., 2008). Historical estimates of tons of underreported catch per ton of reported catch acted as "anchor points" for years where such estimates existed in the literature. In between anchor point years, these estimates of underreporting were linearly interpolated unless otherwise stated. A more in-depth historical context behind these anchor points is presented in the discussion.

We assumed unreported illegal landings were zero from 1950 to 1959. This reflects the conservative assumption that all landed catch was reported during the years of Stalin's rule and immediately following his death. From 1960 to 1975, unreported landings (as a percentage of reported landings) rose steadily from 0 to 33%, to reflect an estimate reported in O'Hearn (1980). This 33% rate was kept steady from 1976 until the last year of the Soviet Union (1990) and was increased thereafter to 40%, to reflect an estimate by the Norwegian Directorate of Fisheries that underreporting had reached a rate of "almost 50 per cent" (Burnett et al., 2008). As the estimate of almost 50% comes from a 2008 report, we assumed 2008 to be the last year of such high underreporting. An underreporting rate of 5% for the year 2014 was chosen given the 2015 Arctic Fisheries Working Group report estimating little to no underreporting (ICES, 2015a); for years between 2008 and 2014, the rate was linearly decreased from 40 to 5%.

The above rates of underreporting were applied to the reported baseline landings of all fish except Atlantic salmon (*Salmo salar*). According to the Working Group on North Atlantic salmon (WGNAS), illegal poaching of salmon is a "considerable" problem in the Barents and White Seas, particularly after the 1990s (ICES, 2015b). The report goes on to say that this high level of underreporting continued into the 2000s. Independent estimates of salmon poaching in the region indicate that poaching may reach underreporting levels as high as 50% (Spiridonov and Nikolaeva, 2005). As such, unreported catches for salmon followed the above unreported rates until 1991, at which point underreporting increased to 50% of reported landings and remained at that level until 2014.

Unreported Artisanal Landings

While all ICES reported landings for Russia were categorized as industrial, Russian national data from the Russian Federation Federal State Statistics Service (федерапьная служба государственной статистики) included catch statistics by species for the White Sea separately from the Barents Sea. These data do not seem to be included in the ICES data. Russian national data for only the Barents Sea generally matched ICES statistics very well, and were thus considered to be comparable to the ICES dataset; there was no comparable match between national data and ICES data for the White Sea. Therefore, we assumed ICES baseline statistics did not include catches for the White Sea, and added the national White Sea data as unreported landings. Because the White Sea is a relatively small, sheltered, shallow body of water that is likely being fished by a smaller coastal fleet, we assumed that all landings from within the White Sea were artisanal in nature. Federal statistics were only available for the years 2010-2013, which were averaged and converted into a percentage of reported Barents Sea landings per year (i.e., 0.2%). For all years from 1950 to 2014, we therefore assumed that White Sea artisanal landings were equivalent to 0.2% of reported Russian Barents Sea landings, broken down by taxa as reported in the national data for the White Sea. These landings were designated as unreported artisanal. While artisanal fishing activity has existed in the Barents Sea region since 1950 (Shevelev et al., 2011), our estimate for the whole area is likely not a very comprehensive representation of artisanal fishing in the entire Barents Sea. We consider our approach to provide a very conservative minimal estimate of artisanal activities in these waters, and we would like to encourage further research on non-industrial fishing in the wider Barents Sea area.

Discards

Discards are unwanted fish (bycatch) that are caught in the process of actively targeting a more desirable species, and are especially common in non-selective fishing gears such as bottom trawls. Bycatch from industrial gears are often discarded overboard and generally experience high mortality rates. While discards happen in nearly all industrial fisheries, there is as of yet no official reporting of Russian discards by fishery within the Barents Sea (ICES, 2015a).

Discards were calculated by associating a fishing gear with a primary commercially targeted species, then using independently published estimates of bycatch rates for that gear to calculate the tonnage of discards per tonnage of landed catch. Discards were therefore calculated as a percentage of total landings (reported plus unreported) by major target taxa and gear associated with that target fishery. Only the largest commercial fisheries with the best available information on gear types were chosen to calculate discards; thus, our discard estimates may be underestimating other discards, as discards likely exist for all other fish caught and reported in the Barents Sea. As gear types and discard rates change over the years with improvements in technology and with changes in regulation, the gear type and discard rates associated with each fishery varied by decade. For example, the installation of sorting grids throughout various fisheries meant that discards decreased as time went on. Not only did discards decrease overall as the decades passed, but improvements in trawling technology and better targeting also meant the overall species composition of discards changed.

The exception to calculating discards by fishing gear was the crab fishery, where a flat discard rate was applied to all crab and miscellaneous marine invertebrate catches, regardless of how they were caught. While there was insufficient information available to associate the crab fisheries with specific gears, there were multiple independent estimates of rates of bycatch within the crab fishery in general.

Gear types

The *Sea Around Us* maintains a reconstructed catch database with standardized fishing gears assigned to each fishery wherever possible, and these gears were used for this reconstruction (Cashion et al., 2018). The main fisheries in the Barents can be divided into two categories: pelagic stocks and demersal stocks. Pelagic stocks include capelin (*Mallotus villosus*), herring (*C. harengus*), and polar cod (*Boreogadus saida*), all of which are primarily targeted by pelagic trawl, followed by purse seining. Demersal stocks include cod (*G. morhua*), haddock (*M. aeglefinus*), saithe (*Pollachius virens*), redfish (*Sebastes* spp.), northern shrimp (*Pandalus borealis*), wolffish (*Anarhicas* spp.), and Greenland halibut (*Reinhardtius hippoglossoides*) (Benko and Ponomarenko, 1972; Wienerroither et al., 2011; ICES, 2015a). All demersal stocks are primarily targeted by bottom trawl with the exception of the wolffish fishery, a majority of which is caught by

TABLE 3 | Percentage composition of catch by fishing gear types within Russian Barents Sea fisheries.

Stock		Pelagic trawl	Purse seine	Bottom trawl	Longline	Source
Pelagic	Capelin	84	16	–	–	Wienerroither et al., 2011
	Herring	84	16	–	–	Wienerroither et al., 2011
	Polar cod	84	16	–	–	Wienerroither et al., 2011
Demersal	Cod	–	–	93	7	Wienerroither et al., 2011
		–	–	95	5	ICES, 2015a
	Haddock	–	–	93	7	Wienerroither et al., 2011
		–	–	95	5	ICES, 2015a
	Saithe	–	–	93	7	Wienerroither et al., 2011
		–	–	100	–	ICES, 2015a
	Redfish	–	–	93	7	Wienerroither et al., 2011
	Northern shrimp	–	–	100	–	ICES, 2015a
	Wolffish	–	–	40	60	ICES, 2015a
	Greenland halibut	–	–	90	10	ICES, 2015a

longlining. A summary of the gear types used in each fishery and the source of the information is in **Table 3**.

Discard rates

Discard rates varied by fishing gear and decade, to reflect improvements in technology and changes in regulations. Six gear types were chosen and assigned to each fishery: pelagic trawl, purse seine, longline, shrimp trawl, finfish bottom trawl, and flatfish bottom trawl (**Table 4**). Previously published estimates of global fisheries discards (Alverson et al., 1994; Kelleher, 2005) were used to determine baseline discard rates for each fishery and gear type. Fishery- and location-specific estimates from Alverson et al. (1994) were used for all fisheries pre-1990. After 1990, discard rates were taken from the FAO's updated Kelleher (2005) discards estimates, and applied during years when sorting grids were introduced into various corresponding fisheries as noted in the literature. Sorting grid regulations were introduced for three fisheries during the study period: the northern shrimp trawl (1993), groundfish (including both finfishes and flatfishes) trawl (1997), and Greenland halibut flatfish trawl (2013; Dingsør, 2001; ICES, 2015a); the lower Kelleher (2005) discard rate estimates were therefore introduced in each of those fisheries during those years, respectively (**Table 4**).

For years between the older Alverson et al. (1994) rates and newer Kelleher (2005) rates, the discard rates were linearly interpolated. Only the lower, so-called "weighted" discard rates as presented in Alverson et al. (1994) and Kelleher (2005) were used, as they represent a more conservative estimate (Kelleher, 2005). Wherever possible, the gears used in geographic regions closest to the Barents Sea (e.g., "Northeast Atlantic") or targeting similar species (e.g., "North Sea shrimp trawl") were used. For a summary of changes in discard rates, see **Table 4**; for a more detailed description of how discard rates varied through time, see the **Supplementary Materials**.

Discard composition

Discard composition for the entire study period was adapted from IMR/PINRO joint trawling and longlining surveys conducted between 2009 and 2012 (McBride et al., 2014). These surveys were used to develop three "baseline" species compositions that are expected to be caught when trawling or longlining for fish: pelagic trawl species; bottom trawl species; and longline species. The baseline species compositions for pelagic trawls and bottom trawls were then modified over time to reflect the adoption of sorting grids and increased mesh sizes in the trawl fisheries. For more information regarding how discard compositions changed over time, see the **Supplementary Materials**; for a full timeline outlining discard changes through time, see **Table S1**.

Crab discards

After the experimental introduction of the non-native red king crab (*Paralithodes camtschaticus*) to the Barents Sea in 1961 in an attempt to start a successful crab fishery (Gjøsæter, 2009), crab fishing has slowly become more popular in the Barents Sea. Because no detailed information on bycatch in the Barents Sea crab fishery has been published, a 6.4% discard rate from a 13 year survey of a similar Bering Sea fishery was used instead (Armstrong et al., 1993). This discard rate was applied to king crabs and to miscellaneous marine invertebrates.

Recreational Fishing

Recreational fishing has historically been popular in Russia (FAO, 2007), particularly for salmon on the Kola Peninsula in the Barents Sea region (**Figure 1**; ICES, 2012, 2015b). The ICES planning group on recreational fishing indicates that on average, recreational fishing accounts for 2–8% of a country's total reported landings (ICES, 2010). However, as there is little to no data on recreational fishing in the Barents Sea region prior to 1990, a likely conservative recreational fishing rate of 0.5% of reported landings was applied for the period 1950-1990. 1990 was likely the year when recreational fishing was first "officially" opened to foreign tourists, and it is assumed that recreational fishing increased in popularity with the increase in tourism to the region after the fall of the Soviet Union. Thus, it was assumed

TABLE 4 | Discard rates as a percentage of retained catch (landings) by major gear types over time for the Russian Barents Sea fisheries.

			Shrimp grids	Groundfish grids	Halibut grids	
	1950–1989	**1990–1992**	**1993–1996**	**1997–2012**	**2013**	**Fisheries**
Pelagic trawl	0.2	3.5	3.5	3.5	3.5	Herring, capelin, polar cod
Purse seine	24.8	1.2	1.2	1.2	1.2	Herring, capelin, polar cod
Bottom trawl (finfish)	283.8	283.8	–	19.6	19.6	Cod, haddock, saithe, redfish, wolffish
Bottom trawl (flatfish)	283.8	283.8	–	53.1	26.6	Greenland halibut
Longline	78.4	7.5	7.5	7.5	7.5	Cod, haddock, saithe, redfish, wolffish
Shrimp trawl	144	–	5.4	5.4	5.4	Northern shrimp

Dashes indicate "transition years" between Alverson et al. (1994) and Kelleher (2005) rates during which discard rates were linearly interpolated. 1993, 1997, and 2013 were years during which sorting grids were introduced in the northern shrimp, groundfish, and Greenland halibut fisheries, respectively.

that from 1991 onwards, the lower end estimate of 2% from ICES (2010) was chosen for calculating recreational catch.

The exception to the data-poor recreational sector in Russia's Barents Sea waters is recreationally caught Atlantic salmon (*S. salar*). Recreational catches of salmon after 1991 are exceptionally well documented by the Working Group on North Atlantic salmon (WGNAS; ICES, 2015b). Data on the number of salmon that were caught and then retained each year in the recreational fishery were obtained from the 2015 Working Group report (ICES, 2015b). The average annual mean fork lengths and whole weights of Atlantic salmon, for all sea ages, for each year from 1991 to 2012, were published by the National Oceanic and Atmospheric Administration (NOAA) and used to convert the number of salmon caught to the weight of salmon caught (Sheehan et al., 2013). For the years 2013 and 2014, the same weight as in 2012 was used.

After calculating the total recreational landings per year, the estimated catch of salmon for that year was subtracted from the total. The recreational catch without salmon was then split evenly between seven commonly targeted recreational species described on numerous Russian fishing websites: cod (*G. morhua*), navaga (*Eleginus nawaga*), polar cod (*B. saida*), wolffish (*Anarhicas lupus*), haddock (*M. aeglefinus*), saithe (*P. virens*), and pollack (*Pollachius pollachius*).

Subsistence Fishing

While the Soviet Union had public cafeterias to ensure nobody went hungry, food shortages were common and diets were supplemented with home cooking. However, obtaining groceries often involved waiting in long lines and paying exorbitant prices. It is likely that non-commercial catching of fish for family consumption (subsistence) complemented the rural diet, particularly in coastal communities.

Catch from subsistence fishing was calculated in two steps: first, the Russian rural population of the Barents Sea was estimated; second, this population estimate was multiplied by per-capita estimates of fish consumption in the USSR and Russia. Per-capita consumption rates were adjusted through time to reflect changes that are noted in the literature. Population data for the period from 1950 to 2001 were obtained from Populstat[3], while from 2002-onwards Russian census data for the years 2002 and 2010 were used. For the years between 2002 and 2010, population data were interpolated; for the years 2010 to 2014, estimates of total population size provided by the Federal State Statistics Service[4] were used. For both per-capita consumption rates and population, estimates in years between data points were linearly interpolated. See **Supplementary Materials** for more details.

In order to estimate the amount of fish consumed that were actually caught via subsistence fishing (as opposed to being purchased at market), we relied on the conservative estimate derived in the Russian Black Sea fisheries reconstruction (Divovich et al., 2015). Thus, it was assumed that 5% of all fish consumed was caught via subsistence fishing until just after the dissolution of the USSR (1992), thereafter increasing to 20% by 1995 and 26% by 2002 to reflect a decreased reliance on government food services and the increased food costs associated with the collapse of state subsidies (Divovich et al., 2015). The derived per-capita subsistence catch rate was then applied to the estimated rural population around the Barents Sea to estimate a likely total tonnage of subsistence fishing. The species disaggregation for subsistence fish was kept the same as in recreational fishing, as both are small-scale fisheries that employ similar methods of fishing. We recognize that there may be overlaps between recreational and subsistence fishing.

RESULTS

Total reconstructed landings (i.e., retained, landed catch that does not include discards) averaged 473,000 t·year^{-1} during the 1950s and 1960s, peaking at ~1.5 million tons in 1977, and declining to a low point of 92,000 tons in 1990 before rebounding to average annual landings of 457,000 t·year^{-1} by 2014 (**Figure 2A**). Landings fluctuated substantially over the time period, with peaks and declines in landings occurring roughly every decade until the mid-2000s, after which landings remained more stable. Officially reported data (accounting for landings only, and excluding discards) under-represented actual total landings for most years, although for the earliest years (1950s)

[3]http://populstat.info/.

[4]http://www.gks.ru/wps/wcm/connect/rosstat_main/rosstat/ru/statistics/population/demography/.

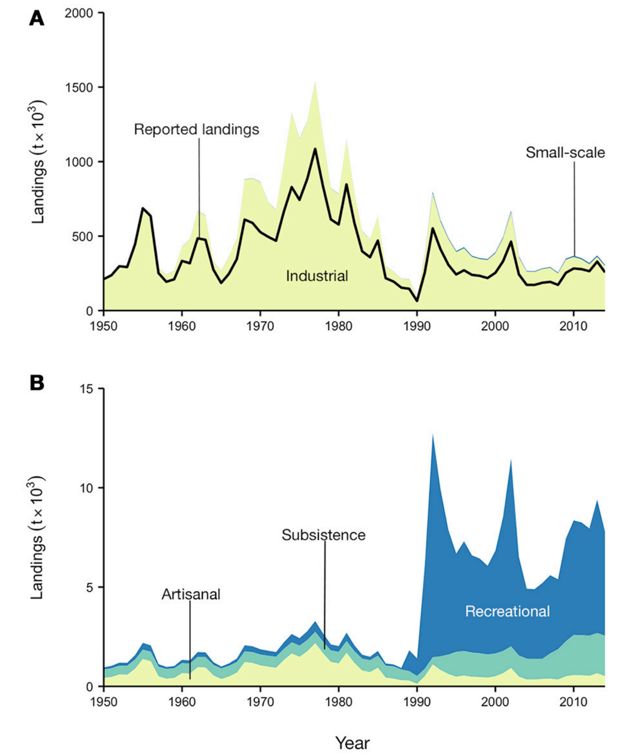

FIGURE 2 | Reconstructed landings for Russia in the Barents Sea with **(A)** total reconstructed landings from 1950 to 2014 by sector. Small-scale sectors (artisanal, recreational, subsistence) represent less than 1% of landings. Reported data are overlaid as a line graph. **(B)** Unreported artisanal, recreational, and subsistence landings, i.e., the "small-scale" component from **(A)**, here expanded for clarity.

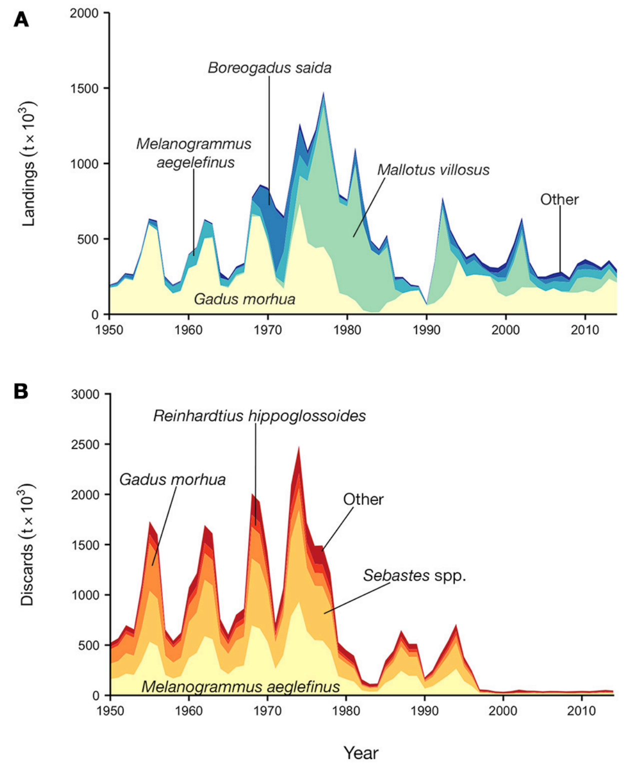

FIGURE 3 | Taxonomic composition of Russian Barents Sea fisheries catches with **(A)** total landings by the four major landed taxa and all other taxa pooled ($n = 59$); and **(B)** total discards by the four major discarded taxa and all other taxa pooled ($n = 19$).

and more recent years (mid-2010s), they seem to account more comprehensively for actual landings (**Figure 2A**).

A relatively small fraction of reconstructed landings was deemed to be small-scale in nature (**Figure 2A**), these being artisanal, recreational, and subsistence landings (all deemed unreported, **Figure 2B**). Combined, these three small-scale sectors averaged less than 1% of the total reconstructed landings. Landings in these three sectors remained relatively steady at an average of 1,700 t·year^{-1} until 1991, which was the year the Russian Federation was declared open to outsiders. At this point, recreational fishing increased dramatically to a total of nearly 12,000 tons in 1992; thereafter, unreported small-scale landings, while varying widely, averaged around 5,600 t·year^{-1} (**Figure 2B**).

Landings throughout the entire time period were dominated by Atlantic cod (*G. morhua*) and capelin (*M. villosus*), which largely drive catch patterns in the Barents (**Figure 3A**). By the mid-late 1970s, declines in cod stocks resulted in an increased demand for capelin. This demand for capelin rapidly pushed the total fisheries landings higher each year until the 1977 peak. Capelin landings thereafter declined until the first collapse of the stock in 1986-1990, second collapse in 1993-1998, and most recent stock collapse in 2004-2006 (**Figure 3A**). Haddock (*M. aeglefinus*), usually caught in fisheries targeting cod, followed similar patterns as the cod catch, while polar cod (*B. saida*) has its own dedicated smaller pelagic trawl fishery. In all cases, regardless of taxon, landings declined after the late 1970s peak. The "Other" category in **Figure 3A** consists of an additional 59 individual taxonomic groups, which on average accounted for ~12% of the total landings (**Figure 3A**). For individual taxon figures, see **Supplementary Figure S2**.

When considering total catches (i.e., including discards) over the 65 years examined here, the total reconstructed catch (77.2 million tons) was approximately three times higher than the total reported catch (25 million tons), a difference of over 52 million tons (**Figure 4**). While unreported landings were a component of this difference in catch (unreported landings accounted for 12% of total reconstructed catch), the 42.7 million tons of discards by far dominated: discards accounted for 55% of total reconstructed catch. Reported landings, then, accounted for only 33% of reconstructed catch (**Table 5**). Thus, total Russian catch (including discarded catch) in the Barents Sea increased from an average of 1.2 million t·year^{-1} in the early 1950s to a peak of 3.8 million tons in 1974, before declining to 330,000 t·year^{-1} by the mid-2010s (**Figure 4**).

Discards were a substantial component of total Russian catch in the Barents Sea until the wide-scale adoption of sorting grids and bycatch-reduction technology starting in the 1980s

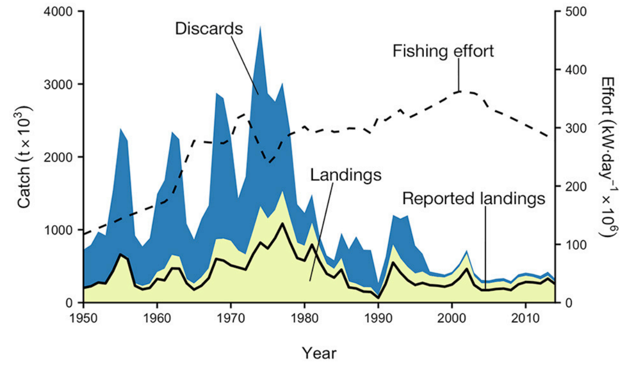

FIGURE 4 | Total reconstructed Russian catch in the Barents Sea, including discards and landings. Reported data (landings only) are overlaid as a black line graph. Fishing effort by the Russian fleet in the Barents Sea from Greer (2014) are overlaid as a secondary black dashed line graph. Note the separate y-axis scales for catch (t·year^{-1}) and effort (kW·day^{-1}).

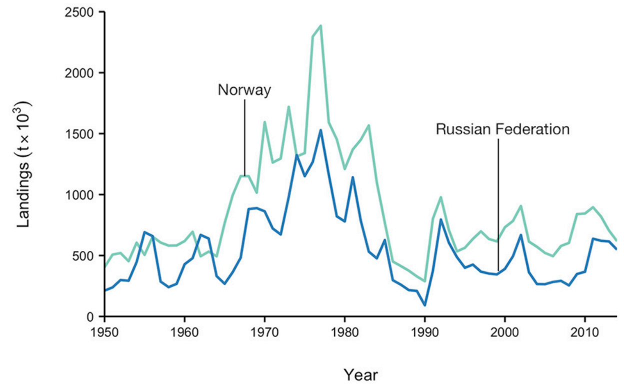

FIGURE 5 | Total reconstructed landings in the Barents Sea (ICES areas Ia and Ib only) by Norwegian (Nedreaas et al., 2015) and Russian fisheries.

TABLE 5 | Summary of total reconstructed catch for the entire 1950-2014 period, broken down by component.

	Catch (tons)	Percentage
Reported landings	25,073,804	32.5
Unreported landings	9,439,264	12.2
Industrial	*9,191,066*	*11.9*
Recreational	*145,505*	*0.2*
Subsistence	*52,545*	*0.1*
Artisanal	*50,148*	*< 0.1*
Discards	42,716,436	55.3
Total	77,229,503	100

Fishing sectors are italicized.

(**Figure 4**). Up until the peak in catches in 1977, discards represented the majority of Russian fisheries catch (greater than 50%). However, after the 1977 peak, discards began to decline. The major driver for this decline was the decrease in discard rates for purse seiners, longliners, and shrimp trawlers (**Table 4**). The introduction of sorting grids in the shrimp trawl fishery in 1993, followed by grids in the groundfish fisheries in 1997, meant that discards declined to an average of 11% of total catch by the early 2000s (**Figure 4**). Bottom trawling gear was the source of a majority of discards.

Discarded catches were dominated primarily by groundfish taxa, including haddock (*M. aeglefinus*), redfish (*Sebastes* spp.), and cod (*G. morhua,* **Figure 3B**). All three species are prominent bycatch species in the cod bottom trawl fishery. The widely distributed Greenland halibut (*R. hippoglossoides*) is the fourth most discarded species. At least an additional 19 other taxonomic groups (comprising the "Other" category) contribute to discarding, making up ∼11% of total discards (**Figure 3B**). For individual taxon figures, see **Supplementary Figure S3**.

DISCUSSION

The Barents Sea has historically been a rich fishing ground, with both Russia and Norway taking advantage of the natural abundance of the region. In the second half of the twentieth century, however, Russian fisheries in the Barents Sea have declined since a historical peak in the late 1970s, which is consistent with other findings indicating that global catch has peaked in the last decades of the twentieth century and is now declining (Pauly and Zeller, 2016). Historical patterns of Russian landings from the Barents Sea are notably quite similar to independently reconstructed Norwegian landings in the region (**Figure 5**; Nedreaas et al., 2015). Given the long history of co-management of Barents Sea resources and the 50–50 quota split agreed upon by the Joint Norwegian-Russian Fisheries Commission, this is not entirely unexpected (Holm and Nielsen, 2007). However, it is also indicative that overall declines in Barents Sea stock abundances are affecting both Russian and Norwegian fisheries equally (Matishov et al., 2004), and addressing any fisheries declines in the region must be tackled just as equally (NMFCA, 2018). In the past, the Joint Norwegian-Russian Fishery Commission has done this successfully (Alexseev et al., 2011; Gullestad et al., 2014), and reconstructed catch notably improved after the 1980s decline for both Russian and Norwegian fisheries.

Historical Context

The Black Market

The planned nature of the former Soviet economy was designed to allocate goods and services as effectively as possible across all sectors of Russian society. During the Stalin years in the first half of the 1950s, harsh authoritarian rule likely prevented the underground economy from thriving. After Stalin's death, however, widespread corruption and a weak economy led to the steady rise of the Soviet "second" or "shadow" economy—i.e., the black market. The black market was so important to maintaining Russians' access to goods and services that unregulated and illegal economic activities were pervasive in all sectors of the economy.

Nearly a third of all food purchased for the home was done so via this black market (Sampson, 1987), and nearly a quarter of the fish produced entered this black market (O'Hearn, 1980).

Soviet fisheries were not immune to this pervasive corruption. Illegal underreporting of catch began to steadily rise following Stalin's death in 1953 and the subsequent loosening of authoritarian control. The government, however, was not ignorant of underreporting; in fact, as one Soviet official noted, "the government knows exactly who is dealing in what—arrests are only made when there is some larger political reason," and data on fish and game in particular was "very good" (O'Hearn, 1980). In reports O'Hearn found in the Soviet press from the 1980s, Soviet observers lamenting the lack of environmental oversight commented on the "painfully large number" of poachers using the black market for personal gain. Small fines for poaching, along with the opportunity to fetch up to 4 to 10 times the "official" Soviet price, meant that poaching was commonplace throughout Soviet fisheries (O'Hearn, 1980). It was standard practice for fishers to first offer catch on the black market and then officially hand in the rest, and it was estimated that by the 1980s, roughly 25% of total commercial catch was meant for the black market. Official Soviet reports note that unreported landings may have been as high as 267% of reported catch (O'Hearn, 1980). To remain conservative, the lower estimate of 25% of total catch, or one third of reported catch, was chosen in the present study for calculating unreported commercial catch during this time period. It is possible that our study therefore underestimated actual catches during the Soviet period.

Following the dissolution of the Soviet Union, underreporting of catch only increased further in all of the former Soviet republics. Rates of illegal fishing increased as a result of the sudden collapse of Soviet regulations and controls and the opening of the market to the outside world as the iron curtain lifted (FAO, 2007). It is during this period from the late 1990s to the early 2000s that the Norwegian Directorate of Fisheries began apprehending Russian fishing vessels in the Barents Sea in order to enforce bilateral quotas and reported their conservative estimate of overfishing "of almost 50 per cent" by Russian ships in the Barents Sea (Burnett et al., 2008).

More recently, reports of illegal catch and underreporting have substantially decreased. This is mostly a result of greater cooperation and enforcement on the part of the Joint Norwegian-Russian Fisheries Commission. In fact, one of the most recent Arctic Fisheries Working Group reports estimates that there has been little to no illegal or unreported commercial catch in recent years (ICES, 2015a). In the case of cod in particular, reports from Norwegian-Russian analysis groups indicate that actual catches of cod have roughly matched officially reported landings of cod since 2009 (ICES, 2015a).

Our conservative estimates of unreported black-market landings during the Soviet era and immediately post-Soviet collapse has interesting implications for discards. Because discards are calculated as a proportion of both reported and unreported landed catch, calculated discards would have more than doubled for the time period if a higher rate of landings underreporting would have been applied, without any change in fishing effort. The subsequent collapse of certain fisheries (such as cod and capelin) could then potentially be attributed not only to the high rate of discarding in Soviet fisheries, but to a high rate of unreported catch as well. Future adjustments and improvements upon this catch reconstruction should aim to refine this estimate of underreporting in Soviet fisheries.

Patterns of Catch

The Barents Sea has experienced considerable fluctuations in both stock abundances and catch that has been documented by the Norwegians as early as 1860, if not earlier (Alexseev et al., 2011). In particular, the capelin stock has been known to be highly variable (Gjøsæter, 2009). Indeed, these large natural variations in capelin are one of the primary reasons fisheries scientists first came to research the Barents Sea (Alexseev et al., 2011). Similar fluctuations in cod, haddock, and saithe catches in the White Sea have been documented as well (Alexseev et al., 2011). Typically, these fluctuations are the result of abiotic factors unique to the biogeography of the region, such as the nutrient load of the system after winter (Matishov et al., 2004). These historical trends appear to have continued into the present day given the fluctuations in capelin and cod catch (**Figure 3A**).

Reported landings of cod in the earlier period of this study (1950-1980) before the stock collapse exhibit regular periodicity, which in turn drive the periodicity behind the majority of unreported landings and discards (**Figures 3A,B**). This periodicity has been well documented in the literature, where it has been found that the Barents Sea cod stock fluctuates in harmony with the Kola temperature cycle (Nakken, 1994; Yndestad, 2003; Ottersen et al., 2014). However, the regular rise and fall of reported catch appears to be unusual and does not closely match any cyclical trends of Norwegian cod catch in the region (**Figure 6**), and could potentially be driven by misreporting to ICES by the former Soviet Union. It remains to be determined if the substantial redirection of (unmonitored) catches to the black market may be a contributing factor to the unusually large fluctuations seen in USSR-reported data on

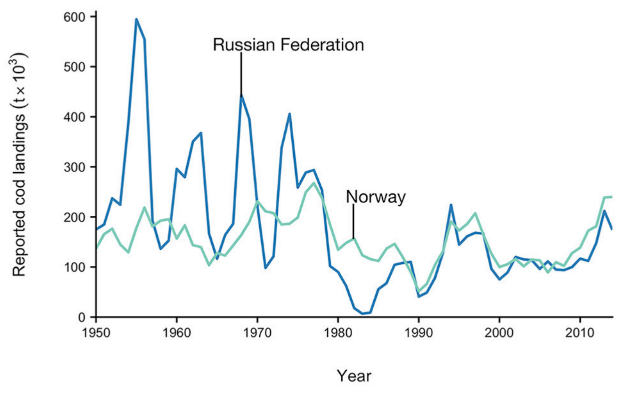

FIGURE 6 | Reported landings of cod (*Gadus morhua*) by both Norway and Russia in the Barents Sea. Norwegian reported landings of Barents Sea cod do not exhibit fluctuations in landings to the same degree that Russian reported landings of cod do.

cod catches in the first 3 decades of the present time series (**Supplementary Figure S1**).

Trawling

Russian fisheries in the Barents are heavily dominated by bottom and pelagic trawling. Trawling had already been established by the 1920s but became especially well developed by the 1950s (Grekov and Pavlenko, 2011; Shevelev et al., 2011) and only intensified through the 1960s-1970s. Initially, trawls primarily targeted cod and other demersal fish stocks, while capelin and herring were only caught as baitfish. As trawling intensified, however, these conventional stocks declined and both Norway and the Soviet Union began to develop purse seine and pelagic trawl fisheries for the industrial targeting of capelin in the Barents Sea (Gjøsæter, 2009). Both pelagic and bottom trawling continued to dominate Russian fisheries, while Norwegians steadily developed longline fisheries at an industrial scale (Gjøsæter, 2009). The first Russian automated longliner, borrowed from well-established Norwegian technology, was only introduced into the Russian fishery in 1982 (Gjøsæter, 2009). By the 1990s, the collapse of the Soviet Union, with the associated collapse of the subsidies system and resulting economic downturn, meant that there was a reduction of trawling effort. Trawlers required more fuel and active fishing time, and were thus more expensive to operate. This led to an overall reduction in catch along with marginal increases in the number of longliners in the Russian Barents Sea fishery (Grekov and Pavlenko, 2011). However, even to the present day, trawlers still dominate the Russian fleet, accounting for around 90% of total Russian catch in the Barents Sea (Nakken, 1998; Grekov and Pavlenko, 2011; Wienerroither et al., 2011; ICES, 2015a).

Recent declines in catch beginning in the 1970s are strongly tied to overexploitation (Matishov et al., 2004; Pavlovich, 2016). Given that Norwegian and Russian researchers and government bodies alike acknowledge overexploitation and discarding of underage fish in the 1970s-1980s as a primary cause for the decline of both pelagic and demersal stocks, including cod (Nakken, 1994; Gullestad et al., 2014), haddock (Kiseleva and Nichols, 2016), redfish (McBride et al., 2014) herring (Gjøsæter, 1995), and capelin (Beverton, 1990; Hjermann et al., 2004), it is not unreasonable to assume other stocks were affected by the excessive fishing effort in the region as well (**Figure 4**). Modern trawling technology is notorious for scooping up entire schools of fish, with midwater and bottom trawl fleets equipped with immense nets that can reach over 100 m in width and several hundred meters in length (Morgan and Chuenpagdee, 2003) and electronics such as echosounders, gyro-compasses, and radio direction finders (introduced into the Barents Sea fishing fleets in the 1950s; Shevelev et al., 2011), all designed to catch as many tons of fish as possible in one trip. Unless considerably larger mesh sizes are introduced, nets capture all age-classes of a stock, preventing any stock recovery let alone growth in the coming years, as happened with the Barents Sea herring and capelin stocks (Beverton, 1990; Alexseev et al., 2011; Shevelev et al., 2011). Bottom trawling, in particular, is known to be highly destructive, decimating slow-growing deep-water stocks of fish and damaging the benthic habitat structures that they may depend on (Løkkeborg and Fosså, 2011; Norse et al., 2012; Puig et al., 2012). The high rates of both pelagic and bottom trawling in combination with high rates of discarding as compared to the Norwegian fleet (Nedreaas et al., 2015) may therefore have contributed to the rapid declines of stocks in the Barents Sea in the 1970s-1980s.

Discarding

While unreported fishing is occurring in both countries, it does not appear to substantially differentiate the total amount of catch landed between the two countries (Nedreaas et al., 2015). The largest discrepancy in total catch between the two countries is instead primarily due to the high amount of discarding within the Russian fishery, as Russian fisheries primarily employ trawlers (rather than longliners; Nakken, 1998; Wienerroither et al., 2011; McBride et al., 2014). Bottom trawlers are especially well-known for being the most non-selective fishing gear, and our study is consistent with global findings that discarding is dominated by bottom trawling gear (Cashion et al., 2018).

Barents Sea discards seem primarily composed of haddock, redfish, and cod that were most likely discarded as a result of being underage or undersized (Spiridonov and Nikolaeva, 2005; Gullestad et al., 2014; ICES, 2015c). Nakken (1994) notes that in the 1980s, discards of cod only increased due to the poor condition of the fish—many of which were too small—which only exacerbated the corrosive cycle of discarding. Reconstructed discards indicate that after the widespread adoption of larger mesh sizes and sorting grids in the 1990s, discards declined considerably, which likely played an important role in the subsequent recovery of capelin, cod, and redfish stocks in the 1990s and 2000s. Redfish species have historically been particularly hard-hit by discarding practices, with golden redfish (*Sebastes marinus*) listed on the Norwegian endangered species list in 2010 and beaked redfish (*Sebastes mentella*) only recently showing signs of stock recovery as a result of improvements to trawling gear in the northern shrimp fishery (Wienerroither et al., 2011; McBride et al., 2014).

The discrepancy in discarding between the two countries may further be driven by the fact that discarding dead or dying cod and haddock has been illegal in Norway since 1987, while discarding has been banned (with some exemptions) for all fishes since 2009 (Gullestad et al., 2014; Ottemo, 2017; NMFCA, 2018). On the other hand, this may also explain why Norway's landed catch in the region is higher than Russia's: Norway simply may not be discarding as much of their catch (**Figure 5**). It has been noted that while discarding has been substantially reduced in the Russian waters of the Barents Sea, it is still a problem (Spiridonov and Nikolaeva, 2005; Burnett et al., 2008). While the Norwegian Directorate of Fisheries says that Russia has "discard regulations" in place for the Barents Sea cod, it is not clear that there is any explicit anti-discarding action in Russia aside from sorting grids (Gullestad et al., 2014). The European Union introduced the concept of a blanket ban on discarding in 2015[5], including in Russian waters within the Baltic (Bekyashev,

[5]https://ec.europa.eu/fisheries/cfp/fishing_rules/discards_en.

2017). Given the discard bans of its neighbors, including within its own waters, these regulations may have future implications in Russian Barents waters: a well-enforced discard ban by the Russian government would clearly benefit not only the shared fish stocks within Russian waters, but also Russian fleets.

Limitations

Small-scale fisheries are notoriously data deficient (Pauly and Charles, 2015; Zeller et al., 2015; Pauly and Zeller, 2016), and those of the Barents Sea are no exception. Numerous assumptions were made in our study while estimating artisanal, recreational, and subsistence fishing. While we are confident that our estimates are conservative and not overestimates, future research should further refine reconstructed small-scale fisheries removals.

The Barents Sea ecosystem today faces additional threats, being in the rapidly warming Arctic region (Johannessen et al., 2004; Drinkwater et al., 2011; Stige and Kvile, 2017). While catch has certainly declined in part due to the intense historical fishing pressure in the region, there are likely other factors at play, and it is uncertain exactly to what degree fluctuations in catch are the result of variable or unsustainably high fishing mortality or from other abiotic or climatic factors. There is evidence that species composition in the Barents Sea is shifting as communities move farther north with the warming waters (Kortsch et al., 2012; Frainer et al., 2017). In addition, the Barents Sea is not unaffected by the scourge of introduced species invasions, including the deliberate introduction of red king crab (*Paralithodes camtschaticus*), which can result in changes in food web, trophic, and community structure (Pedersen et al., 2018). As such, both climate change and introduced species may be contributing to changes in catch and catch composition that this study could not address.

CONCLUSIONS

The rise of industrial trawling in the Russian Barents Sea fisheries during the second half of the twentieth century came at an unfortunate price: a monumental five-fold increase in discards between 1950 and the mid-1970s. This, combined with steadily rising fishing effort in the region during the first five decades, resulted in numerous stock collapses and associated declines in catches. The subsequent poor state of the cod stock in the 1980s spurred one of the more successful jointly managed straddling fish stock management systems in recent history, and played a key role in the decline in discards by the 1980s. While reducing discards plays an important role in stock recovery (Matishov et al., 2004; Zeller et al., 2018), it is only with the cooperation of all parties involved and precautionary, long-term sustainable management that the recovery of the shared Barents Sea resources is possible (Misund et al., 2011). Preservation of the cod stock in the Barents Sea was the primary impetus behind this steady and impressive cooperative effort, with both Russia and Norway—two countries with major cultural and political differences—in agreement on closing fishing areas and reducing discards as a fisheries management strategy for cod recovery (Gullestad et al., 2014; Ottemo, 2017). It is in this sense that the cooperative effort to rebuild and manage stocks between both Russia and Norway is remarkable.

AUTHOR CONTRIBUTIONS

SP reconstructed the catch, and SP and DZ prepared the manuscript.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2018.00266/full#supplementary-material

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Corrigendum: Reconstructed Russian Fisheries Catches in the Barents Sea: 1950-2014

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In the original article, there was a mistake in **Table 3** as published. The "Northern shrimp" fishery was incorrectly cited as being divided into 93% "Bottom trawl" and 7% "Longline," and the incorrect source was cited. The corrected **Table 3** appears below.

The authors apologize for this error and state that this does not change the scientific conclusions of the article in any way. The original article has been updated.

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TABLE 3 | Percentage composition of catch by fishing gear types within Russian Barents Sea fisheries.

Stock		Pelagic trawl	Purse seine	Bottom trawl	Longline	Source
Pelagic	Capelin	84	16	–	–	Wienerroither et al., 2011
	Herring	84	16	–	–	Wienerroither et al., 2011
	Polar cod	84	16	–	–	Wienerroither et al., 2011
Demersal	Cod	–	–	93	7	Wienerroither et al., 2011
		–	–	95	5	ICES, 2015a
	Haddock	–	–	93	7	Wienerroither et al., 2011
		–	–	95	5	ICES, 2015a
	Saithe	–	–	93	7	Wienerroither et al., 2011
		–	–	100	–	ICES, 2015a
	Redfish	–	–	93	7	Wienerroither et al., 2011
	Northern shrimp	–	–	100	–	ICES, 2015a
	Wolffish	–	–	40	60	ICES, 2015a
	Greenland halibut	–	–	90	10	ICES, 2015a

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Thailand's Missing Marine Fisheries Catch (1950–2014)

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Overexploitation of marine resources has led to declining catches in many countries worldwide, and often also leads to fishing effort being exported to waters of neighboring countries or high seas areas. Thailand is currently under pressure to curb illegal fishing and human rights violations within its distant water fleets or face a European Union import ban. Simultaneously, Thailand is attempting to reduce fishing effort within its Exclusive Economic Zone (EEZ). Crucial to these endeavors is a comprehensive knowledge of total fisheries catches over time. A reconstruction of fisheries catches within Thailand's EEZ and by Thailand's fleet in neighboring countries' EEZs was undertaken for 1950–2014 to derive a comprehensive historical time series of total catches. This includes landings and discards that were not accounted for in official, reported statistics. Reconstructed Thai catches from within Thailand's EEZ increased from approximately 400,000 t·year^{-1} in 1950 to a peak of 2.6 million t·year^{-1} in 1987, before declining to around 1.7 million t·year^{-1} in 2014. Catches taken by Thai vessels outside their own EEZ increased from 52,000 t·year^{-1} in 1965 to a peak of 7.6 million t·year^{-1} in 1996, before declining to around 3.7 million t·year^{-1} by 2014. In total, reconstructed catches were estimated to be nearly three times larger than data reported by Thailand to the Food and Agriculture Organization of the United Nations (FAO). Reconstructed Thai distant-water fleet catches were almost seven times higher than the comparable non-domestic catch deemed reported for Thailand. Thai landings from recreational fishing were conservatively estimated for the first time, and while they contributed less than 1% of current catch, they can be expected to grow in volume and importance with increasing tourism. As Thailand takes measures to reduce fishing effort within its EEZs and increases monitoring and enforcement of illegal and foreign fishing, it should take note of the present catch reconstruction as a comprehensive historical foundation that can point to needed improvements in data collection, policy development, and monitoring and enforcement.

Keywords: artisanal fisheries, catch reconstruction, industrial fisheries, large-scale fisheries, recreational fisheries, small-scale fisheries, subsistence fisheries, unreported catches

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INTRODUCTION

Catches from global fisheries have been declining since the mid-1990s due to global overfishing, mainly by industrial fleets, and resource depletion in many areas (Pauly and Zeller, 2016a,b, 2017a). As marine species respond to ocean warming, which will have severe impacts in tropical regions (Cheung et al., 2010), fisheries in ecosystems that are already under intense pressure will need to be managed in more precautionary manner in order to reduce overfishing, and have any hope of eventually turning toward sustainability (Pauly et al., 2002).

In many developing countries, fisheries catch data are often the only information available on their fisheries (Pauly, 2013), and can be used for first-order evaluation of stock status (Froese et al., 2012, 2013; Kleisner et al., 2013). Catch data can also be used for stock assessments, even in the absence of other fisheries and survey data (Martell and Froese, 2013). One method that can help countries to develop more comprehensive statistics for fisheries policy development and management is through a catch reconstruction approach, whereby components of catch that are not accounted for in official national statistics (e.g., due to resource limitations) are estimated using a variety of alternative information sources (Zeller et al., 2016). Most importantly, catch reconstructions of fisheries data can provide comprehensive historical time series foundation of fisheries catches, and thereby overcome the "presentist bias" unfortunately inherent in most official reported data time series (Zeller et al., 2007; Pauly and Zeller, 2017a).

Fisheries in Southeast Asia are expected to be most heavily impacted by ocean warming due to their tropical location (Cheung et al., 2009, 2010) and developing economies (Sumaila et al., 2011; Lam et al., 2012). Furthermore, populations in these and other tropical areas are most reliant on fish for food and essential micronutrient security (Golden et al., 2016). Unfortunately, many fisheries in Southeast Asia are facing substantial pressures due to human population pressures, overexploitation of marine resources and poor enforcement or lack of fishing regulations targeting stock sustainability. Considerable amounts of catch are frequently unreported in Southeast Asia (e.g., Philippines: Palomares and Pauly, 2014; Cambodia: Teh et al., 2014), and in recent years, some countries have adopted stricter policies to try and curb illegal fishing by closing their EEZs to foreign fishing entities or destroying illegal fishing vessels (Amindoni, 2015; DoF, 2015; Makur, 2016).

In Thailand, the introduction of trawlers in the early 1960s led to rapid expansion of commercial fisheries and subsequent overexploitation, stock depletion, and changes in ecosystem trophic functioning (Pauly, 1979; Christensen, 1998; Pimoljinda, 2002; Pauly and Chuenpagdee, 2003). Declining catch from local waters (now Thailand's EEZ) in the early 1970s led to Thai trawlers traveling further afield to fish in the waters of neighboring countries in the South China Sea, Indonesian archipelago, and Bay of Bengal under a series of official and private agreements as well as illegally (DoF, 1979; Butcher, 2004). For example, the majority of Thailand trawlers fished without permission in the waters of neighboring countries until the mid-1980s when authorities started to enact laws to restrict access to their EEZs and began seizing Thai vessels that were fishing without permission (Butcher, 2004). As a result, Thailand turned to a series of official and private agreements in the 1990s with Indonesia, Myanmar, Australia, India and others, with the majority of these agreements focusing on Indonesia and Myanmar (Butcher, 2004). However, Indonesia and Myanmar have tightened restrictions on foreign fishing access within their EEZs since 2000, leading to a decline in catches by Thai vessels in foreign waters (Butcher, 2004). Furthermore, despite attempts by the Thai government to establish a commercial trawl ban within 3 km (later extended to 3 nautical miles) off Thailand's shore, violations continued due to weak monitoring, control and surveillance (MCS) and poor enforcement (Pimoljinda, 2002). However, all commercial fishing vessels of more than 10 gross tones are currently prohibited by law to fish within 3 nautical miles, and more effective MCS is being devised and implemented (DoF, 2015).

In addition to attempting to rebuild fisheries stocks within its EEZ, Thailand is currently under considerable pressure to assert stronger control over its fishing fleets in order to address rampant illegal fishing and serious accusations of labor abuses occurring on its vessels (McDowell et al., 2015). For example, the European Union (EU) issued a "yellow card" status to Thailand's marine fisheries in April 2015 as a warning to strengthen laws against illegal fishing, improve monitoring, control and surveillance systems (MCS) and traceability of landings, or face a ban of Thai exports into the EU market (Neslen, 2015). As Thailand is considered the fourth largest seafood exporter in the world, such a ban could be very damaging to the economy of Thailand (Anon, 2015; FAO, 2016). One action Thailand has taken to address human rights violations (Walk Free Foundation, 2016; see also https://www.globalslaveryindex.org/country/thailand/) was to impose a temporary ban of at-sea transshipments within and outside of its EEZ, and require all Thai vessels to return to port within 30 days at sea (Anon, 2017). Furthermore, Thai Union, one of the world's largest seafood producers, has committed itself in 2014 to refrain from purchasing seafood from vessels involved in transshipments in Thailand's EEZ (Anon, 2016). At the time of writing the present contribution, Thailand remains on the "yellow card" status despite improvements to its legal framework (DoF, 2015; Hodal, 2016). While these changes have led to multiple arrests for illegal fishing, some reports suggest that significant levels of illegal activity continue, with vessels responding by traveling further distances to fish rather than comply with strict new measures (Greenpeace, 2016; Hodal, 2016). However, as demanded by Thailand's current fisheries law, fishing vessels of over 30 gross tones (including transshipment vessels) must be equipped with a Vessel Monitor System (VMS) and every port-entry and port-exit must be reported to one of the 32 "Port-In and Port-Out Control Centers," which perform inspection at port, at sea, and on land to ensure that fishing vessels are operating legally[1] (DoF, 2015).

[1]http://www.europetouch.in.th/FileFishery/File/File1/F160202155948.pdf
http://www.iotc.org/sites/default/files/documents/2016/06/IOTC-2016-WPNT06-13_-_Thailand.pdf
http://thaiembdc.org/2016/03/07/thailands-fisheries-reform/

One component that can help inform general fisheries policy development is the historical context as provided through comprehensive historical baselines of data. Catch reconstructions (Zeller et al., 2016) can provide such baselines, by illustrating the best available picture of total catch trends over the last 60+ years. For example, through careful consideration of such data and associated trends, Thailand can evaluate the substantial social, economic as well as nutritional benefits obtained by their domestic small-scale and recreational fisheries sectors that are significantly under-represented in both national data systems as well as policy/management frameworks (Pauly and Zeller, 2016a, 2017a,b). Knowledge of the extent of unreported catches both by their domestic as well as their distant-water fleets (due to flag-state responsibilities) can help Thailand develop monitoring and enforcement protocols to better cover all sectors in order to make its fisheries more accountable as well as sustainable.

Our aim in this study was to reconstruct total Thai catches from marine fisheries for 1950–2014 by complementing official reported data with conservative estimates of unreported landings and discards taken by Thailand's fleets from within Thailand's EEZs (**Figure 1**) and the EEZs of neighboring countries, including Indonesia, Malaysia, Cambodia, Myanmar, Viet Nam, Bangladesh and Somalia. We view such reconstructions as living documents that are open to improvements and refinement, and we welcome input and feedback from interested parties to strengthen and improve on the existing data, as well as correct any potential errors.

METHODS

Total marine fisheries catches from 1950 to 2014 were estimated using the well-established catch reconstruction approach of Zeller et al. (2016), which was initially applied in Zeller et al. (2006) and first described in Zeller et al. (2007). The present contribution is an update of the original catch reconstruction of Thailand's marine fisheries from 1950-2010 which is detailed in Teh et al. (2015)[2]. Landings of large pelagic taxa such as tunas, billfishes and pelagic sharks by targeted industrial fisheries were excluded from the present dataset as they were estimated by a separate *Sea Around Us* study (Le Manach et al., 2016), but are integrated in the data available for Thailand at www.seaaroundus.org.

Reported Data

FAO FishStatJ data were compared to national reports produced by Thailand's Department of Fisheries (DoF) and found to provide a more comprehensive estimate of total reported catch for 1950–2014 for Indian and Pacific Ocean waters accessed by Thai fishing fleets, likely due to FAO's harmonization of multiple data sources in addition to national data (Garibaldi, 2012). National logbook survey data from DoF's Information Technology Centre were available from 1998 to 2009, and were used to derive estimates of reported industrial (i.e., large-scale sector) landings for each FAO statistical area during this period. Industrial fishing was assumed to have started in 1962 with the introduction of otter trawls in Thailand, and is thought to have increased to account for approximately 57% of reported landings by the mid-1960s (Butcher, 1999). Linear interpolation was used to estimate reported industrial landings between 1962–1965 and 1967–1997. An average ratio of industrial catch reported by the DoF logbook survey to total catch reported by FAO was determined for 1998–2009. This proportion was held constant and applied to the total FAO reported landings for 2010–2014 to determine industrial reported catch. Small-scale reported landings were calculated as the difference between total reported catch and industrial reported catch for 1950–2014.

Fishing in Other Countries

Trawling by Thai vessels expanded outside of Thailand's domestic waters (later being declared as Thailand's Exclusive Economic Zone, EEZ in 1981[3] in 1968 (Phasuk, 1987). The percentage of reported catch outside of Thailand's EEZ was interpolated to the 1998 level from zero in 1967 and was held constant at the 2009 proportion for 2010–2014. DoF logbook survey data from 1998 to 2009 were used to estimate the percentage of reported catch caught outside of Thailand's EEZ.

For 1968–2014, approximately 20% of total landings of demersal taxa were estimated to be unreported and originated from outside Thailand's EEZ, based on Phasuk (1987). Total unreported landings from outside Thailand's EEZ were assumed to be equivalent to the unreported landings of demersal taxa in 1968 and were linearly interpolated to 1996 when 70% of catch was caught illegally (Butcher, 1999) and deemed unreported. The 1996 percentage of unreported catch was carried forward to 2014. In order to prevent any double counting of unreported demersal landings from foreign waters, the unreported demersal catch was subtracted from total unreported landings outside Thailand's EEZ.

Landings taken outside of Thailand's EEZ were assigned to EEZs of neighboring countries based on the number of Thai boats known to have agreements to fish in the EEZs of other coastal countries according to data presented in Lymer et al. (2008). Landings taken in Indonesian and Malaysian waters were further allocated into individual EEZ components within Indonesia and Malaysia (to match *Sea Around Us* EEZ entity definitions, see www.seaaroundus.org) based on the relative EEZ component surface area ratios within each country. Offshore landings were allocated to EEZs at constant proportions for 1968–2014. These constant proportions thus may underrepresent potential time series variations of use of foreign EEZs by Thai fleets.

Small-Scale Artisanal and Subsistence Sectors

Although national catch reports by DoF have existed since 1957, reports did not include gear type until 1974 or community fishing

[2]The detailed technical catch reconstruction report for this study is freely available at http://www.seaaroundus.org/doc/publications/wp/2015/Teh-et-al-Thailand.pdf, and can also be found at the Thailand EEZ data pages at http://www.seaaroundus.org/data/#/eez/956?chart=catch-chart&dimension=taxon&measure=tonnage&limit=10 and http://www.seaaroundus.org/data/#/eez/957?chart=catch-chart&dimension=taxon&measure=tonnage&limit=10

[3]http://www.un.org/depts/los/LEGISLATIONANDTREATIES/PDFFILES/THA_1981_Proclamation.pdf

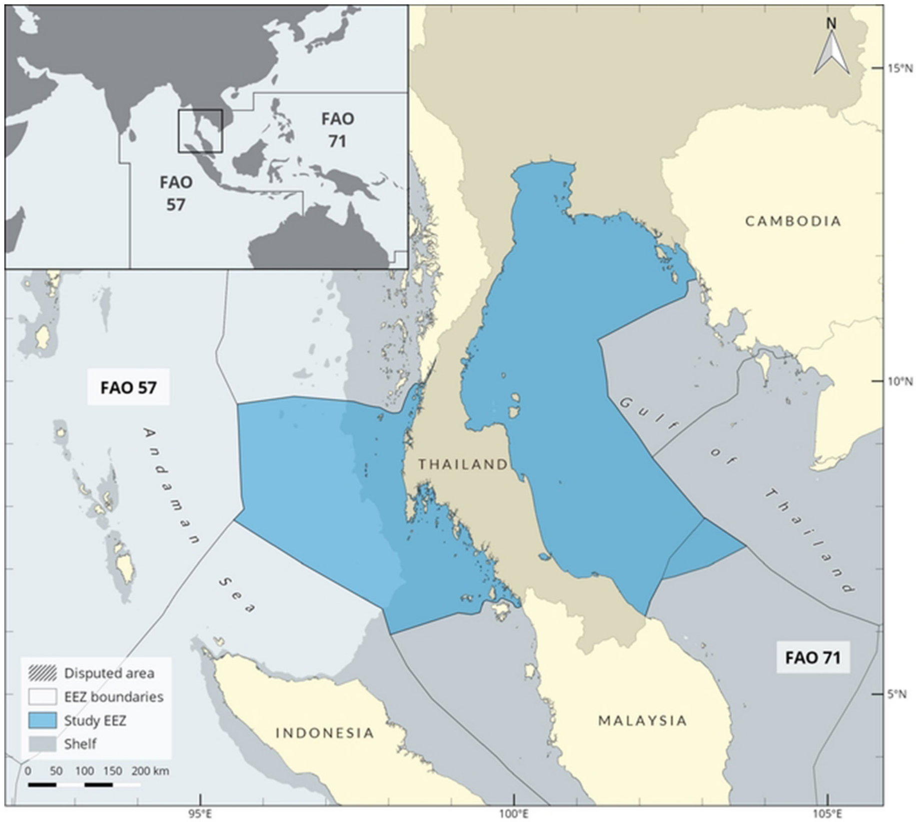

FIGURE 1 | Thailand's Exclusive Economic Zone (EEZ) and shelf waters to 200 m depth, in both the Andaman Sea (Eastern Indian Ocean, FAO area 57) and the Gulf of Thailand (Western Central Pacific, FAO area 71). Overlapping EEZ claims are indicated.

survey data until 1998. Phasuk (1987), based on DoF statistics, estimated that 8.3% of total catch from the Gulf of Thailand originated from small-scale fishing. In contrast, Juntarashote and Chuenpagdee (1991), based on hired labor data taken from the Marine Fisheries Census conducted in 1967 and 1985, estimated that 25.7% of catches were from small-scale fishing. To remain within the range of estimates suggested in the literature, an assumed average 17.4% of unreported small-scale catch was added to the reported data for all years prior to 1998.

From 1998 to 2014, unreported small-scale catches were estimated as a percentage of total reported catches based on published reports and case studies. Anchor points were established in 2002 and 2005. Total fishing effort was calculated using average annual fishing effort and number of fishers. The small-scale catch rate of 3 t·fisher^{-1}·year^{-1} in 2002 was estimated based on fishing effort from a case study of small-scale fisheries in the Gulf of Thailand (Lunn and Dearden, 2006), assuming fishers fished 9½ months of the year. Annual catch per fisher was multiplied by the 94,229 small-scale fishers derived for 2004 (Lymer et al., 2008). Based on this, unreported small-scale catches were equal to 11% of total reported marine fish caught in 2002. Panjarat (2008) estimated that unreported small-scale catches were equal to 16.5% of total marine fisheries catch in the mid-2000s. Thus, 11% of total reported catch was added as small-scale unreported catches for 1998–2002, and then linearly interpolated for 2003–2004 to the 2005 rate of 16.5%, which was maintained until 2014.

Further adjustments to unreported small-scale catches were performed by estimating local *per capita* fish consumption. Estimated small-scale landings as derived above were divided by the coastal population and graphed to visualize changes in consumption rates of domestic small-scale catches over time. These appeared to be underestimated from 1950 to 1970. Coastal population was defined as the total population living within 100 km of the coast and was sourced from NASA Socioeconomic Data and Applications Center (McGranahan et al., 2007). It was assumed that the coastal fish consumption rate in the 1950s and 1960s was similar to the consumption rate when the industrial sector began (i.e., 53 kg·person^{-1}·year^{-1}), but was conservatively used as 50 kg·person^{-1}·year^{-1} from 1950-1969, and reverted to unadjusted consumption rates for 1970–2014. Unreported small-scale sector catches from 1950 to 1969 were increased by the difference that was obtained from using the 50 kg·person^{-1}·year^{-1} consumption rate and the unadjusted consumption rate, multiplied by the coastal population.

Total estimated small-scale catches were divided between artisanal and subsistence sectors based on fisheries inventory surveys in the late 1960s and 1970s (Panayotou and Jetanavanich, 1987). Panayotou and Jetanavanich (1987) estimated subsistence households to make up 70% of fishing households in 1967. Subsistence households were defined to consist of two or fewer family members fishing. This assumption reflected the fact that households with fewer members would be more likely to have a lower economic status and therefore be more likely to engage in subsistence fishing. The 1967 proportion of subsistence fishers was maintained from 1950 to 1967. Anchor points of 70%, 74%, 67%, and 63% were estimated for 1969, 1970, 1973, and 1976, respectively (Panayotou and Jetanavanich, 1987). Linear interpolation was used to fill in years with missing data. Further information on subsistence fishing was not available for later years, and thus subsistence fishing was assumed to have decreased to 20% of small-scale catches in 2008 based on related data for Malaysia (Teh and Teh, 2014). This 2008 proportion was held constant to 2014. These percentages were directly applied to the total reconstructed small-scale catches to divide small-scale catches into artisanal and subsistence sectors in line with *Sea Around Us* database definitions (Zeller et al., 2016).

Discards

Thailand utilizes low value fish, often discarded in many other countries, to produce fish sauce and fish meal, and therefore, the rate of discarding is expected to be low (Pauly, 1996). The proportion of low value fish out of total catch was about 31% in 1999, 95% of that was derived by trawling (Kaewnern and Wangvoralak, 2004). As a result of the demand for low value fish, discards from small-scale and commercial fisheries are low (Funge-Smith et al., 2005), and estimated at 1% of total marine catches (Kelleher, 2005). However, conflicting information regarding the level of discarding exists. FAO (2004) estimated discarding from shrimp and demersal trawl fisheries at 22% of total landings while Kungsawan (1996) reported little discarding from Thai shrimp fisheries. In order to estimate discards, it was assumed that discarding initially occurred at 22% of reported catch when trawling began in the 1960s, but declined as a market for low value catch developed, which lead to an estimated discard level of 1% of total catches by 2000, which was held constant to 2014.

Recreational

Recreational fishing is performed by both tourists and Thai anglers. The approximate catch from recreational fishing was estimated by multiplying the number of recreational fishers by an average catch rate. Coastal recreational fishing by tourists and Thai citizens were estimated separately from "big game" fishing for tuna and billfishes.

Recreational fishing by locals was assumed to begin in 1980. In a global study of marine recreational fishing, the average participation rate of recreational fishers in Asia was 18.2% (Cisneros-Montemayor and Sumaila, 2010). Because most of Thailand's recreational fishing is performed by tourists[4], and to remain conservative, the national participation rate was assumed to be half the rate estimated by Cisneros-Montemayor and Sumaila (2010), i.e., 9.1% for 2010. Because recreational fishing is unlikely to be undertaken by people living under the poverty level (who would engage in subsistence fishing, see above) or far from the coast, local recreational catch per year n from 2010-2014 was estimated as:

$$C_{local,\,n} = (P_{coastal} - P_{poverty})_n \times T \times C_t$$

Where $C_{local,n}$ is local recreation catch in year n, $P_{coastal}$ is the number of people living within 100 km from the coast, $P_{poverty}$ is the number of people living under the poverty level (UNCTAD, 2012), T is the participation rate (here 9.1%), and C_t is the average annual recreational catch rate (kg·fisher^{-1}·year^{-1}). The number of recreational fishers for each year n prior to 2010 was estimated by adjusting the number of recreational fishers for year n by the relative changes to Thailand's *per capita* annual average GDP growth from year *n-1* to year n. GDP values were obtained from the United Nations Conference on Trade and Development (UNCTAD, 2012). No estimates of Thailand's per fisher recreational catch rates were found and so the recreational catch rate estimated for Malaysia (7 kg·fisher^{-1}·year^{-1}) was used as it was expected to be similar in Thailand (Teh and Teh, 2014). This catch rate was assumed constant from 1980 to 2014.

Recreational fishing by tourists was assumed to have only begun in earnest in 1990 (Kontogeorgopoulos, 1998). The number of coastal tourists that fish was multiplied by a tourist recreational catch rate for 1990–2014. The total number of tourists that participated in recreational fishing was determined for 2007 by multiplying the number of fishing operators by the number of clients per trip and number of fishing trips taken per year. In 2007, the number of big game operators and coastal fishing operators were assumed to be the same. An average of 22 big game operators was estimated for the Andaman Coast and half as many in the Gulf of Thailand based on available anecdotal accounts[5] Based on written reports and photos of tourist coastal fishing trips, an average of 4 clients per trip was assumed. Coastal fishing operators were assumed to run five fishing trips per week during peak months of November to March and half as many during non-peak months.

Estimates of tourist arrivals to Phuket for 1989–2005[6], 2008–2010[7] and 2014[8] were obtained and linear interpolation was used to estimate years without data. The change in tourist arrivals per year was used to estimate the number of coastal tourist fishers before and after 2007. Catches varied widely from 0 fish to 40 tunas caught by 7 participants in a single day[9] As a result, a likely conservative catch rate of 3 kg·fisher^{-1}·trip^{-1} was assumed for 1990–2014, assuming each tourist who fished participated in one fishing trip per year.

[4]https://www.angloinfo.com/how-to/thailand/lifestyle/sports-leisure/fishing

[5]http://megafishingthailand.com/guided-fishing-in-thailand/deep-sea-fishing-gulf-of-thailand-koh-chang-koh-kut/

[6]http://phuketland.com/phuket_links/touristinfo.htm

[7]http://www.c9hotelworks.com/press-best-year-ever-for-phuket-tourism-arrivals.htm

[8]http://www.thephuketnews.com/phuket-sees-over-seven-per-cent-increase-in-tourist-arrivals-on-2014-51903.php; http://www.c9hotelworks.com/downloads/phuket-hotel-market-update-2014-09.pdf

[9]http://www.tripadvisor.com/ShowUserReviews-g1389361-d1873466-r126026076-Puket_Fishing_Charters_Chalong_Phuket.html#REVIEWS

Big game fishing was assumed to be performed mainly by foreign tourists and so catches by locals were not estimated. Based on reports in 2007 and 2008 from a sport fishing operator[10], it was estimated that an average of three multi-day trips were performed per operator from the high season of March to November with an average of 2.6 clients per trip. During the non-peak season, clients were assumed to drop by 50%. Thus, for 2007, 2 115 big game fishers were estimated. The number of big game fishers was assumed to fluctuate with tourist arrivals in Phuket for 1990–2014 as described above. Average big game catch per client was estimated from trip reports and photographs posted on the internet[11]. From three trip reports, average catch per big game fisher was estimated at 60 kg·fisher^{-1}·trip^{-1} for 1990–2014, assuming fishers participated in one trip per year, with no catch and release.

Taxonomic Composition

The taxonomic composition of unreported landings was assumed to be similar to reported landings for each sector. Landings reported as "marine fishes nei" (nei = "not elsewhere included"; assumed to largely represent catches of low value taxa) were disaggregated with greater taxonomic composition based on the top 10 species that accounted for 60% of total composition from sampling surveys of so-called "trash" fish and low-value fish caught in the Gulf of Thailand in 1966 and 1999 (APFIC, 2007). The percentage breakdown of low-value species was interpolated between 1966 and 1999 anchors and held constant prior to 1966 and at the 1999 breakdown for 1999–2014. This composition was also applied to discards (**Table 1**).

Recreational catch composition was different for big game fishing and coastal fishing trips. Big game catches included marlins and sailfishes (Istiophoridae), tunas (Scombridae), dolphinfish (*Coryphaena hippurus*), barracudas (Sphyraenidae), and giant trevally (*Caranx ignoblis*) based on reports from fishing trips. Coastal recreational catch was composed of Scombridae, Carangidae, Sphyraenidae and demersal fish including Serranidae, Lutjanidae, Nemipteridae, Holocentridae, Lethrinidae and Dasyatidae. All taxa were assigned equal proportions except for Scombridae and demersal fish taxa, which were weighted double because catches were likely more common.

Data Uncertainty

Reconstructed catch data by fishing sector were evaluated in terms of underlying data uncertainty or reliability using the methods applied globally in Pauly and Zeller (2016a), which updated an earlier use in Zeller et al. (2015). This approach is modified from the method used by the Intergovernmental Panel on Climate Change for evaluating uncertainty of information sources (Mastrandrea et al., 2010). For each time period (1950–1969, 1970–1989, 1990–2014) the data and information sources were scored for data reliability between 1 (very low) and 4 (very high), with no option for "medium" (**Table 2**). We deliberately exclude an uninformative "medium" score, to avoid the "non-choice" that this option would effectively represent. Each of these scores is assigned a percentage uncertainty range (**Table 2**), which allows the overall mean weighted percentage uncertainty (over all sectors) to be computed for Thai fishing.

TABLE 1 | Percentage composition of major species of so-called "trash" and low value fish caught in the Gulf of Thailand in 1966 and 1999.

Taxon	Percentage of total catch	
	1966	1999
Nemipteridae	30.6	26.8
Synodontidae	15.7	14.2
Leiognathidae	13.6	20.2
Cynoglossidae	10.9	10.0
Platycephalidae	10.8	10.0
Sciaenidae	9.5	8.9
Carangidae	8.9	10.0

TABLE 2 | Scoring system for evaluating the quality and reliability of time series of reconstructed catches, for deriving uncertainty (reliability) bands for reconstructed catches.

Score	Reliability	+/− %[a]	Corresponding IPCC criteria[b]
1	Very low	50	Less than high agreement and less than robust evidence
2	Low	30	High agreement and limited evidence ***or*** medium agreement and medium evidence ***or*** low agreement and robust evidence
3	High	20	High agreement and medium evidence ***or*** medium agreement and robust evidence
4	Very high	10	High agreement and robust evidence

Adapted and modified from Mastrandrea et al. (2010). [a] *Percentage uncertainty derived from Monte-Carlo simulations (Ainsworth and Pitcher, 2005; Tesfamichael and Pitcher, 2007).*
[b] *"Confidence increases" (and hence percentage ranges are reduced) "when there are multiple, consistent independent lines of high-quality evidence" (Mastrandrea et al., 2010).*

RESULTS

Thailand's total reconstructed catch for 1950–2014 was on average 2.9 times the data Thailand reported to FAO for the Eastern Indian Ocean and Western Central Pacific Ocean (**Figure 2**). Surprisingly, while Thailand is known to fish also in the Western Indian Ocean, no data were reported by FAO for this area (FAO area 51) other than landings of sharks and large pelagic taxa. Reconstructed total catches increased from just over 400,000 t·year^{-1} in 1950 to a peak of nearly 10 million tons in 1996, before declining to just over 5.5 million t·year^{-1} by 2014 (**Figure 2**). Of the total reconstructed catch, 84% was attributed to the industrial sector, approximately 5% of which was discarded, 16% was assigned as small-scale fisheries (artisanal and subsistence) and less than 1% was deemed from recreational fishing (**Figure 2**). The industrial, artisanal, subsistence and recreational sectors contributed 154, 14, 12, and 0.3 million tons of unreported

[10]http://www.fishing-khaolak.com/reports/index.html
[11]http://www.fishing-khaolak.com/reports/index.html

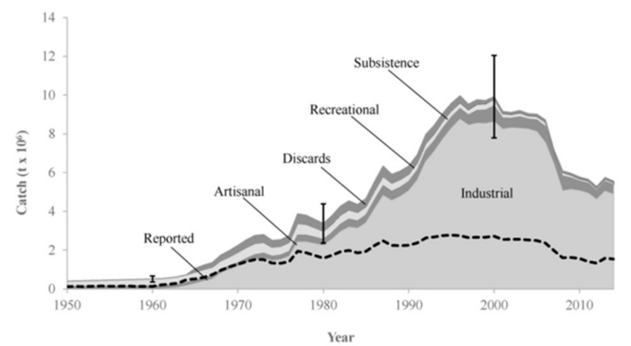

FIGURE 2 | Reconstructed total catches for Thailand for 1950–2014 (catches within and outside of Thailand's EEZ), showing contributions of different fisheries sectors. Reported landings data are overlaid as a dashed line.

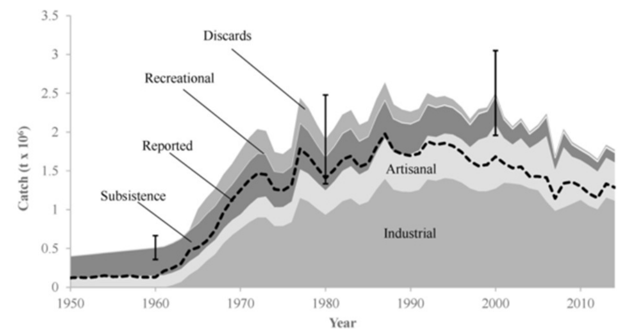

FIGURE 3 | Reconstructed domestic catches for Thailand within Thailand's EEZ only for 1950–2014, showing contribution of different sectors. Reported landings data are overlaid as a dashed line.

landings respectively, while 13 million tons were discarded over the entire time period.

Thai catches taken within the two separate EEZ entities of Thailand (Gulf of Thailand and Andaman Sea EEZs, **Figure 1**) increased from 400,000 tons in 1950 to a peak of 2.6 million tons in 1987, before beginning a gradual but continuous decline to 1.7 million tons by 2014 (**Figure 3**). The majority of unreported catches, as estimated here, were derived by Thai fisheries operating outside of Thailand's EEZ (**Figure 4**). Under the current assumptions for assigning "offshore" catches to neighboring EEZs, Indonesian, Cambodian and Malaysian waters accounted for the majority of catches taken by Thai fishers outside of their own domestic waters (**Figure 4**). However, Thai fishers have operated as far as Somalia in the Western Indian Ocean (Bahadur, 2011), and in eastern Indonesian waters in the east (**Figure 4**). The strong decline in total catches starting in the mid-2000s seems to be driven mainly by major declines in Thai catches from Indonesian and Malaysian waters (**Figure 4**), due mainly to increased efforts by these countries to reduce illegal foreign fishing (DoF, 2015).

The major taxonomic groups in the total catch of Thailand are Nemipteridae (threadfin breams), *Rastrelliger brachysoma* (short mackerel), Leiognathidae (ponyfishes), Carangidae (jacks and scads), Engraulidae (anchovies), *Sardinella* spp. (sardinellas), Synodontidae (lizardfishes), *Decapterus russelli* (Indian scad), Scyphozoa (jellyfish) and Sciaenidae (croackers), with around 75 additional taxa accounting for the remainder of total reconstructed catches (**Figure 5**).

All data presented here are free available for downloading via www.seaaroundus.org.

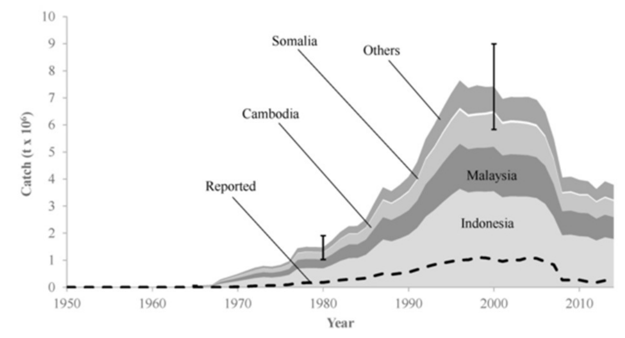

FIGURE 4 | Reconstructed catches for Thai fleets fishing outside of Thailand's EEZ for 1950–2014. Reported landings data are overlaid as a dashed line, illustrating the poor catch data monitoring and reporting by 'offshore' fleets fishing internationally. "Others" includes Myanmar, Bangladesh and India.

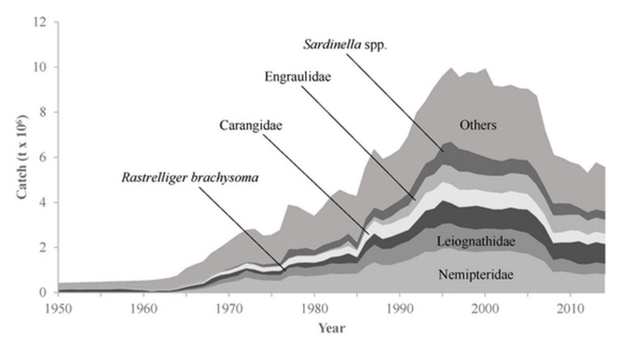

FIGURE 5 | Taxonomic composition of total reconstructed catches for Thailand, 1950–2014. Major taxonomic groups are shown only. "Others" includes 79 additional taxonomic groups.

DISCUSSION

Total reconstructed catch from Thailand's marine fisheries in the Indian and Western Pacific Oceans is almost three times higher than the data reported by Thailand to FAO for 1950–2014. Considering that Thailand is currently working to reform its fisheries and reduce fishing effort to levels that have been estimated as leading to Maximum Sustainable Yields (MSY) (DoF, 2015), the level of catch that is currently not accounted for by official statistics is disconcerting. However, most unreported catch seems to be derived from offshore fisheries in neighboring EEZs (and likely not considered in the stock MSY estimations above) rather than Thai EEZ waters. Of concern, and likely also indicative of the status of stocks and associated ecosystems, is the observation that catches within Thai's EEZ have been on a continuous declining trend for many years (Pauly, 1979; Christensen, 1998; Pimoljinda, 2002), despite increasing domestic fishing effort. Future research should examine comprehensive catch-per-unit-effort trends over time to determine more closely potential status and trend of stocks. This will require an equally detailed reconstruction of total fishing effort by all Thai vessels and fleets, to complement existing fleet effort data sets.

Reconstructed Thai catches from waters outside of Thailand's EEZ were nearly seven times higher than the catch that was reported to the Department of Fisheries as being obtained outside Thai waters. Reports of the number of vessels fishing outside of Thailand's waters and the EEZs where fishing was occurring varied substantially. Furthermore, fishing by Thai vessels took place under both official and private agreements, as well as illegally.

The number of industrial vessels fishing outside of Thailand's EEZ that were known to the Department of Fisheries were likely around 760 in 2007 (Lymer et al., 2008). However, as many as 3,889 Thai vessels were reported to operate in other countries' waters in 1996, only 28% of which were estimated to be fishing legally according to a report by the Foreign Ministry of Thailand cited by Butcher (1999). Our reconstructed catch by Thailand's fishing vessels from other countries' EEZs may even represent an underestimate as it may not encompass all countries where Thailand's fleets have been fishing. Catches from outside of Thailand's EEZ seem to have declined since their peak in the late 1990s-early 2000s (around 77% of total Thai catches), and by 2014, such catches had declined to less than 70% of total Thai catches. Declining catches from outside Thailand's EEZ are driven by declining stocks, countries imposing restrictions, ending foreign fishing permits and increasing their crackdown on illegal fishing (Amindoni, 2015; DoF, 2015; Makur, 2016).

Uncertainty over the level of fishing that is occurring outside of Thailand's EEZ results in fisheries policy and management challenges. This is of particular concern to Thailand as it attempts to address illegal, unsustainable fishing practices and human rights violations by its offshore fishing fleets in order to prevent trade sanctions from being imposed by the EU (Neslen, 2015). In the last few years, Thailand has been strengthening Monitoring, Control, and Surveillance to deter illegal fishing activities and updating its legal framework to improve labor conditions on board its fishing vessels (DoF, 2015; Hodal, 2016). Despite these improvements, the EU continues to maintain Thailand's fisheries at "yellow card" status. Some reports suggest that illegal fishing, slavery, and human trafficking are still widespread, and illegal fishing vessels are simply moving further afield to avoid Thailand's new policies and enforcement (Greenpeace, 2016; Hodal, 2016; Walk Free Foundation, 2016). This will continue to provide a substantial challenge for Thai authorities, who will have to consider addressing these issues as what they are: international and transnational criminal and law enforcement activities, rather than fisheries management issues (UNODC, 2011; Ewell et al., 2017). For example, to support member countries in identifying, deterring and disrupting transnational fisheries crime, INTERPOL has established Project Scale (https://www.interpol.int/Crime-areas/Environmental-crime/Projects/Project-Scale) that is willing to assist member countries upon request.

Receiving a "yellow card" status from the European Union in 2015 marked a major turning point for Thai fisheries. Within a few months of being issued the "yellow card" status, a country-wide survey of existing Thai-flagged fishing vessels was conducted with urgency[12] Several tools have since been developed to tackle illegal fishing both in domestic waters and distant waters, including an electronic fishing licensing system, logbook reporting system and a Vessel Monitoring System (VMS) (DoF, 2015). Furthermore, a fisheries observer program has been launched and implemented first on Thailand's overseas fishing fleet[13] with observers onboard domestic vessels intended to be stationed later (DoF, 2015). Fisheries landings are now validated by Port-In and Port-Out Control Centers. Moreover, the national fisheries data collection system is planned to be established in 2017 (DoF, 2015), and is billed as one of the most significant reforms of catch data collection. It is hoped that these newly developed instruments will benefit catch data collection and that observers will play an important role as demonstrated by observer programs in several developed countries (Karp and McElderry, 1999; Porter, 2010).

To our knowledge, recreational catches have not been previously estimated for Thailand. While reconstructed recreational catch estimates contributed less than 1% of total catch, they are part of the general tourist attraction for Thailand, and as such contribute far more to the general economy than the catch tonnages would suggest. As the government continues to build the tourism industry, removal of marine species by growing numbers of visitors should not be overlooked by fisheries management officials. For example, the number of tourists to Phuket, Thailand, has grown from 1.25 million in 1990 to 3.76 million tourists in 2014 (Thepbamrung, 2015). Estimates of recreational fishing are highly uncertain due to the lack of information, but present a first estimate of an important and often overlooked contributor to the economy of Thailand.

Overexploitation of nearshore marine resources is common in Southeast Asian countries (Funge-Smith et al., 2012). While average catches for the Western Central Pacific began to decline in the late 2000s, average catches in the Eastern Indian Ocean appear to be stable but are highly questionable, in part due to fundamental mis-reporting and due to the "presentist bias" (Pauly and Zeller, 2016a, 2017a). However, based on Thailand's recent stock assessments, the current fishing effort of demersal fisheries is greater than the effort required to reach Maximum Sustainable Yield by 32.8% in the Gulf of Thailand and 5.2% in the Andaman Sea, while the fishing effort of pelagic fisheries exceeds the optimum level by 27.0% in the Gulf of Thailand and 16.5% in the Andaman Sea (DoF, 2015). Consequently, substantial and ongoing reductions in fishing effort are urgently

[12] http://www.thaiembassy.org/bucharest/contents/files/news-20170125-163408-373852.pdf

[13] http://www.thaiembassy.org/bucharest/contents/files/news-20170125-163408-373852.pdf

needed. Trawl catch per unit effort (CPUE) estimates have declined in the Gulf of Thailand by an order of magnitude from 300 kg·hour^{-1} in the early 1960s (Boonyubol and Pramokchutima, 1984; DoF, 2015) to around 20–30 kg·hour^{-1} by the 1990s (Pauly, 1979; DoF, 2015). In the Andaman Sea, the trawler catch rate in 2014 had declined by 75% compared to the mid-1960s (DoF, 2015). CPUE has also been declining for the majority of fisheries in the Gulf of Thailand, South China Sea, and Bay of Bengal (Funge-Smith et al., 2012).

Between 1950 and 2014, the proportion of catch of low-value (unfortunately mislabeled as "trash-fish") species has increased while landings of marketable demersal fish have declined, and in recent years, small pelagic species contribute the most significant proportion of catch. The latest estimates by DoF (2015) report that 82% of demersal species and 78% of pelagic species within Thailand's waters are overexploited. It has been estimated in 2007 that 42% of trawler catch in the Gulf of Thailand is comprised of small, low-value fish with 35% of these fish belonging to juvenile members of commercial fish species (Supongpan and Boonchuwong, 2010). The shift in catch composition toward low-value and juvenile fish is not unique to Thailand, but is common to fisheries in many parts of Asia due to many years with unsustainable exploitation rates and excessive fishing effort (Funge-Smith et al., 2012; Cao et al., 2015).

By evaluating available information, our reconstructed catch data by fisheries sectors were estimated with uncertainty ranges of ± 20–30%, depending on sector and time period. In the case of recreational catches, uncertainty was higher at ± 50% due to the paucity of information available. While it is theoretically possible that the reconstructed catches presented here have been overestimated, it is more likely that, given our conservative approach to using and interpreting data (Pauly and Zeller, 2016a, 2017a), our estimates may be underestimates (or minimal estimates) of the likely true, but unknown actual total past catch. Nevertheless, the levels of uncertainty in Thailand's reconstructed catch data further highlight the need to improve data reporting and data collection systems. It also suggests that further, focus research should target the past, to potentially refine and improve historical data for Thai fishing.

Furthermore, the reader should note that proper uncertainty estimates (such as confidence intervals etc.) actually address issues of statistical *precision* of sampled data, while catch reconstructions address issue of statistical *accuracy* in data, on which statistical theory is essentially silent in terms of "confidence" or "uncertainty." Thus, the ranges of "uncertainty" around our estimates need to be treated with caution, as they cannot be interpreted as one would interpret normal confidence intervals or error bars. Finally, it needs to be clearly stated that official reported data (both national data as well as data presented by FAO on behalf of countries) are also largely based on estimates in most countries, with their own sources of uncertainty (see also Pauly and Zeller, 2017a). Yet no official reported time series data are ever presented with confidence intervals or other indicators of data uncertainty.

We attempted to remain conservative during reconstruction of unreported components and compared estimates from different methods, where possible. For example, reconstructed landings from small-scale fisheries were compared to an analysis of coastal fish consumption to confirm small-scale catches were high enough to meet local demand for fish. This reconstruction of Thailand's marine fisheries was also compared with other reconstructions in the same general region that eventually contributed to a global study (Pauly and Zeller, 2016a,b). High levels of unreported catches occur in many countries in the Southeast Asia region. For example, separate reconstructions for Malaysia and Cambodia determined unreported components of marine fisheries in these countries to be on average 1 and 2 times the reported catches (Teh and Teh, 2014; Teh et al., 2014).

Here we present comprehensive estimates of unreported marine fisheries catches by Thai fishing fleets, both inside and outside domestic waters, for the period 1950–2014. This study highlights areas for improvement to fisheries data collection in Thailand to better encompass all fishing sectors and components. Furthermore, we highlight the need for retroactive corrections to earlier decades of nationally and internationally reported data, to ensure a proper historical foundation of actual total reported catches exists on which to base policy considerations and discussions of Thai fisheries. This would also address the "presentist bias" of current reported data sets (Pauly and Zeller, 2017a). Recent efforts to improve fisheries legislation, catch statistics, limit fishing effort, and curb illegal fishing and human trafficking show promise, but much remains to be done to place Thai fisheries on the path to sustainability (Pauly et al., 2002).

AUTHOR CONTRIBUTIONS

BD: Completed data reconstruction update to 2014, and revised and drafted the manuscript. PN: Contributed country-specific information to the manuscript and co-wrote the manuscript. DZ: Advised on methods, guided analysis, contributed to the manuscript and reviewed and edited the manuscript. LT: Completed earlier data reconstruction and analysis and edited the manuscript. DP: Guided the conceptualization of the study.

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An Improved Reconstruction of Total Marine Fisheries Catches for the New Hebrides and the Republic of Vanuatu, 1950–2014

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For many small island nations, fisheries provide residents with both food security and economic stability. However, in order to create effective and sustainable fisheries policies and management that will ensure a growing population can prosper, policy makers need to know what is being fished and how much is fished. Vanuatu, the smallest country in Melanesia, has a declared and claimed Exclusive Economic Zone (EEZ) of over 820,000 km^2 and fisheries resources play a large part in the food security and economic stability of this country. This reconstruction of the total marine fisheries catch of Vanuatu for 1950–2014 faced major data gaps. It showed that the reconstructed total catches of nearly 1.4 million tonnes (metric tons) 40% higher than the 977,997 tonnes reported by the Food and Agriculture Organization (FAO) on behalf of Vanuatu for the same period. However, if large-scale industrial catches are excluded, the reconstructed small-scale fisheries catches (~270,000 tonnes) were over 200% higher than the 114,862 tonnes of reported catch that were assumed to represent the small-scale sector in FAO data. Subsistence catches made up almost 93% of small-scale catches, followed by artisanal and recreational catches with ~7 and <1%, respectively. By continuously improving the fisheries data of Vanuatu for both the past and the present, policy makers, stakeholders, and fishers can make better decisions that will maintain the benefits of marine fishery resources.

Keywords: unreported catches, small-scale fisheries, artisanal fisheries, subsistence fisheries, Vanuatu

INTRODUCTION

Vanuatu (former New Hebrides) is a Pacific island country consisting of 117 islands (73 permanently inhabited) located between 13°04′−20°15′S and 166°32′−170°14′E (Seto et al., 2017; **Figure 1**). The country became independent in 1980 from the French-British condominium established in 1906. Vanuatu's land extends over 12,000 km^2, which makes it the smallest country in Melanesia. Vanuatu's Exclusive Economic Zone (EEZ) was declared in 1982 and covers over 820,000 km^2, including the area disputed with New Caledonia (**Figure 1**). In line with standard *Sea Around Us* procedures (Zeller et al., 2016), any catches by Vanuatu fishers within the disputed

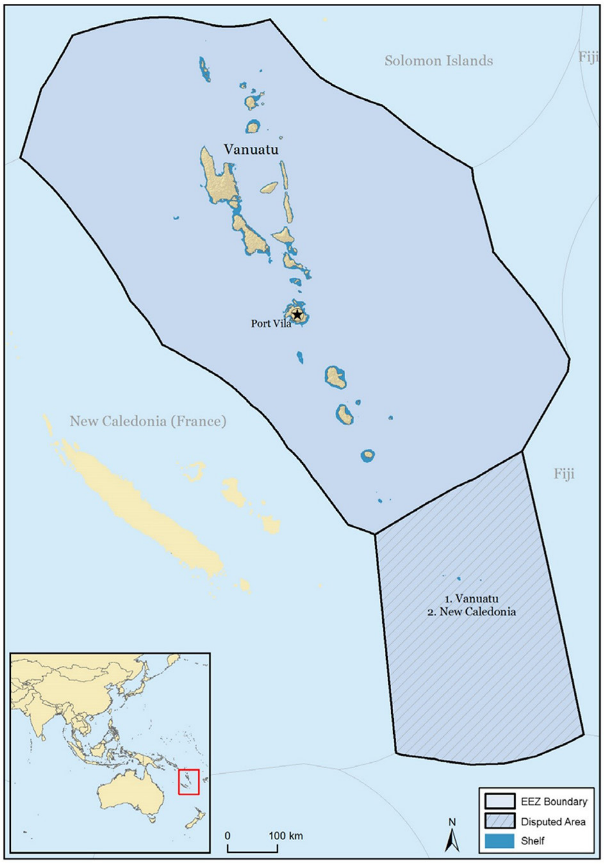

FIGURE 1 | Exclusive Economic Zone (EEZ) and shelf waters to 200 m depth of Vanuatu. Source: *Sea Around Us* (http://www.seaaroundus.org/).

EEZ area was here deemed to be part of Vanuatu catches, while any French/New Caledonian catches in this area forms part of New Caledonia's reconstruction (Harper et al., 2009). Since the EEZ makes up almost 99% of the total land and maritime area of Vanuatu, it only makes sense that according to the Vanuatu 2010 house hold income and expenditure survey (HIES) more than three quarters of the adult population is involved in at least one form of fishing (Pauly and Zeller, 2017). The marine fisheries of Vanuatu were previously described, and a preliminary catch reconstruction undertaken by Zylich et al. (2014) for the years 1950–2010, based on limited online reports. Here, the description of the fisheries of Vanuatu is based on the more extensive data sets available locally to the authors, and covers a period of 64 years from 1950 to 2014.

Marine fisheries in Vanuatu's waters include both large-scale (industrial) and small-scale sectors. The offshore large-scale sector targets tuna and tuna-like species, including by-catch species within the EEZ. This industrial sector started in 1957 with the establishment of the South Pacific Fishing Company Limited (SPFC) in Palekula on Santo Island. It was dominated by longliners although some pole-and-line vessels and purse seiners sporadically fished in the area in the 1970s and 2000s, respectively (Nunoo et al., 2014; Pauly et al., in press). The fishery was mainly operated by foreign vessels from Japan, Korea, Taiwan, China, and Fiji under joint-venture or bilateral fishing agreements. The Chinese fleet has been dominant in Vanuatu's EEZ since the 2000s both in terms of vessel numbers and capacity, followed by Taiwan and Fiji, while the domestic fleet has slowly expanded since the mid-1990s.

The coastal small-scale sector is composed of two sub-sectors, (i) the deep-bottom, and (ii) the shallow water fisheries. On the one hand, the deep-bottom fisheries developed in Vanuatu in 1980 as part of an ambitious, foreign-aided fishing development program (VFDP, Village Fisheries Development Program). This program aimed at targeting previously unexploited resources of snappers and groupers that inhabit deeper waters (100–450 m) using drop lines and bottom longlines. This program initiated commercial fishing activities in the country, and supplies local urban markets on Santo and Efate islands. On the other hand, the shallow water fisheries include small-scale export and non-export fisheries. Export fisheries mainly target valuable coral reef invertebrate resources, namely trochus (*Tectus niloticus*), green snail (*Turbo marmoratus*), and sea cucumbers (∼20 species belonging to Holothuriidae and Stichopodidae), for commercial purpose. There are also anecdotal reports of export of lobster and deep-bottom fish, however in this report we only considered trochus, green snail, and sea cucumbers to be exported. Non-export fisheries are dominated by subsistence and artisanal fishing activities of rural households that target reef finfish and invertebrate species for local consumption and sale. Recreational coastal and big-game fishing charters are limited to a few boats operating from Luganville and Port-Vila urban areas. Recreational catches (although unreported) were not estimated here due to their very low anticipated level relative to the other fisheries that target the same species in Vanuatu's waters.

MATERIALS AND METHODS

The total marine fisheries catches for Vanuatu's waters were estimated for the offshore large-scale and coastal small-scale sectors separately.

Offshore Large-Scale Sector

Catch records in Vanuatu waters were provided in Jacquet (2016) and Grandperrin and Brouard (1983) for 1957–1981. No large-scale, industrial fishing is thought to have occurred in this area prior to 1957. Annual catches from 1982 to 1999 were reported in Vanuatu Fisheries Department (VFD) national reports (Amos, 2007). As an approximation, linear interpolation was performed for filling data gaps in 1991–1992 because we did not find evidence of noticeable and short-lasting change in fishing operations at that period in available reports. Records of the Western and Central Pacific Fisheries Commission (WCPFC) were used as estimates of the annual catches in the Vanuatu EEZ since 2000 as reported in VFD national reports to the WCPFC (VFD, 2009, 2015; Nunoo et al., 2014). The reports cover the fishing activities in the Vanuatu EEZ and operations of the Vanuatu flag vessels that were active in the WCPFC and other regional fisheries management organization (RFMO) areas. They mainly focus on the fleet structure, annual catch estimates and catch/effort distributions. These data were originally collected and supplied in logbooks and extrapolated based on logbook coverage rates with the assistance of the Secretariat of the Pacific Community. Although discarded catch associated with the large-scale tuna and billfish fisheries in Vanuatu waters likely occurred as in other ocean basins, such data were not included here.

The taxonomic composition of catches was provided by Naviti (2005); Amos (2007) and VFD (2009, 2014, 2015) for 1980–2014 for the three main commercial species: albacore tuna (*Thunnus alalunga*), yellowfin tuna (*Thunnus albacares*), and bigeye tuna (*Thunnus obesus*). The bycatch of billfish species (Istiophoridae and Xiphiidae) was also provided in the above sources. As an approximation for earlier years (1958–1979), the average catch composition for 1980–1986 was used for the 1958–1979 period. This was supported by Jacquet (2016), who mentioned that average albacore catch represented about 70% of total annual catches in the pre-1982 period.

Shark catches were estimated separately from bycatch species because exports of dried shark fins were high when the SPFC operated in Vanuatu, but thereafter decreased substantially. We therefore assumed that they have been low since 1987 although there is no record that supports that hypothesis. Export records of dried shark fins were provided by Amos (2007) for 1980–1986 and averaged 0.26% (range: 0.1–0.4%) of tuna and billfish landings. As an approximation, this ratio was used to estimate dried fin exports for 1958–1979 based on reported tuna and billfish landings given that the nature of fishing operations within the large-scale sector was broadly similar over that period. The derived tonnages of dried fins were multiplied by 77.5 to estimate corresponding wet weight shark catches using the mean conversion rates from wet to dry fin mass (43%) and from round mass to wet fin mass (3%) provided by Biery and Pauly (2012).

Although the coastal small-scale sector also occasionally targets the same species as the offshore sector, available data (e.g., Amos, 2007) suggested that its contribution to total tuna catch and associated bycatch in Vanuatu's waters has been very small (i.e., ∼0.1%, <10 tonnes/year). Consequently, these catches of the small-scale sector were not included in our tuna catch reconstruction.

Coastal Small-Scale Sector

Although Vanuatu's public institutions attach great importance to the development of subsistence and commercial (artisanal) small-scale fisheries, they present great difficulties for the collection of catch information (Gillett, 2010). For the purpose of this study, the coastal small-scale sector was structured into two sub-sectors, i.e., deep and shallow water fisheries. The latter sub-sector was further separated into export and non-export fisheries.

Deep-Bottom Fisheries

The deep-bottom fishery has been monitored by the VFD and foreign research agencies (e.g., Institut de Recherche pour le Développement, IRD, France, formerly known as ORSTOM) since its early stage of development. Deep-bottom catches were therefore estimated using commercial landing statistics available in Schaan et al. (1987) for 1982, David and Cillaurren (1988) for 1983–1987, Amos (2007) for 1988–1999, and the VFD database for 2000–2014. Since available reports and literature did not provide evidence of discards in this fishery, we assumed that it created very little if any discarded catch. To account for missing statistics for some provinces of Vanuatu for 1993–1995 and 1999, we calculated the average catch from the years with catch data for an individual province to estimate the missing annual production for that province. This was repeated for each province and then all provinces summed to get an approximation of the estimated total annual catch for all provinces combined. Furthermore, deep-bottom catches have not been comprehensively recorded by the VFD throughout the country since 2000. Although a data collection system was put in place by the VFD using duty-free fuel as an incentive for fishers to submit catch data, not all fishers involved in this fishery have participated. Based on local evidence of deep-bottom fishing activities, we therefore used the annual records in 1999 as a rough and uncertain approximation of the annual production for the 2001–2014 period.

The taxonomic composition of deep-bottom catches was reliably monitored during the 1980–1991 period (Brouard and Grandperrin, 1984; Cillaurren et al., 2001). For the 1982–1984 period, taxonomic information was also available from Schaan et al. (1987). The fishery mainly targeted 11 species of snappers (family Lutjanidae) and groupers (Serranidae), which contributed 70–95% of annual deep-bottom catch. Ninety-six other species belonging to 29 families were identified in the bycatch of this multispecies fishery, including sharks (Brouard and Grandperrin, 1984; **Table 1**). The same species breakdown as that of the 1980–1991 period was used for the 1992–2014 period to roughly approximate the taxonomic composition of more recent catches, although no taxonomic survey was available to support that assumption (**Table 2**).

Shallow Water Export Fisheries

We used export statistics as a reliable proxy for the annual catches of exported invertebrate species, and treated these catches as artisanal in nature (i.e., small-scale, commercial). Sea cucumbers are not consumed in Vanuatu, while trochus and green snail shells are sold for export although their flesh is consumed locally.

Export records for trochus were available from Devambez (1959, 1960) for 1950–1960, from Brouard and Grandperrin (1984) for 1969–1982 and from the VFD for 1983–2012. Linear interpolation was performed for filling the data gaps (1961–1968, 1983–1984, and 1999–2000) as an approximation although available records suggested that annual exports occasionally highly varied between consecutive years (e.g., in the 1970s). We used the reported catch in 2012 as a rough estimate of the annual catch in 2013 and 2014. The trochus shell export tonnages were converted to whole, wet weight of trochus using a conversion factor of 1.51, assuming that each ton of trochus shell represents 49% of raw trochus (Teh et al., 2014).

Reliable sea cucumber export data were available from the VFD for 1983–2014. Sporadic exports may have occurred between 1950 and 1983 as the fishery started in the region in the nineteenth century, although no records are available. Since sea cucumbers were processed, dried and reported as bêche-de-mer without species reference, we used a multispecies conversion

TABLE 1 | List of bycatch species of the coastal deep-bottom fisheries in Vanuatu.

Taxon	Number of species
BONY FISHES	
Etilidae	14
Lutjanidae	17
Serranidae	20
Lethrinidae	8
Carangidae	6
Pentapodidae	5
Labridae	1
Emmelichthyidae	1
Sphyraenidae	5
Holocentridae	2
Priacanthidae	2
Branchiostegidae	1
Triglidae	1
Gempylidae	3
Scombridae	1
Plymixiidae	1
Bramidae	1
Triodontidae	1
Chimaeridae	1
Echeneidae	1
Congridae	1
SHARKS	
Carcharhinidae	8
Triakidae	1
Alopiidae	1
Spinacidae	1
Hexanchidae	2
Lamnidae	1
Squalidae	1
Total	108

Source: Brouard and Grandperrin (1984).

TABLE 2 | Estimated taxonomic breakdown of the finfish catches of the deep-bottom fisheries in Vanuatu, 1950–2014.

Taxon	Catch composition (proportional by weight)					
	1982[a]	1983[b]	1984[b]	1985[b]	1986[b]	1987-2014[c]
LUTJANIDAE						
Aphareus rutilans	0.011	0.000	0.016	0.014	0.015	0.021
Etelis carbunculus	0.200	0.308	0.115	0.189	0.189	0.294
Etelis coruscans	0.110	0.095	0.091	0.145	0.110	0.167
Etelis radiosus	0.029	0.023	0.039	0.027	0.028	0.028
Lutjanus malabaricus	0.061	0.051	0.091	0.062	0.039	0.080
Pristimoides filamentosus	0.044	0.012	0.070	0.031	0.064	0.055
Pristimoides flavipinnis	0.053	0.058	0.053	0.046	0.053	0.064
Pristimoides multidens	0.145	0.129	0.178	0.130	0.143	0.156
SERRANIDAE						
Epinephelus magniscuttis	0.022	0.010	0.022	0.032	0.023	0.023
Epinephelus morrhua	0.021	0.019	0.022	0.021	0.021	0.019
Epinephelus septemfasciatus	0.018	0.009	0.016	0.017	0.030	0.047
Sub-total (11 species)	0.713	0.713	0.713	0.713	0.713	0.952
Others	0.287	0.287	0.287	0.287	0.287	0.048

[a]*Average of 1983–1986 rates.*
[b]*Schaan et al. (1987).*
[c]*Cillaurren et al. (2001).*

factor, i.e., dried weight = 7% wet weight to estimate the wet weight of the corresponding exports of bêche-de-mer.

Data on green snail exports were available from Van Pel (1956) for 1950–1956, from Brouard and Grandperrin (1984) for 1969–1980 and from Amos (2007) for 1986–2004. The fishery was effectively closed in 2005 for 15 years. Linear interpolation was performed for years without data (1956–1968 and 1981–1985) as a rough approximation although there was no fishery information to support that assumption. Green snail export tonnages were converted to whole, wet weight of green snails using the same conversion rate as used for trochus shells.

Shallow Water Non-export Fisheries

Shallow water catches that were not destined for export were estimated using the results of the large-scale socioeconomic survey conducted in 1983–1984 (David, 1991). To date, this study has been the only country-wide survey of shallow water fisheries in Vanuatu. These fisheries target coral reef and coastal pelagic resources over fishing grounds to ∼100 m depth. Resources consist of a very large diversity of species of finfish (i.e., over 370 species from 32 families) and over 60 species of mollusks, echinoderms and crustaceans (Van Pel, 1956; Cillaurren et al., 2001; Amos, 2007; Friedman et al., 2008; Poupin and Juncker, 2010; Beckensteiner, 2011; Jimenez et al., 2011). We assumed that shallow water non-export fisheries created very little if any discarded catch.

The annual average catch per rural fishing household in Vanuatu in 1984 was estimated by David (1991) by dividing the annual catches of shallow water fisheries by the number of rural households engaged in fishing in 1984, and included the associated 95% confidence interval of this estimate. As an approximation, we assumed that this level of catch has been steady for the entire study period, although the technological, economic, and urban development has affected fish production and effective reporting over the last 60+ years. Indeed, our assumption is supported by the fact that any potential change in annual household catch has likely been (at least partially) mitigated by three factors. Firstly, the last agricultural census (VNSO, 2007) provided evidence that subsistence fishing still dominates coastal fishing activities in Vanuatu and that the overall proportion of rural fishing household engaged in commercial activities has not increased since the 1980s (i.e., around 30%). This survey suggested that households go fishing primarily for self-consumption and occasional sale, resulting in only slight changes of household needs for marine products since the 1980s, as confirmed also by Johannes and Hickey (2004) and Léopold et al. (2013). Secondly, the shallow water fisheries production was proportional to fishing effort (in number of fishing trips) across 11 island groups in 1984 (David, 1991; **Figure 2**). This linear relationship suggests that shallow water

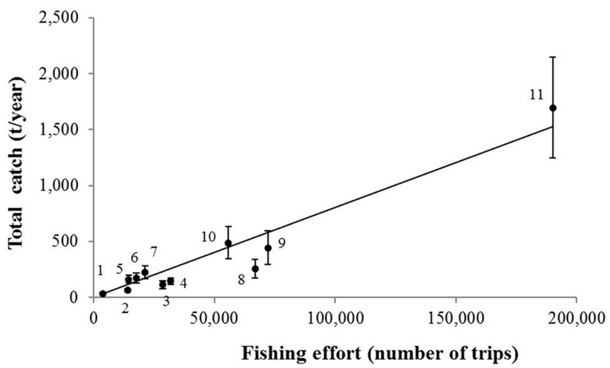

FIGURE 2 | Regression ($y = 0.008x$, $R^2 = 0.927$) of estimated total annual catch and fishing effort of the shallow water fisheries not destined for export in 11 island groups in Vanuatu in 1984. Conservative 95% confidence intervals are represented. The taxonomic composition of the catch includes finfish, mollusks and lobsters. Derived from data from David (1991). (1) Paama Island; (2) Ambrym Island; (3) Ambae & Maewo Island; (4) Sheperds Island; (5) Pentecost Island; (6) Epi Island; (7) Sanma Province; (8) Torba Province; (9) Tafeo Province; (10) Efate Island; (11) Malekula Island.

resources were not overexploited at the country scale at that time, and consequently that production could likely be increased by increasing fishing effort, conditionally to the spatial allocation of that additional fishing pressure. Thirdly, although the increasing use of more effective gears (i.e., gillnets, waterproof torches for night spear fishing) may have had a positive influence on individual fishing yields, the increasing total fishing pressure due to human population growth in coastal villages may have, at least partially counterbalanced this effect.

The annual average catch per rural fishing household was derived from David (1991) separately for fish, shellfish, lobsters, and octopus. The total annual catch of each taxonomic group was then inferred from the average annual household catch of this species group and the total number of rural fishing households each year between 1950 and 2014. The latter was estimated by multiplying the total number of rural households by the percentage of these households that was engaged in fishing. The number of rural households in Vanuatu was obtained from national population census in 1967, 1979, 1989, 1999, and 2009 (VNSO, 2009). Household data for years between census years were linearly interpolated. We used the World Bank's model of Vanuatu rural population (http://donnees.banquemondiale.org/) and average household size over the 1967–1979 period to estimate the number of annual rural households for 1950–1966. The percentage of rural households engaged in fishing was available from David (1991) for 1979 and 1984, and from VNSO (2007) for 1992 and 2007. Percentage data for years without surveys were linearly interpolated. As an approximation the average percentage of rural households engaged in fishing between 1979 and 1984 was used as an estimate of the annual rate for each year between 1950 and 1978.

The total annual catch of each taxonomic group was further broken down into family-level taxa. A conservative percentage range was used in the family breakdown of each group to account for the very large number of target species (particularly for fish), important data gaps, and inherent strong inter-annual variability of small-scale fishing activities (**Table 3**).

RESULTS

Offshore Large-Scale Sector

The offshore large-scale sector displayed two main periods that highlighted an up-and-down developing trend (**Figure 3**). During the first phase (1957–1986), all offshore catches by the SPFC and foreign vessels were landed at Palekula transshipment base on Esperitu Santo Island. Total catches ranged between 1,600 and 15,600 tonnes/year. These facilities were closed in 1986 as the SPFC ceased its activities following the drop of fishing yields and the establishment of the EEZ. During the second phase (1987–2013) most of the catch was directly delivered to Fijian, Papua New Guinean and American Samoan ports. Total catches ranged between 1,500 and 13,800 tonnes/year (**Figure 3**). The fishery was characterized by an expansion of fishing effort until 2006 but then decreased until 2014 due to the relocation of the foreign fleets to the Solomon Islands in particular.

The estimated catch composition has been dominated by albacore tuna (52–94%), yellowfin tuna (3–31%), and bigeye tuna (1–14%) for the entire period (**Figure 3**). Other important tuna and billfish species caught in the Vanuatu EEZ are skipjack (*Katsuwonus pelamis*), black marlin (*Makaira indica*), blue marlin (*Makaira nigricans*), striped marlin (*Tetrapturus audax*), and swordfish (*Xiphias gladius*). The main shark species caught as bycatch include blue shark (*Prionace glauca*), silky shark (*Carcharhinus falciformis*), oceanic whitetip shark (*Carcharhinus longimanus*), and mako shark (*Isurus* spp.). Catches of other shark species and other finfish species (e.g., dolphinfish *Coryphaena hippurus*) have not been explicitly recorded, although they have been sporadically reported by onboard observers from the VFD since 2009.

Coastal Small-Scale Sector

Deep-Bottom Fishery

Catches of the deep-bottom fishery increased rapidly after its start in 1980, peaked at 130 tonnes in 1986, which was followed by a highly variable catches of between 50 and 100 tonnes/year on a generally declining trend until the late 1990s (**Figure 4**). More recently, catches are thought to have been much lower at around 27–30 tonnes/year (**Figure 4**).

Shallow Water Export Fisheries

Export catches of trochus, sea cucumber and green snail initially displayed an overall increasing trend since 1970 with a peak in total catches of these three taxa in 1992 (**Figure 5**). However, after 1992, catches began to decline. Specifically, the sea cucumber fisheries followed a typical boom-and-bust cycle and collapsed in the early 2000s. The green snail fisheries collapsed in the mid-1990s after decades of exploitation. Exports of trochus shells have declined to levels of around a quarter of those in previous decades (**Figure 5**).

TABLE 3 | Derived taxonomic composition of the finfish, lobster, octopus, and shellfish catches for the shallow water fisheries in Vanuatu, 1950–2014.

Target group	Family[a]	Number of species	Estimated catch composition (% weight)		
			Minimum	Maximum	Average
Finfish[b]		**372**			
Main targets	Acanthuridae	28	1.0	10	5.0
	Balistidae	10	3.0	10	5.0
	Belonidae	2	3.0	10	5.0
	Carangidae	13	3.0	10	5.0
	Haemulidae	7	3.0	10	5.0
	Hemiramphidae	1	3.0	10	5.0
	Holocentridae	21	3.0	10	5.0
	Kyphosidae	1	3.0	10	5.0
	Labridae	81	3.0	10	5.0
	Lethrinidae	10	3.0	10	5.0
	Lutjanidae	19	3.0	10	5.0
	Mugilidae	5	3.0	10	5.0
	Mullidae	11	3.0	10	5.0
	Scaridae	21	3.0	10	5.0
	Serranidae	49	3.0	10	5.0
	Siganidae	6	3.0	10	5.0
	Sphyraenidae	2	3.0	10	5.0
Secondary targets	Albulidae	2	0.1	3	1.0
	Atherinidae	2	0.1	3	1.0
	Carcharhinidae	5	0.1	3	1.0
	Chaetodontidae	31	0.1	3	1.0
	Chanidae	1	0.1	3	1.0
	Clupeidae	3	0.1	3	1.0
	Dasyatidae	3	0.1	3	1.0
	Diodontidae	2	0.1	3	1.0
	Ephipiddae	2	0.1	3	1.0
	Gerreidae	2	0.1	3	1.0
	Nemipteridae	5	0.1	3	1.0
	Ostraciidae	4	0.1	3	1.0
	Pomacanthidae	18	0.1	3	1.0
	Priacanthidae	4	0.1	3	1.0
	Scombridae	2	0.1	3	1.0
Lobster[c]		**7**			
	Palinuridae	5	80.0	99	90.0
	Scyllaridae	2	1.0	20	10.0
Octopus[d]		**1**			
	Octopodidae	1	100.0	100	100.0
Shellfish[d]		**43**			
Bivalves	Arcidae	1	0.1	10	5.3
	Cardiidae	4	0.1	10	5.3
	Mytilidae	1	0.1	10	5.3
	Ostreidae	2	0.1	10	5.3
	Pterridae	1	0.1	10	5.3
	Spondylidae	2	0.1	10	5.3
	Tellinidae	2	0.1	10	5.3
	Veneridae	5	0.1	10	5.3
Gastropods	Fasciolariidae	2	0.1	10	5.3
	Muricidae	2	0.1	10	5.3
	Naticidae	2	0.1	10	5.3
	Neritidae	4	0.1	10	5.3
	Patellidae	1	0.1	10	5.3
	Planaxidae	1	0.1	10	5.3
	Strombidae	5	0.1	10	5.3
	Tegulidae	2	0.1	10	5.3
	Terebridae	1	0.1	10	5.3
	Turbinidae	4	0.1	10	5.3
	Vermetidae	1	0.1	10	5.3

(Continued)

TABLE 3 | Continued

[a] *Target families from Amos (2007), Friedman et al. (2008) and Beckensteiner (2011).*
[b] *Fricke et al. (2011) and Kulbicki et al. (2011).*
[c] *Poupin and Juncker (2010).*
[d] *Friedman et al. (2008).*

Shallow Water Non-export Fisheries

Our reconstruction suggested that shallow water catches for household and local use (i.e., subsistence and local artisanal catches) have followed an increasing trend over time throughout the country, which is entirely driven by the growth in and distribution of the rural human population in coastal villages (**Figure 6**). Total estimated catches increased by 480% from 1,400 tonnes in 1950 to 6,700 tonnes in 2014, resulting in an increase in area catch rate from 3.2 to 15 tonnes/km^2. In 2014, estimated shallow catches reached 3,100 ± 1,300 tonnes of finfish, 2,100 ± 260 tonnes of shellfish, 1,300 ± 300 tonnes of lobsters and 150 ± 25 tonnes of octopus (**Figure 6**). Overall finfish represented 46% of total reconstructed shallow water catches followed by shellfish (32%), lobsters (20%), and octopus (2%).

Total Catch

Combining the reconstructed catches from the individual components detailed above, suggests a total reconstructed catch over the 1950–2014 time period of nearly 1.4 million tonnes. This contrasts with reported catches of 977,997 tonnes over the same time period. Thus, reconstructed total catches were over 40% higher than reported data would suggest. This positive difference was attributed to large-scale industrial catches (+ 230,000 tonnes, + 100%) and small-scale fisheries catches (+150,000 tonnes, + 200%), respectively.

DISCUSSION

Overall, the catch reconstruction for Vanuatu suggests that the development of fishing sectors initiated 35 years ago at the time of independence of Vanuatu has not been an unmitigated success. The deep-bottom and offshore fisheries remain under-exploited or dominated by foreign fleets, respectively. Thus,

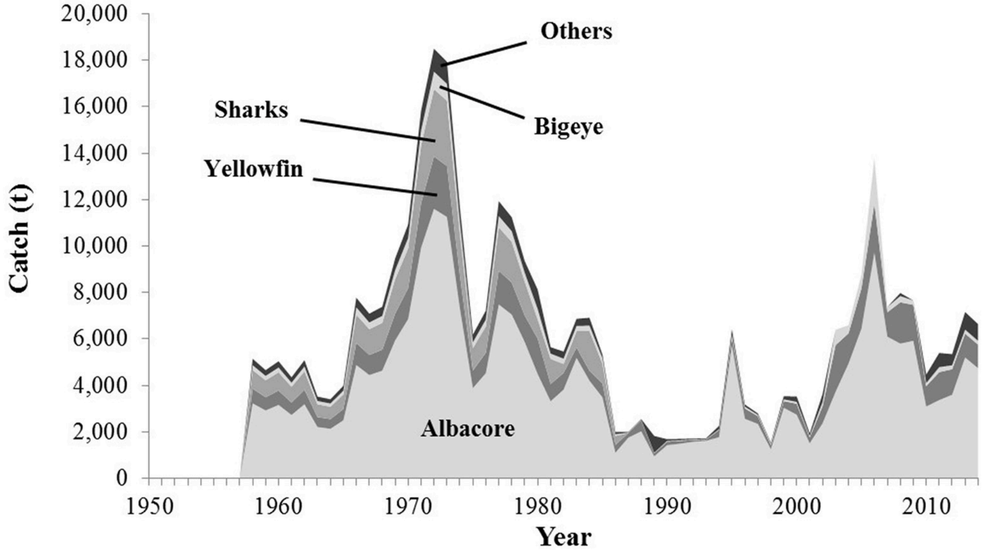

FIGURE 3 | Total reconstructed offshore large-scale catches as derived here for Vanuatu waters, 1950–2014 by major taxonomic group. Others includes bycatch species such as, marlins.

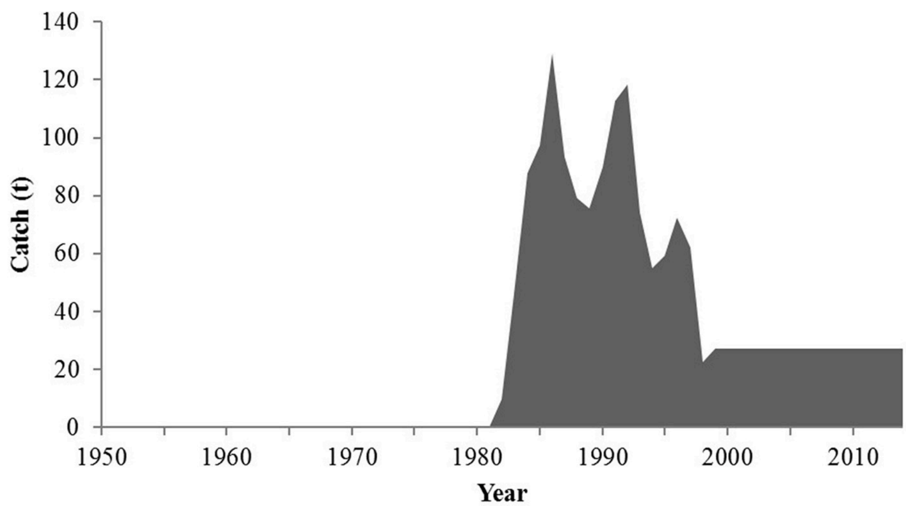

FIGURE 4 | Total reconstructed deep-bottom catches (included bycatch) in Vanuatu waters, 1950–2014.

neither fishery contributes as strongly as expected to the country's economy (David, 2014). In recent years, the non-export fisheries, and the coral reef fisheries in particular have likely contributed the most to the domestic fishing sector, which is the main livelihood and food security contributor of all the fisheries in Vanuatu.

Large-Scale Fisheries

The reconstruction of the offshore catches for tuna and billfishes (and sharks) exhibited differences with FAO fisheries statistics. In total the reconstructed large-scale industrial catches (over 1.1 million tonnes) were 127% higher than the 865,000 tonnes reported by the FAO on behalf of Vanuatu for the same period. Difference in annual estimates ranged between 0 and 17,000 tonnes (3,600 tonnes on average). This is due to the fact that FAO fisheries statistics consider the catch of all Vanuatu-flagged fishing vessels as catch of Vanuatu, with no consideration given to the spatial location (e.g., EEZ) of catches beyond the extremely broad FAO statistical areas. This flag-state-only focus has two implications. First, the catches that occurred during the first phase of the development of the industry in the waters surrounding Vanuatu (and the former New-Hebrides) have not been reported in FAO statistics for Vanuatu, as they were taken by foreign flagged vessels. Second, some of the Vanuatu-flagged vessels (i.e., purse seiner and pole-and line vessels) whose catches exceeded those of the longliners have not operated in the Vanuatu EEZ since the 1990s. More insidious, the Vanuatu International Shipping Registry

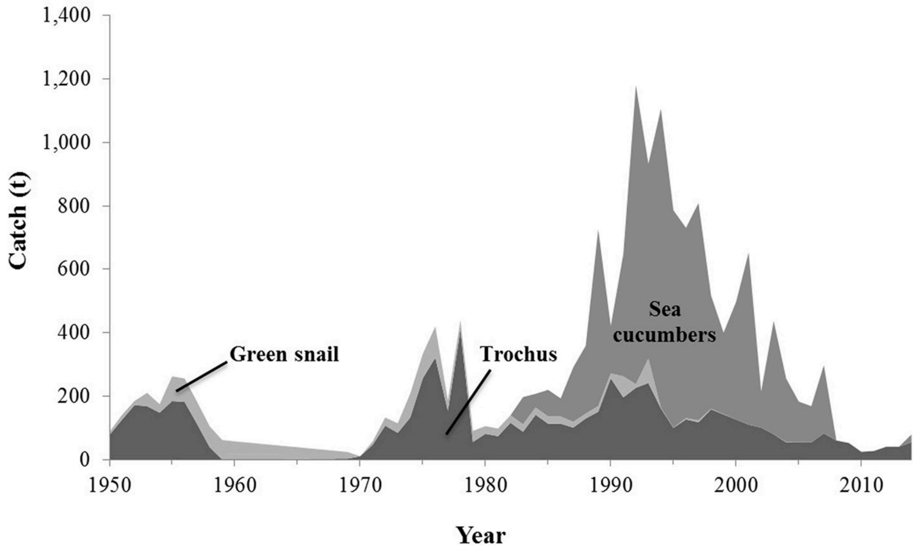

FIGURE 5 | Total reconstructed shallow water catches for export (i.e., artisanal) in Vanuatu, 1950–2014 by major taxonomic groups (all whole, wet weight).

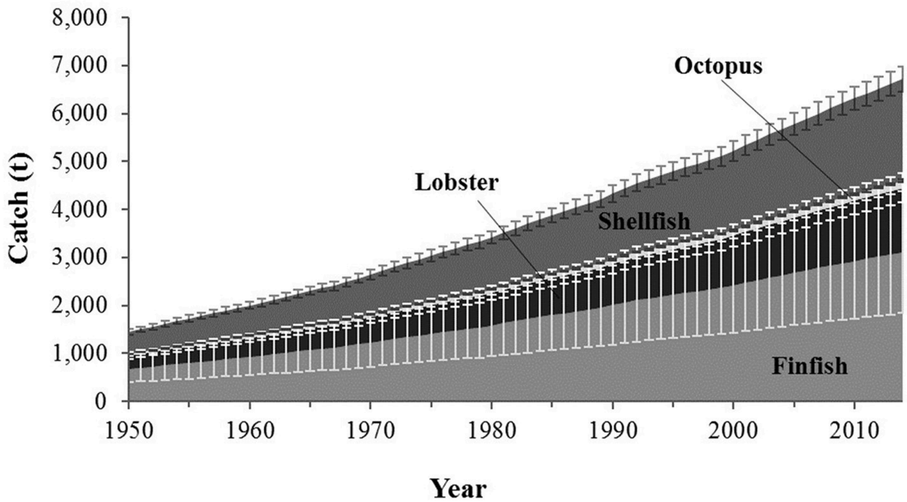

FIGURE 6 | Total reconstructed shallow water catches not for export (i.e., subsistence and local artisanal) in Vanuatu, 1950–2014 by major taxonomic groups. 95% confidence intervals of estimates are represented.

allows foreign fishing companies to register as Vanuatu-flagged vessels under contract. The result is that Vanuatu is a Flag of Convenience country, which creates substantial problems for proper accounting and global data transparency of fisheries catches. This leads also to considerable misrepresentation of the contribution of fisheries to the food security and livelihood, as well as economic benefits for Vanuatu. As a result, our reconstruction of offshore catches showed that the FAO statistics are not representative of offshore catches in the Vanuatu EEZ over this period. Clearly, both flag-sate accounting as well as spatial representation of fishing are important in data on fisheries, as is being shown by the *Sea Around Us* (http://www.seaaroundus.org) for all countries in the world (Pauly and Zeller, 2016).

Data uncertainty also affected the reconstruction of offshore catches. For example, longliners from the SPFC were reported to undertake long-distance fishing trips from their Palekula base (Jacquet, 2016). Available information on fishing locations between 1979 and 1981 suggests that only a small part of the SPFC landings (i.e., <10%) for 1958–1986 may actually have been caught in the immediate waters surrounding Vanuatu. Thus, the reconstruction presented here may have overestimated tuna catch and bycatch in the EEZ waters around Vanuatu between 1958 and 1986. Furthermore, although the use of Vessel

Monitoring Systems (VMS) on fishing vessels has provided increasing information on the spatial allocation of effort (even if not publicly available), logbook coverage of foreign fishing fleets has been variable across years. Consequently, foreign catches in Vanuatu's EEZ may have been miss-estimated for some years, particularly in the 1990s. Both limitations created uncertainties that should be taken into account when interpreting catch variations in the waters surrounding Vanuatu. This also reinforces the need for better data collection and reporting systems, with both flag-state and detailed spatial dimensions.

Growing attention is given by the VFD and regional agencies (e.g., the Secretariat of the Pacific Community and the Forum Fishing Agency) to fill critical data gaps and to provide more reliable estimates of catches and effort in the Vanuatu EEZ. Catch and fishing effort data have been recorded extensively from the fleets of Vanuatu, Fiji and China since the 2000s. Since 2009, the VFD has also accomplished full on-board observer coverage for the locally-based foreign fishing vessels and full port sampling of fresh fish unloaded in ports, including transshipments. Furthermore, the total number of licenses has been limited to 115 (i.e., 75 foreign access licenses and 40 locally-based foreign licenses) while annual license fee has increased by 50% to ensure appropriate financial returns to the Vanuatu government.

Small-Scale Fisheries

Deep-Bottom Fisheries

Our reconstruction of deep-bottom catches likely underestimated real withdrawals, particularly since the 2000s. First, deep-bottom fish is occasionally used for self-consumption throughout Vanuatu, although one may reasonably assume that this use of deep-bottom fish represented only a negligible proportion of catches, given the clear market-oriented nature of these fisheries. Second, some catches of the commercial sector have likely been sold directly to households or tourist operators, and thus remained unreported to the VFD. Third, the capacity of the Fisheries Extension Centers for maintaining a reliable and accurate monitoring program throughout the Vanuatu archipelago has varied over the years. In particular, data gaps have increased to an unknown level since the 2000s, despite the role of these fisheries in local economies. Overall, the reconstructed deep-bottom catches should therefore be interpreted as rough approximations.

Yet a plausible interpretation may be hypothesized from estimated trends. The deep-bottom fisheries have not emerged as a structuring fishing sector in Vanuatu as documented since their early stage of development by David and Cillaurren (1992). Variations in catches were likely linked to fluctuations in fishing effort rather than changes in resource abundance except in the vicinity of main urban areas, and the overall economic potential of this sub-sector has likely been maintained. If the deep-bottom fishery is in fact the only not overexploited commercial coastal fishery in Vanuatu, then there is an opportunity here for the government to create a sustainable management plan. This could allow the fishery to grow to a sustainable capacity, and provide a valuable source of protein to communities while increasing the economic contributions and benefits of this fishery. This strongly reinforces the need for maintaining an accurate data collection system for deep bottom catches and fishing effort, including their spatial dimensions.

Shallow Water Export Fisheries

The shallow water export fisheries have shown an alarming decreasing trend since 1950 following the recurrent exploitation of the valuable invertebrate resources since the nineteenth century. Specifically, the sea cucumber and green snail exports collapsed in the 2000s, leading to national closures in 2008 (for 6 years) and 2005 (projected for 15 years), respectively. Limited catches of sea cucumbers were allowed in 2014 based on species-specific total allowable catches (Léopold, 2016). Trochus resources displayed early signs of depletion as far back as 1957 (Devambez, 1959) and the fishery was consequently closed for 2 years. Overexploitation of trochus resources intensified in the 1980s due to high demand on world markets and resultant increases in purchase prices (Marchandise, 1990). Finally, the number of operational shell-processing factories dropped from six in 1994 to one after 2004. This factory relied on imports of trochus shells in 2014 to maintain production (M. Léopold, pers. obs.) providing evidence of severe resource depletion in most islands of Vanuatu. Reconstructed catch data in 2013 (∼41 tonnes) and 2014 (∼55 tonnes) therefore likely overestimated real domestic trochus catches within the Vanuatu EEZ.

Management of shallow export fisheries aimed at rebuilding overexploited stocks through strict enforcement of national fishing rules (e.g., size limits, spatially explicit total allowable catch, and rotational fishing closure) is urgently needed in Vanuatu. This would allow at least some of the economic potential of these historical fisheries to recover. Indeed, given the recurrent demand for such shells on world markets, our reconstructed catch patterns predict that these fisheries will not recover and will eventually close if national governing agencies do not actively engage in effective harvest control.

Shallow Water Non-export Fisheries

The reconstruction of shallow water catches not destined for export (i.e., largely subsistence and local artisanal fisheries) was affected by high uncertainty due to an obvious scarcity of data since the early 1980s, particularly for subsistence activities. Specifically, we assumed that annual household catch rates in rural areas have remained similar for the last 30 years to infer these catches from population census data. Although this seemed reasonable based on available information, whether or not shallow water areas have been able to cope with the estimated increase in fishing effort and resultant catch density since 1984 (e.g., for finfish: from 3.9 ± 1.6 tonnes/km^2 in 1984 to 6.9 ± 2.8 tonnes/km^2 in 2014) is highly questionable, especially those close to market networks. Updated data on household fishing at national scale is required to estimate their current catch levels across islands. This is particularly important in light of the importance of these largely subsistence oriented fisheries in the Pacific (Zeller et al., 2015).

Such new and improved data would also allow for improving the precision of catch estimates and their taxonomic composition, and for interpreting the increasing trend of shallow water non-export catches that was derived here. For instance, estimated catches increased more slowly than Vanuatu's population growth over the period, thus suggesting a decreasing per capita consumption rate from 32 kg/person in 1950 (all species included) to 26 kg/person in 2014. Similarly estimated per capita finfish consumption decreased from 14.7 ± 6 kg in 1950 to 12.1 ± 4.9 kg in 2014. This trend is driven by the assumed fixed household catch rate and the fact that Vanuatu's overall population growth has been higher than that of the rural population since 1950. The potentially decreasing trend should be examined in more detail through a new countrywide socioeconomic survey, which should also include marine and land crab fisheries. The latter were not included in our analysis although they constitute important local food and commercial resources.

CONCLUSION

The reconstruction process faced major data gaps, particularly and unsurprisingly with regards to the composition and the level of the catches of the coastal small-scale sector. Therefore, uncertainty of estimates has been acknowledged. This reconstruction of total marine fisheries catch of Vanuatu for 1950–2014 showed that the reconstructed total catches were 40% higher than those reported by the FAO on behalf of Vanuatu for the same period. In recent years, this difference was mainly attributed to misreporting of non-export catches. Interestingly we observed different trends in catches among the fisheries studied (i.e., roughly stabilized or slightly decreasing within the large-scale and small-scale deep-bottom fisheries; collapsing within the shallow water export fisheries; and continuously increasing within the shallow water non-export fisheries). The study therefore stresses the need for (i) meaningful management insights for apparently overexploited fisheries such as, export invertebrate fisheries, and (ii) appropriately monitoring developing small-scale fisheries (subsistence and artisanal) to confirm or deny estimated trends and inform management decisions. Although poorly monitored, shallow non-export fisheries have been facing increasing sustainability challenges due to the general population growth and the increasing number of people requiring livelihoods. Given the resource limitations (both financial as well as technical) faced by the VFD as most developing small-island countries, such monitoring needs to emphasize the use of targeted fisheries questions in regular household surveys and general survey and census approaches, combined with country-wide raising factors (Zeller et al., 2015).

AUTHOR CONTRIBUTIONS

ML, Collaborated to complete the data reconstruction update to 2014, contributed country specific information, and helped write the manuscript; GD, Collaborated to complete the data reconstruction update to 2014, contributed country specific information, and helped write the manuscript; JR, Collaborated to complete the data reconstruction update to 2014, contributed country specific information, and helped write the manuscript; JK, Collaborated to complete the data reconstruction update to 2014, contributed country specific information, and helped write the manuscript; LH, Changed the raw data to conform with the standard reconstruction methodology and practices in the Sea Around Us database, contributed to the manuscript and reviewed and edited the manuscript; DZ, Advised on methods, guided analysis, contributed to the manuscript, and reviewed and edited the manuscript.

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frontiers in Marine Science

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Reconstructed Marine Fisheries Catches at a Remote Island Group: Pitcairn Islands (1950–2014)

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The remote Pitcairn Island Group in the South Pacific was designated one of the world's largest marine reserves in 2016, encompassing some of the few remaining near-pristine areas within EEZ boundaries. Pitcairn's domestic fisheries are small-scale, and consist mainly of subsistence (non-commercial) and limited artisanal (commercial) catches. There is no locally-based industrial (large-scale commercial) fishery and the level of foreign industrial activity in recent times has been minimal, due in part to the low biomass of commercially valuable species, along with economic constraints of the EEZ's geographic isolation. Using a catch reconstruction method we estimated the total domestic marine catches for the Pitcairn Islands from 1950 to 2014. We show that overall the Pitcairn Islands' small-scale fisheries catches were almost 2.5 times higher than the data reported by the Food and Agriculture Organization (FAO) of the United Nations on behalf of the Pitcairn Islands, however, this primarily reflects discrepancies prior to the 1980s. Overall, catches for the subsistence and artisanal sectors started with around 12 t·year^{-1} in 1950, but declined to 4 t·year^{-1} by 2014. Domestic reconstructed subsistence catch levels were entirely driven by changes in the human population on the island, with reconstructed artisanal catches only occurring in recent years (2000 onwards). Industrial fishing is entirely executed by foreign vessels, this catch is considerably variable throughout the years and ceases entirely in 2006. The implementation of one of the world's largest marine reserves surrounding the offshore waters of Pitcairn Island has been specifically designed not to affect the rates of subsistence and artisanal fishing conducted by the resident population. Although there is no industrial fishing in the Pitcairn EEZ at present, climate change is predicted to influence the routes of migrating commercially-targeted species, potentially altering fishing effort levels and shift target fishing zones. Implementation of MPAs such as the Pitcairn Island Marine Reserve protect large oceanic areas from risk of future industrial exploitation, whilst protecting near-shore reef and deep-water zones, maintaining domestic coastal fisheries vital for local communities.

Keywords: unreported catches, artisanal fisheries, subsistence fisheries, small-scale fisheries, marine protected area, exclusive economic zone

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INTRODUCTION

Marine Protected Areas (MPAs) are a well-recognized and increasingly utilized tool for managing and protecting marine ecosystems from the existing or potential impacts of anthropogenic activities. In 2010, the Convention on Biological Diversity called for formal protection of at least 10% of the world's marine and coastal areas by 2020, under Aichi Biodiversity Target 11[1]. Much of the progress toward this target is being attempted through the establishment of very large MPAs (>100,000 km^2), with ∼62% of the total global marine area under protection contained within 24 such MPAs (Jones and De Santo, 2016). A trend of establishing these very large MPAs in locations described as "residual" to extractive or commercial uses has also been identified (Devillers et al., 2015). These observations have led to concerns that emphasis on meeting conservation targets through coverage in square kilometers or political "ease of establishment" (Devillers et al., 2015) is resulting in additional Aichi target objectives (such as reserve connectivity and representativeness) being side lined (Singleton and Roberts, 2014; Devillers et al., 2015; Jones and De Santo, 2016). Given that the expansion of fishing to newly exploited areas has declined since its peak in the 1980s (Swartz et al., 2010), it is likely that areas currently considered "residual" to fishing have already been determined unviable based on failed fisheries or low assessed catch. Fishery resource assessments are performed by projects such as the Skipjack Survey and Assessment Programme by the South Pacific Commission (Dalzell et al., 1996). The low fisheries activity in these remote areas is therefore more likely a result of other causes, such as low biomass of commercially valuable species, or economic constraints such as distance from markets. With changes to catch potential projected under climate change scenarios (Cheung et al., 2010), and shifts in the species being targeted by industrial fleets (Pauly and Palomares, 2005), understanding the historic and underlying causes of why an area is not targeted by commercial fisheries can provide insights into how MPAs may function in the context of future fisheries and conservation objectives.

In 2016, the United Kingdom designated the waters surrounding its sole Pacific Overseas Territory, the Pitcairn Islands' group, as one of the world's largest marine reserves (**Figure 1**). Located in the central South Pacific, the Pitcairn Islands are among the most remote on the planet (Dawson, 2015), with their nearest neighbor, the Gambier Islands' group of French Polynesia, being 390 km to the north-west. Despite having a relatively small combined land area of 49 km^2 (Irving and Dawson, 2012), the farthest two islands in the Pitcairn group are separated by a distance of ∼560 km (Irving and Dawson, 2012), resulting in an Exclusive Economic Zone (EEZ) of over 836,000 km^2[2]. Of the four islands within the Pitcairn Islands' group, only Pitcairn Island itself is inhabited by people, with two of the remaining islands (Oeno and Ducie atolls) being relatively untouched (Irving and Dawson, 2012); and Henderson Island a World Heritage Site as one of the last near-pristine elevated atolls in the world (UNESCO)[3]. The reserve is designed to allow the continuation of small-scale fishing by the local population by excluding the waters up to 12 nautical miles (or ∼22 km) offshore from each of the four islands, along with a corridor of ocean connecting Pitcairn Island to a nearby seamount, locally known as 40 Mile Reef. The remaining EEZ is encompassed in a total no-take area, covering over 830,000 km^2 of ocean (Dawson, 2015).

The purpose of this study was to utilize the available information on fishing by the subsistence, artisanal and (foreign) industrial fisheries operating within the Pitcairn Island EEZ or EEZ-equivalent waters (prior to EEZ declaration), in order to reconstruct best estimates of total fisheries catches from 1950 to 2014, using the well-established catch reconstruction method (Zeller et al., 2016). We also compared the reconstructed domestic catch estimates to the official statistics for the Pitcairn Islands presented on behalf of the United Kingdom's territory by the Food and Agriculture Organization (FAO) of the United Nations. We then considered the historical and on-going levels of catch for the Pitcairn Islands within the context of implementing large-scale marine reserves in remote, and fisheries residual areas.

METHODS

Exclusive Economic Zone (EEZ)

The Pitcairn EEZ (based on the *Sea Around Us* spatial database, Pauly and Zeller, 2015) was established in 1997, has a total area of over 836,000 km^2 (**Figure 1**), and a very small shelf area of 155 km^2.

Human Population Data

Human population trends for Pitcairn Island were primarily derived from the Pitcairn Study Centre census database[4] and The World Factbook[5]. We linearly interpolated between data points to estimate population time series for 1950–2014. As of 2014, only 49 inhabitants resided on Pitcairn Island (Leguerrier et al., 2014), with a relatively steady decline from 163 residents in 1943.

Subsistence Fisheries

We followed the definition of subsistence fisheries outlined by Zeller et al. (2016) as "those fisheries that often are conducted by women and/or non-commercial fishers for consumption by one's family... [along with] the fraction of the catch of artisanal boats that is given away to the crews' families or the local community." Subsistence *per capita* catch rates were estimated for Pitcairn Island and applied to human population data to estimate the total

[1]Convention on Biological Diversity. Available online at: www.cbd.int/sp/targets/rationale/target-11 (Accessed 24 April 2017).

[2]*Sea Around Us*. Available online at: http://www.seaaroundus.org/data/#/eez/612?chart=catch-chart&dimension=taxon&measure=tonnage&limit=10 (Accessed 2017 April 27).

[3]UNESCO World Heritage Centre. "Henderson Island". Available online at: http://whc.unesco.org/en/list/487 (Accessed 2016 May 28).

[4]Pacific Union College (2011) "Pitcairn Islands Study Centre: Census Data". Available online at: http://library.puc.edu/pitcairn/pitcairn/census.shtml (Accessed: 2016 May 26).

[5]Central Intelligence Agency. "The World Factbook: Pitcairn Islands" (2016). Available online at: https://www.cia.gov/library/publications/the-world-factbook/geos/pc.html (Accessed 2016 May 26).

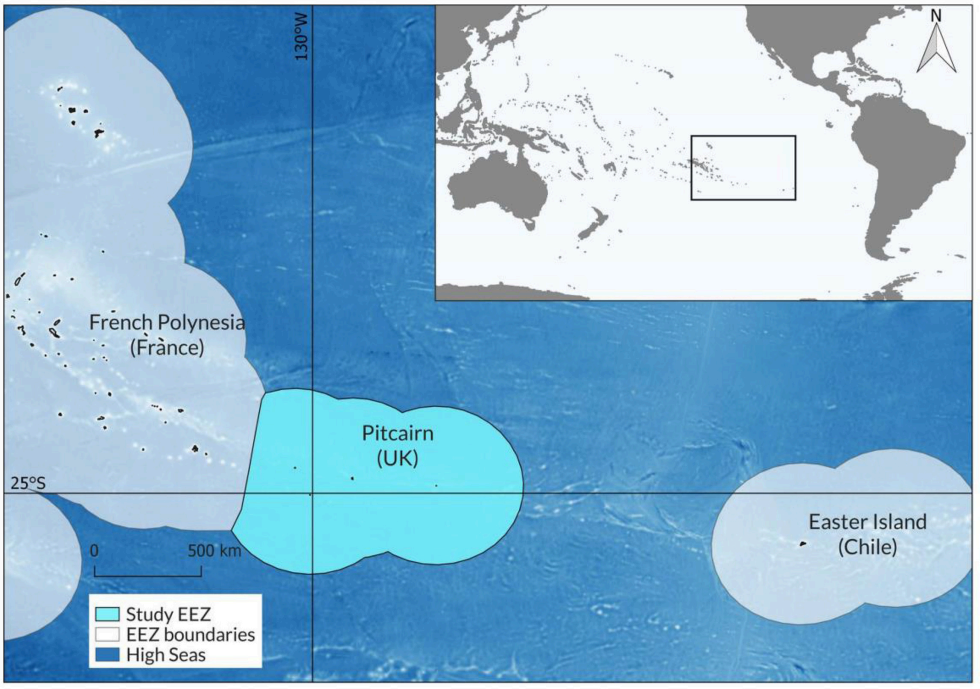

FIGURE 1 | The Exclusive Economic Zone (EEZ) of the Pitcairn Islands, an overseas territory of the United Kingdom (UK), and the EEZs of neighboring French Polynesia (a territory of France) and Easter Island (a territory of Chile), with surrounding High Seas.

annual subsistence demand. We conservatively assumed that all catch is landed with no discards due to the non-commercial nature of a subsistence fishery, expecting that all landed catch is utilized and all unwanted catch is released alive. Considerable information on fisheries and subsistence catches in the Pitcairn Islands' waters was derived from Gillett (2009), Adams and Langley (2005), Götesson (2012), and Irving and Dawson (2012). Catch rates were derived from the answers provided by 90% of the island's population ($n = 22$) to an unpublished survey in 2011 on the frequency and amount (kg) consumed per household, with mean consumption of 71.5 kg·person^{-1}·year^{-1}. Although Gillett (2009) estimated consumption at 140 kg·person^{-1}·year^{-1}, this was not based on data from the islanders, and considerably less fish was consumed by islanders in recent years. This is due to a declining number of fishers and an increased access to alternative sources of protein through a freight shipping service to Pitcairn from New Zealand which has been operating since 2002. Meanwhile, Dalzell et al. (1996) reported 8 tons of subsistence catch for Pitcairn between 1989 and 1994, which amounts to 1.6 t·year^{-1}, although it is not clear how this estimate was derived. Here, we chose the more conservative estimate, although the previous reconstruction by Chaitanya et al. (2012) used that provided by Gillett (2009). As there was limited information indicating how consumption rates have changed over the study time period, we fixed the consumption rate of 71.5 kg·person^{-1}·year^{-1} back to 1950.

Once the total subsistence catch for the island was estimated, we approximated the species composition with information from Gillett (2009), Sharples (1994), Adams and Langley (2005), Götesson (2012), and Dalzell et al. (1996). Our breakdown included miscellaneous invertebrates and fishes as well as specific species, genera and families. Due to the large variety of snappers (Lutjanidae) and groupers (Serranidae) that were caught, we did not break this down further besides the highly targeted *Epinephelus fasciatus, Variola louti,* and *Kyphosus pacificus;* spiny lobster (*Panulirus* spp.—essentially *Panulirus pascuensis* and *Panulirus penicillatus*), and slipper lobster (*Scyllarides haanii*). The taxonomic breakdown was separated into two periods, 1950–2003 and 2004–2014. From 1950 to 2003, no lobster catch was consumed by islanders due to the religious influence of the Seventh Day Adventist Church on their diets. However, within the 10 year period from 2004 to 2014, this influence decreased and lobster catch increased for both artisanal sale and personal consumption, with a recent decrease in lobster catch possibly related to localized depletion (Götesson, 2012).

Between 1976 and 1996, catch data consisting of number of fish caught each month were sporadically recorded in the local newsletter, the *Pitcairn Miscellany* (Gillett, 2009; Götesson, 2012; Duffy, 2014); with the island's fishing and diving club recording catch into the 2000s (Duffy, 2014). However, as no size parameters were recorded and the purpose of the landings (subsistence or artisanal) was not available, we were unable to use these data here.

Artisanal Fisheries

Artisanal fishing is defined as predominantly commercial catch taken by small-scale and fixed gears (Zeller et al., 2016). Due to the small-scale nature of artisanal fishing we assumed that all catch is sold, given away, or released, resulting is no discarded catch. Irving and Dawson (2012) indicated that around four cruise ships purchased on average ∼600 kg of tuna, wahoo, and reef fish, and 400 kg of lobster. Artisanal fisheries sales to cruise ships occur on an *ad-hoc* basis, with the sales noted by Irving and Dawson (2012) probably first occurring around 2000. The artisanal sale of lobster to certain visiting cruise ships began about 10 years ago (Michel Blanc, Fisheries Development Adviser, Pacific Community, pers. commun. 2011). Gillett (2009) suggested that Pitcairn's artisanal fisheries catch may amount to ∼5 t·year^{-1}, which is five times that derived from the four ship orders observed by Irving and Dawson (2012). Gillett (2009) based his estimation on an assumption that artisanal catch would likely be less than that which the islanders consumed themselves, but still of some financial value, providing no other grounds for this tonnage. Artisanal catches from the cruise ship orders observed by Irving and Dawson (2012) provided the more conservative estimate of artisanal catch (although did not include the likely trade of smaller amounts to other vessels), and were used here. Note that this differs from the estimates provided by Gillett (2009), which were used in the previous reconstruction by Chaitanya et al. (2012). Estimates can also be derived through other means, such as the annual return of a fishery and the known price for which fish are sold. According to Sharp (2011), the Pitcairn islanders were earning about US $12,800 per year in revenue through the sale of fish to cruise ships. The wholesale fish price of US $8 kg^{-1} in nearby Mangareva estimated by Sharp (2011), was applied to ∼1.6 tons of miscellaneous fish sold to cruise ships each year. This is 0.6 tons more than the amount from observed cruise ship orders. Note that Götesson (2012) states fish were usually sold at USD $5 kg^{-1}, and lobsters for USD $10 kg^{-1}, which gives an average price of around USD $7 kg^{-1}, similar to the USD $8 kg^{-1} suggested by Sharp (2011). Assuming the catch breakdown of 40% lobster and 60% fish (from the average cruise ship orders mentioned previously) applies to other artisanal sales, at USD $5 kg^{-1} and USD $10 kg^{-1}, respectively: a total revenue of USD $12,800 would result from a sale of 0.64 tons of lobster and 1.5 tons of fish, totaling 2.2 tons of catch. We used the most conservative estimate of 0.6 t·year^{-1} before lobster was caught and 1 t·year^{-1} after, as this is the only approximation based on a given commercial order rather than derived from estimated revenue and estimated sale prices. Cruise ships have visited the islands since 1914 in relatively consistent numbers[6], alongside privately owned yachts and other passing vessels. Despite this, in a comprehensive review covering hundreds of accounts of trade and barter between Pitcairn Islanders and passing vessels, fewer than a dozen mentions were made of fish being provided or sold (Herb Ford, 2017, pers. commun. 31st May). Rather, vessels visiting Pitcairn were often well stocked with meat, with the main commodities procured by ships during visits being wood, water and fruit (Herb Ford, 2017, pers. commun. 31st May). According to Dalzell et al. (1996) there were no artisanal fish sales for the Pitcairn Islands in the early 1990s. However, by 1994 instances of fish being traded with cruise ships had been noted (Sharples, 1994), although there is no information on the frequency or quantity of fish traded. To provide a conservative estimate, we assumed all catch was landed and chose to limit our reconstruction of artisanal fisheries to 1999 onwards, with no artisanal sales estimated before this point. Lobster catch (0.4 t·year^{-1}) was only included for the final 10 years of the reconstruction, with 0.6 t·year^{-1} of artisanal fish catch held constant from 2000 until the inclusion of lobster in 2004, and 1 t·year^{-1} of the same ratio of fish to lobster held constant until 2014.

The species breakdown for the artisanal fishery was primarily based on Irving and Dawson (2012); tonnage was split evenly between tuna (*Thunnus* spp.), wahoo (*Acanthocybium solandri*), reef fish ["marine fishes not elsewhere included (nei)"], and lobsters (*S. haanii*. and *Panulirus* spp.). We did not separate tuna into species. While the islanders primarily catch yellowfin tuna (*T. albacares*), they also catch skipjack tuna (*Katsuwonus pelamis*) with occasional landings of albacore tuna (*T. alalunga*) and bigeye tuna (*T. obesus*) (Adams and Langley, 2005; Götesson, 2012; Irving and Dawson, 2012; Duffy, 2014). We did not assign specific tonnages to individual reef fish species due to the high species variety and relatively low tonnages. However, common taxa include *K. pacificus*, *V. louti*, and *Epinephelus tauvina* (Irving and Dawson, 2012). Data on shark catches are sporadically available, but there is little information on the consistency of the targeting of sharks by local fishers over time. Nonetheless, there is some indication that the fishing pressure on sharks around Pitcairn Island, when compared to the remaining islands, may be considerable according to a study by Duffy (2014). From the data available, Götesson (2012) reports 714 sharks were caught through the years 1977–1997 and 12 sharks caught in the year 2008. Duffy (2014) stated data on shark catches were collected for 20 months over 2006–2008 by the community, with 28 sharks being caught during this period. As some recorded years have a zero count for shark catch, we felt we were unjustified in extrapolating shark catches beyond the years for which we had data. As sharks are primarily targeted for their teeth which are used in carvings, mainly small sharks are caught, including juveniles (Götesson, 2012; Duffy, 2014), making an average weight of the sharks caught difficult to estimate, and thus estimated landed tonnages difficult to derive. In order to remain conservative, we excluded shark catch from our reconstruction, despite the potential for this contribution to be substantial to the overall yearly catch and artisanal catch composition.

Industrial Fisheries

According to Adams and Langley (2005), very little industrial fishing occurred in the area of their study, which included the Pitcairn EEZ (∼50% of the total study area) and surrounding areas. Adams and Langley (2005) suggested this is a consequence of the islands being farther south than the distribution of pole-and-line and purse-seine fleets, with the only industrial fishing activity in this area being performed by foreign longliners. To remain concise and focused on domestic fisheries we do not detail discards in this analysis, this is due to the complexity of multiple foreign fishing entities using a variety of gears in the Pitcairn EEZ since 1950. The discard rates are dependent on the

[6]Pitcairn Islands Office. "Pitcairn's History." Available online at: http://www.government.pn/Pitcairnshistory.php (Accessed 2016 May 27).

country fishing, target species and gear used, these discards along with the rest of the industrial catch was estimated in a separate analysis (see Le Manach et al., 2016). Industrial fishing vessels were not based at the Pitcairn Islands, as the existing harbor is too small for berthing, there are no processing facilities and no exporting opportunities (e.g., no airport on the island). Foreign industrial fishing within the waters of the Pitcairn Islands began in the 1950s with Japanese longliners targeting tuna, followed in the 1960s by industrial fleets from Taiwan and Korea (although China and French Polynesia were said to fish in the vicinity as well), these peaking in the early 1970s, with the Japanese and Korean fleets largely by-passing the Pitcairn Islands from the 1980s onwards (Adams and Langley, 2005; Irving and Dawson, 2012). According to Gillett (2009), there is only one accessible document noting the historic allowance of foreign vessels in the Pitcairn Islands EEZ, an access agreement that permitted up to 20 Japanese longliners to operate within the waters of the Pitcairn Islands. Gillett (2009) also revealed that the most recent access agreement in 2006 was for a longliner (of unspecified nationality) with a single fee of $1,000 (resulting in less than a week's fishing), although this information was provided to Gillett (2009) by personal communication and is not available elsewhere. The Forum Fisheries Agency (2008) produced a single report that contained data on tuna catch in the waters of the Pitcairn Islands, with 5 tons of albacore (*Thunnus alalunga*) caught by a foreign (unnamed) longline vessel in 2005 (Gillett, 2009). The global industrial catch of large-pelagic fish was reconstructed as a separate data layer by the *Sea Around Us* (Le Manach et al., 2016).

Reconciling Reported Data with Reconstructed Estimates

Data from the FAO of the United Nations (FAO, 2016) were used as the reported data baseline for the domestic fisheries. We assigned reported catches as being artisanal in nature. When more than our estimated artisanal catch (0.6–1 t·year^{-1}) was said to be reported, we assumed the FAO catch amounts included subsistence catch. Any remaining estimated catch was then assigned as unreported catch. Thus, we assumed that 100% of artisanal catches were deemed reported. For foreign industrial fisheries, reported landings were based on the spatially allocated global reconstructed catch database of the *Sea Around Us* (Zeller et al., 2016).

RESULTS

Total Reconstructed Catches

Overall, reconstructed catches for Pitcairn Island, which consist of subsistence and artisanal sector catches, totaled about 418 tons for the period 1950–2014 (**Figure 2A**). This reconstructed catch was almost 2.5 times more than the 173 tons reported by FAO on behalf of the Pitcairn Island for the same time period (**Figure 2A**). Nevertheless, our reconstructed catches correspond more closely with those reported to FAO from the 1980s onwards, this agreement is likely due to a "presentist" bias of improving data quality over the years as described in Pauly and Zeller (2017). Given the close linkage between the (declining) human population and domestic catches, along with the decline and eventual cessation of foreign industrial catch (see below), it is not surprising that total catches declined steadily over the time period examined. Subsistence catches dominated the domestic reconstructed catch, accounting for ∼97% of the reconstructed total catch (decreasing to ∼78% by 2014 when the population had dropped to 49 people), while artisanal fishing accounted for ∼3%. With no domestic industrial fisheries, foreign industrial catch accounted for all large-scale fishing activity, showing substantial fluctuations in catch until the end of this activity in 2006 (**Figure 2B**).

Subsistence Catches

Overall, reconstructed subsistence catches totaled 406 tons between 1950 and 2014. Subsistence catches fell throughout this period due to the declining population, with average catch declining from 12 to ∼4 t·year^{-1} by 2014 (Appendix 1 in Supplementary Material). Fluctuations in our reconstructed catches over this time period are entirely due to human population fluctuations, as alternative sources of variations in subsistence catch (such as poor weather) were not considered in our estimation. Subsistence catches were dominated by *E. fasciatus*, *V. louti,* and *K. pacificus*, while general Lutjanidae, Serranidae, and "marine fishes not elsewhere included (nei)" also occurred in the catch throughout the entire time period (Appendix 2 in Supplementary Material). Catches after 2003 included "miscellaneous aquatic invertebrates," representing *S. haanii* and *Panulirus* spp.

Artisanal Catches

Artisanal catches totaled 13.4 tons over the 1950–2014 period, derived from an estimated catch of 0.6 t·year^{-1} from 2000 to 2003, followed by 1 t·year^{-1} from 2004 to 2014 (based on our assumptions, see Appendix 1 in Supplementary Material for data). Transportation issues, erratic weather patterns, rough seas, and a lack of tourist accessibility to the island likely contributed to fluctuations in the annual catch that could not be reflected here due to insufficient data on these variables. Artisanal catch consisted exclusively of finfish from 2000 to 2004, after which we included 40% of the catch as crustaceans. Total tonnage in recent years was split evenly between slipper lobster (*S. haanii*), spiny lobster (*Panulirus* spp.), tuna (*Thunnus* spp.), wahoo (*A. solandri*), and reef fishes ("marine fishes nei").

Foreign Industrial Fisheries

While there was some foreign fishing in Pitcairn waters in the early years of our study period, from 2006 onwards there appears to have been no major industrial fishing activity within the EEZ (**Figure 2B**). Throughout the time period of this reconstruction, there is some fluctuation in foreign catches, with foreign catches appearing to be very low in the 1950s and early 1960s. Foreign catches in the EEZ increased to between 5,000 and 12,000 t·year^{-1} in the 1960–1980s, but remained highly variable (**Figure 2B**). Foreign fishing seemed to have declined substantially in the 1990s, before ceasing in the mid-2000s (**Figure 2B**).

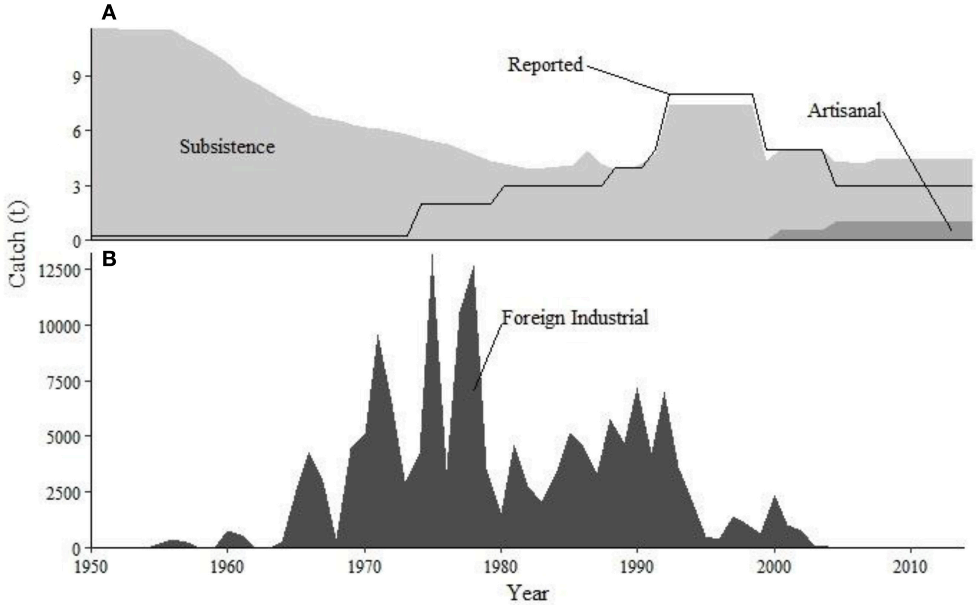

FIGURE 2 | Reconstructed catch (tons) for the Pitcairn Islands Exclusive Economic Zone (EEZ) for 1950–2014, **(A)** Reconstructed domestic catch by sector, with the domestic catch reported to FAO superimposed as a black line; and **(B)** Reconstructed foreign industrial catch.

DISCUSSION

Reconstructing Fisheries Catches

The reconstruction of total domestic fisheries catches for the Pitcairn Islands from 1950 to 2014 suggests that actual catches were likely almost 2.5 times greater than the data provided to the FAO at the beginning of the time period. As many of the Pacific Island countries and territories rely heavily on (mainly coastal) fish stocks for food security and livelihoods (Zeller et al., 2015; Charlton et al., 2016), appropriate monitoring, reporting, and management of coastal marine fisheries is vital for ensuring food and nutritional security (Golden, 2016; Golden et al., 2016). Our study illustrates the importance of accounting comprehensively for non-commercial fisheries catches (e.g., subsistence), as has also been shown for other Pacific island countries (Zeller et al., 2015). Small-scale fisheries, and especially non-commercial subsistence fisheries, are consistently under-represented in globally reported data (Pauly and Zeller, 2016), as are recreational catches (Smith and Zeller, 2016). While this is most prevalent in developing countries (Zeller et al., 2015), under-reporting also exists in highly developed countries (Zeller et al., 2011). We used information from a variety of sources including FAO, the Secretariat of the Pacific Community (SPC) and independent studies in the attempt to maximize reliability of data and information sources, however our estimates rely heavily on self-reporting and assumptions, and therefore are subject to limitations including underestimation and generalization.

With regards to artisanal fisheries, our catch estimation for the period 1950–2014 (totaling 13.4 tons) was ∼22 times less than that of a previous, preliminary reconstruction attempt by Chaitanya et al. (2012), who estimated 300 tons of artisanal catch over the same time period. This discrepancy is due to our more conservative use of the four large cruise ship orders as the baseline of artisanal catch, rather than the less conservative estimate of 5 t·year^{-1} suggested by Gillett (2009) and subsequently used by Chaitanya et al. (2012). Our estimate of 0.6 t·year^{-1} for artisanal catch from 2000 to 2004, and 1 t·year^{-1} thereafter, is closer to the 1.6 t·year^{-1} of artisanal catch which can be derived by dividing the estimated annual revenue of fish sales to cruise ships by the estimated cost per kilo of landed fish at the closest market in Mangareva (Sharp's, 2011). Even the alternative approach of applying Götesson's (2012) suggested market price to Sharp's (2011) revenue estimate (resulting in 2.2 t·year^{-1}) is closer to the conservative estimate we have used than that suggested by Gillett (2009).

Such low levels of artisanal catch compared to the yearly subsistence catch is unsurprising, as Gillett (2009) suggested that subsistence fisheries were of greater magnitude due to the remote nature of the islands. The development of the artisanal fisheries sector in the Pitcairn Islands has been constrained by a number of factors, including: a lack of transportation infrastructure (Amoamo, 2011), limited freezer storage facilities (Irving and Dawson, 2012), difficult and weather dependent accessibility (Irving and Dawson, 2012), distance from the nearest market (Adams and Langley, 2005), and the likely limited sustainability of the local near-shore fisheries resources themselves (Adams and Langley, 2005; Palomares et al., 2011). Furthermore, despite a recent increase in cruise ship visits, artisanal sales to these vessels is likely to decline in the near future due to health and safety restrictions, a lack of recognized provenance for the catches, and a declining population of fishers.

The subsistence catch shown here replicates the declining human population trend shown by Chaitanya et al. (2012), remaining constant from 2007 onwards when the population stabilized at ~48 people. The *per capita* estimate used in this reconstruction was derived from an unpublished survey based on levels of consumption in 2011 (Schuttenberg and Dawson, 2012). While comparing monthly catch data from 2008 to that collected a decade prior, Duffy (2014) noticed a decrease in catch amounts, despite no change in the population size. Duffy (2014) suggested that this decrease may be a consequence of the aging population. Additionally, as diet preferences have shifted over time, particularly recently with increased access to external food supplies from a regular supply ship, our estimate is likely to be rather conservative for earlier years. Under religious restrictions forbidding the consumption of certain taxa, lobsters were mainly caught for bait and artisanal sales, however, in more recent years lobsters have also become a part of some islanders' diets (Götesson, 2012). To remain conservative, we only included lobster catch in recent years (2004–2014). Meanwhile, stock sizes of sea chub (*K. pacificus*) were suggested to have increased in recent years (Götesson, 2012), with landings decreasing from an estimated 2.3 tons in 1950—0.6 tons in 2014 in our reconstruction.

While there has never been any domestic industrial fishing activity within the Pitcairn EEZ, some information is available on the foreign industrial fisheries operating within these waters. Japanese, Korean and Taiwanese industrial fishing boats have targeted yellowfin, big eye, and albacore tunas in Pitcairn's waters (Götesson, 2012). Specifically, in 1963 Japanese vessels were active in these waters targeting tuna, bonito, and mackerel, and in 1966 a South Korean vessel was active in the area. This foreign fleet activity peaked around 1975, with Japanese and Korean activities declining in the following 10 years. Catches were highly variable throughout the period of the study, including at the peak of the fishery (Götesson, 2012). Industrial fishing within the Pitcairn EEZ has been deemed to be economically unviable (Adams and Langley, 2005). Furthermore, an access agreement worth $1,000 by an unknown fishing entity in 2006 reportedly only resulted in a few days of fishing (Gillett, 2009), and was not renewed, further suggesting the unviability of industrial-scale fishing in these waters at present. A recent remote monitoring trial (Jan. 2015–Mar. 2016) carried out by Project Eyes on the Seas on behalf of the UK government observed no vessels displaying illegal fishing behavior, suggesting likely little illegal fishing activity is occurring in the EEZ[7].

The Pitcairn EEZ seems unsuitable for industrial fishing activities at present due to the low abundance of valuable species such as tuna (Adams and Langley, 2005). Furthermore, the low diversity of fish species resulting from the isolated location and distance from the equator (Friedlander et al., 2014) is likely to limit industrial interests at present. While Catch Per Unit Effort (CPUE) for albacore (*Thunnus alaunga*) within the wider vicinity of the Pitcairn Islands from 1958 to 2002 was noted by Adams and Langley (2005) to be similar to the regional average, the largest hotspots for the cumulative longline catch from 1990 to 2003 were observed outside of the Pitcairn EEZ. Adams and Langley (2005) further noted the considerable temporal constraints on the tuna fisheries in the region, being limited by the short and unpredictable fishing season (~October to March), along with high inter-annual variability in landings. Such unpredictability in annual catch likely poses an investment risk to commercial fishing operations in such remote locations.

Implications for Large Oceans MPAs

Given that historical levels of industrial, artisanal, and subsistence fishing activities have never been substantial in the Pitcairn EEZ, and that industrial fisheries have ceased altogether, it is reasonable to describe the Pitcairn EEZ as an area that is currently "residual" to fishery interests. One of the arguments proposed against investing in the establishment of remote large MPAs is that such reserves may provide little protection to the species and ecosystems currently impacted by anthropogenic activities (Devillers et al., 2015). However, the cause of unprofitable fisheries resulting in "residual areas" need not always be the lack of target species biomass, and may instead reflect economic (e.g., cost) or technological constraints which are subject to change.

Historical reconstructions of fisheries can provide insights into why fisheries never developed or stalled in these residual regions, which may be of value when determining whether an ecosystem is at risk of future exploitation. Data on fisheries landings from the FAO alone do not provide a whole picture of whether an ecosystem is indeed heavily fished, as FAO statistics report what the UK sent them on behalf of Pitcairn. While in the case of the Pitcairn Islands' waters, artisanal and industrial fisheries have likely been constrained by low biomass of commercially valuable species, some species (such as sharks) have likely been safeguarded from exploitation by their distance from markets, as opposed to the levels of their abundance. Ducie Island in particular exhibits high top predator biomass, accounting for 62% of the total fish biomass (or ~1 ton per hectare) (Friedlander et al., 2014). Overall, 46% of top predator biomass in the Pitcairn Island group was comprised of gray reef sharks, followed by whitetip reef sharks at 12% (Friedlander et al., 2014). So long as the value of shark products remains high, coupled with decreasing biomass in heavily fished areas (Worm et al., 2013), even remote or previously untargeted regions may be at risk of opportunistic shark fishing.

The data discrepancies between the reported FAO data and the reconstructed catch have greatly decreased since the 1980's, showing an improvement in fisheries data collection, despite this, local surveillance, and enforcement in the area may still be weak. Thus, although there is some evidence of sharks caught around Pitcairn Island, it is unclear how much fishing pressure they have faced around Ducie, Oeno, and Henderson Islands (Duffy, 2014). The elevated shark biomass around Ducie Island is correlated to high coral coverage (56%), a drastically different marine environment compared to Pitcairn Island, which has the lowest coral coverage (5%) and is instead 42% covered by

[7] Pew Charitable Trusts Fact Sheet (2016). Effective Surveillance in the waters of the Pitcairn Islands Marine Reserve. Available online at: *http://www.pewtrusts.org/en/research-and-analysis/fact-sheets/2016/09/effective-surveillance-in-the-waters-of-the-pitcairn-islands-marine-reserve* (Accessed 2017 April 20).

erect macroalgae (Friedlander et al., 2014). The difference in habitat surrounding the four islands in the Pitcairn EEZ gives an uncertainty to the degree in which fishing pressure has effected fish composition and levels of biomass of Pitcairn Island compared to the remaining uninhabited islands. Regardless, shark biomass is substantially lower surrounding Pitcairn Island (Friedlander et al., 2014) and particularly juvenile individuals are subject to targeted fishing (Duffy, 2014), thus new regulations have been proposed to completely ban shark fishing and provide an alternative source for shark teeth (the primary fishing reason), such as through beach collections and aquariums (Dawson et al., 2017). Despite local shark fishing, the Pitcairn Island group's remoteness and small human population, in particular the distant unpopulated islands, cultivates a minimal risk of small-scale fisheries exploitation. The main focus of this MPA however, is not aimed at near-shore small-scale fisheries, but rather offshore industrial fisheries. Given the industrial catch in the Pitcairn EEZ has been highly variable since the 1950's, peaking at around 12,000 $t \cdot year^{-1}$ in the mid-70's, the implementation of the Pitcairn marine reserve provides refuge for these high-value target species from future industrial exploitation.

A comprehensive report on the potential impacts of climate change on the ecosystems of Pacific Island countries (Bell et al., 2011) projected varying impacts on different fish functional groups. The demersal and invertebrate species targeted by the islanders' small-scale fisheries such as snappers and slipper lobsters are predicted to decline in productivity across this region due to reduced currents, increased sea surface temperatures, habitat loss, and ocean acidification (Bell et al., 2011). Meanwhile, Bell et al. (2011) suggest that tuna stocks may increase within Pitcairn's waters due to climate-driven shifts in the distributions of these taxa (see also Cheung et al., 2009). Adams and Langley (2005) indicated that catch of albacore tuna within the Pitcairn Islands EEZ generally coincided with seasonal variability in oceanographic conditions, with low catches associated with cooler water and higher catches with sea surface temperature increases. Changes to the sea surface temperature and current strength in the South Pacific gyre are anticipated in the coming decades, likely resulting in shifts in the distribution of large pelagic fishes (Bell et al., 2011). As tuna stocks have previously been targeted in the Pitcairn EEZ (Götesson, 2012) and been shown to have high levels just outside of the EEZ (Adams and Langley, 2005), it is likely these projected temperature changes could promote higher levels of tunas in the area, notably within the economic zone, as predicted by Bell et al. (2011).

Projected increases in sea surface temperature and ocean acidification may not only increase tuna production within the EEZ but in combination with the projected negative impacts on demersal and invertebrate species (Bell et al., 2011), could force the Pitcairn islanders to target more pelagic species such as tunas for subsistence, rather than the currently targeted reef fishes. As the fishing pressure is unlikely to increase due to the small and aging population (Duffy, 2014), fishers may have to change fishing tactics and sacrifice the profits from traditionally artisanal catch to feed their families. The proposed MPA regulations to ban shark fishing and provide an alternative source for shark teeth could help mitigate these combined effects of climate change and fishing pressure on sharks whilst still providing a livelihood to the fishers (Dawson et al., 2017). Coastal fishing near reefs is the dominant small-scale fishery of Pitcairn and other Pacific islands (Dalzell et al., 1996) and is projected to be of the most effected by climate change (Bell et al., 2011). The reconstructed catch data can provide an insight into the fish targeted by different communities, for what purpose (subsistence or commercial) and the method of fishing. In combination with climate change projections, reconstructed catches can help craft an MPA such as the Pitcairn Island marine reserve that allows the local population to maintain coastal demersal and pelagic fishing, providing flexibility to change fishing tactics and target species whilst protecting the depletion of further offshore resources. In addition, historical catch reconstructions can provide understanding into the processes underlying an area's residuality to fishing, with a scope covering not only large-scale fisheries but also small-scale activities of great community importance. This information can be valuable for the establishment and management of marine protected areas, particularly in the face of changes to the selection and distribution of species targeted by small and large-scale fisheries.

AUTHOR CONTRIBUTIONS

AC and RW: Reconstruction and synthesis; TD and RI: Regional expertise; DZ: Supervision; MP: Biodiversity expertise.

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SUPPLEMENTARY MATERIAL

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Local Ecological Knowledge (LEK) on Fish Behavior Around Anchored FADs: the Case of Tuna Purse Seine and Ringnet Fishers from Southern Philippines

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The Fishing Industry in the Philippines plays an important role in the food and employment need of Filipino fishers. By using anchored Fish Aggregating Devices (FADs or *payao*), the Philippine tuna fisheries was transformed into a million-dollar industry. Minimal studies on exploitation rates and fish behavior around anchored FADs hampered further understanding of this fishery practice. Studies on fish behavior using Local Ecological Knowledge (LEK) are good complement where data is limited. A study using semi-structured interview (n = 46) and three focus group discussions (n = 39 participants) to record fishers' knowledge and observations on the behavior of different fish species around anchored FADs was conducted. This particularly focused on attraction, retention, and departure behavior of fishes in identified FAD sites. Based on the fishers' knowledge, tuna schools are attracted to anchored FADs at 10 km distance. In anchored FADs, tuna form schools segregated by species and size. There was no relationship between the attraction distance and the reported school size and the various waiting times for fish to aggregate below the FADs. There was no variation between the species present at day or night time although fishers have reported a distinction of species found near the surface (0–10 m) and those found at other depths (11–20 m). Juvenile yellowfin tuna (*Thunnus albacares*), skipjack (*Katsuwonus pelamis*), and frigate and bullet tunas (*Auxis* spp.) are found to stay at 25–50 m from the FAD at a depth of >20 m. Adult oceanic tunas reside in deeper waters (75 m). The fish visual census produced similar results with the semi-structured interviews and FGDs but did not observe oceanic tunas at depths of 15–20 m in the anchored FADs examined.

Keywords: FADs, fish aggregating devices, LEK, *payao*, Philippines, tuna

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INTRODUCTION

Fishers are highly dependent on marine resources in terms of food and income, which led to resource over-exploitation and decline (Bell et al., 2009; Nañola et al., 2011). Some fisheries, such as tuna, have been fished down to its threshold sustainable yields, bordering toward non-sustainability (Juan-Jordá et al., 2011). Increased demand for food due to burgeoning population and the improvement of fishing efficiency has caused marine species population declines because of the advent of technological advancement in fisheries such as real-time weather monitoring, three dimensional sonars and chlorophyll *a* productivity patterns in many fishing grounds (Pauly et al., 2002; Anticamara et al., 2011; McCauley et al., 2015). Moreover, the increasing knowledge on fish behavior has aided in the increased fishing efficiency of fishers, even further increasing the exploitation rates in the fisheries (Anticamara et al., 2011). For example, the knowledge that fish tends to be attracted to floating structures in the ocean led to the development and utilization of fish aggregating devices (FADs) (Freon and Dagorn, 2000; Dempster and Taquet, 2004). The effectiveness of FADs in increasing fish catch instigated its extensive use for both artisanal and industrial fishing (Fonteneau et al., 2000; Freon and Dagorn, 2000). According to Fonteneau et al. (2000), the proliferation of FADs globally introduced uncertainties to marine fishery. For instance, the application of FADs to artisanal fishery have led to difficulties in assessing the effects of this fishing method due to a high number of artisanal fishers, making assessment logistically challenging (Teh and Sumaila, 2013). Until now, the use of anchored FADs in the commercial tuna fisheries in the Philippines have not been investigated in terms of perceptions and local ecological knowledge (LEK) of purse seine and ringnet fishers on the behavior of tuna and other pelagic fish species around anchored FADs. Fish schools often aggregate around anchored FADs and other floating objects possibly utilizing these objects as meeting points to form even larger schools (Soria et al., 2009). There are many factors that influence the schooling behavior of fishes which includes increasing its survival through predator avoidance and increasing foraging efficiency, among others (Hoare et al., 2000). The schooling behavior of fish also plays an important role on the time spent by fishes under the FADs, the mechanisms of fish aggregations under floating objects and other causes for fish departure. An understanding of the schooling behavior of tunas especially how they can replenish the harvested biomass under the FADs will be useful in predicting the catch of fishers per FAD. This study was carried out in the context of providing an overview on the tuna exploitation and fishing patterns of purse seine and ringnet fishers around anchored FADs while particularly focusing on tuna behavior.

The Philippine Tuna Fisheries

Tuna fishery in the Philippines started after World War II. From 1947 to 1950, the fisheries program was launched, in conjunction with a series of studies on oceanographic and fishing investigations in Philippine waters (Aprieto, 2011). In 1974, massive exploitation of tuna fishery for commercial purposes started, capturing skipjack (*Katsuwonus pelamis*), yellowfin (*Thunnus albacares*), bigeye (*Thunnus obesus*), and roundscads (*Decapterus* spp.) as well as other small pelagics (*Auxis* spp., *Selar crumenophthalmus, Elagatis bipinnulata, Megalaspis cordyla, Coryphaena hippurus*) (Macusi et al., 2015). The purse seine and ringnet fisheries pioneered the use of FADs to capture pelagic species and have since then been deployed in various coastal areas of the Philippines (Dickson and Natividad, 2000). The increase in FAD use has led to an increase in fisheries production (Macusi et al., 2015). In the 1980s, fishing operations were preferred to be close to the shore which ensured lower fuel costs and fresh catch (Libre et al., 2015). However, this changed in the 1990s as the distance between FAD deployment areas and the homeport increased from 100 to 500 km offshore (Macusi et al., 2015). This was due to the fact that better catches were reported in FADs located farther away from the shore (Kakuma, 2000).

As the tuna fisheries saw its growth, more fishers and ancillary industries relocated to General Santos City, in southern Philippines. Investments in private shipyards, docking stations, net, and rope factories and steel fabrications, pre-harvest and post-harvest facilities, cold storage plants, ice plants ,and canning factories soon followed—making General Santos City the “tuna export capital of the country” (Macusi et al., 2017). At present, there are six tuna processing and canning plants in General Santos City and two processing plants in Zamboanga City. These processing plants have an annual capacity of 124,000 MT of tuna with an average total annual export value of 21.6 billion pesos in the last 5 years (2010–2014) (Barut and Garvilles, 2015).

According to the Philippine Fisheries Code of 1998, a fisher in the Philippines can be classified as a commercial fisher if he owns a motorized boat with a capacity of 3.1 GT and above and fishes offshore starting at 15 km. Anchored FADs are not cited as a requirement to be a commercial fisher in the Philippines but most of the commercial fishers utilize FADs (*payao*) to significantly increase their catch (Dickson and Natividad, 2000). The use of anchored FADs in the Philippines had been widely adapted by both artisanal and commercial fishers (Dickson and Natividad, 2000; Aprieto, 2011). There are two kinds of FADs—anchored and drifting. Anchored FADs are distinguished from drifting FADs by the presence of a mooring system that anchors their floaters made of bamboo rafts, styrofoam, or steel drums to the sea bottom. A near-shore FAD to be deployed at 10–15 km would normally cost Php 30,000.00 (U$500) per unit. FADs that are anchored at depths of 2500–5000 m in Mati (Philippine Sea), Celebes and Sulu seas, however, would cost Php 120,000.00 (U$2500) per unit. FAD deployments are adjusted according to the availability of space in the fishing grounds and productivity of the area in terms of catch (Libre et al., 2015; Macusi et al., 2015).

FADs play a significant role for purse seine and ringnet fishing. A typical purse seine and ringnet fishing fleet in the Philippines is comprised of a catcher vessel, two carrier boats, and three lightboats. The master fisher mans the purse seine while aboard the catcher vessel. He oversees and manages the daily fishing operations (Dickson and Natividad, 2000). Since anchored FADs play a significant role in the fleet's fishing activities (Aprieto, 2011), the small multirole vessels (lightboats) are used together with the catcher vessel to guard the FADs and monitor the biomass of fish beneath the FADs (Macusi et al., 2015). Once a sufficient biomass of fish has settled or aggregated in the FADs, carrier vessels are sent to the site. To attract more fishes on the site, lighting of the FADs during the evening is done while nets are set at dawn. Carrier vessels with catcher vessels operating in the High Seas usually unload fish catch once a month in homeport while other carrier vessels that operate in Philippine waters may go back twice a month to gather and bring in the catch.

Local Ecological Knowledge

In the past, LEK was often dismissed as anecdotal and of lower scientific value (Johannes and Neis, 2007). LEK, however, has played an important role in conservation studies and policies. For example, Rajamani (2013) and Rajamani and Marsh (2010) utilized LEK to identify gaps in dugong (*Dugong dugon*) conservation in areas of the Sulu Sea where data are limited. Recent developments in the fisheries management recognize the significance of LEK, especially in cases where minimal empirical data are available (Silvano and Valbo-Jørgensen, 2008). Fishers spend substantial amount of time fishing at sea, thus accumulating important information on fish diversity, reproduction, ecology, and behavior through their experiences (Baird and Flaherty, 2005; Johannes and Neis, 2007; Lavides et al., 2010). LEK has been proven to be a good complement to empirical data and has proven its significance in many cases. According to Johannes et al. (2000) when LEK was ignored, underestimation of biological samples or populations would usually transpire.

Investigations on fish behavior were carried out with the aim of understanding fundamental behavior patterns (Pitcher, 1993; Cooke et al., 2004). One of the reasons why researchers study fish behavior is to understand its effect on physiological functions (Cooke et al., 2004). Fréon and Misund (1999) stated that there are very few studies on fish behavior around anchored FADs and therefore there is lack of information on this field. Gathering fishers' LEK is a good methodology to help bridge this information gap. In this case, LEK of Filipino purse seine and ringnet fishers, who spend so much time at sea acquiring detailed knowledge of their prey and of their fishing grounds necessary to be given significance. Among the ranks of FAD-based fishers, the master fishers, boat captains, master netters, and divers are the ones who are the most knowledgeable on fishing operations. These fishers are experts who can provide reliable information on fish behavior because of their constant exposure to the fishing areas during their daily fishing operations. There are four very important individuals in this area. First is the *piado* (master fisher) who oversees the fishing fleet in the fishing ground. He has both the navigational and leadership skills to lead in the boat. He crafts and executes fishing expeditions and he decides when and where to deploy the FADs. He is familiar and knowledgeable of the movement patterns of fish, current directions, and waves. He is also accustomed to the flow of the weather in the area and its impacts on the fishing grounds. Second is the *kapitan* (the boat captain) who possesses navigational skills in using compass, maps, GPS, and oceanographic knowledge. *The kapitan* is also exposed to daily fishing operations. Third is the *maestro bosero* (master diver) who gets the estimates of the biomass of fish gathered below an FAD during monitoring or before an FAD can be lighted or set. Finally, there is *maestro pokotero* (master netter) that oversees the deployment of nets during fishing operations and is in charge of keeping collection of the nets clean and organized.

Data from other sources show that the above-mentioned fishers understand the three-dimensional aspect of fish movement, schooling, and aggregation behavior around anchored FADs (Moreno et al., 2007b,a). Because of their sufficient understanding of fish behavior such as the patterns of movement as well as abundance of tuna in their specified fishing grounds, they can decide where, when and how to deploy their fishing gears and accessories which aid them in capturing fish more effectively (Moreno et al., 2007b). The deployment of a FAD is based on well-calculated decision by these fishers and not by random choice. Such decision is influenced by their anticipated risks, projected abundance of catch and foreseen operational factors or constraints (Libre et al., 2015; Macusi et al., 2015). The daily experience of fishers become a very strong information that can be very useful to field researchers as it can provide detailed knowledge on the studies of fish behavior (Johannes et al., 2000; van Densen, 2001).

Gathering data on fish behaviors from fishers is a critical and relevant move for researchers who are focused on the fishing industry. Integration of behavioral studies in conservation biology has seen positive results (Sutherland, 1998). Caro (2007) recognizes the contribution of descriptive behavioral information in addressing specific conservation challenges. With the dwindling fisheries resources (Anticamara and Go, 2016), understanding fish behavior could aid in the conservation and management of these resources.

The objectives of this study are the following: (1) to catalog fishers' knowledge and perceptions on tuna and other pelagic fish behavior around anchored FADs; (2) to identify fish species characteristics and distribution; and (3) to test whether the reported school size, large or multiple schools have any association with attraction distance, fish aggregation, length of stay of tunas below the FADs.

MATERIALS AND METHODS

Conduct of Interview

All interviews were carried out in accordance with the Wageningen Code of Conduct for Scientific Practice, approved by the Executive Board of Wageningen University and Research on September 15, 2008. All interviewee information was de-identified in the analysis. Letters of consent for interviews were sent to the local offices of the Bureau of Fisheries and Aquatic and Resources (BFAR), Philippine Fisheries Development Authority (PFDA), and the Philippines Ports Authority (PPA) before the survey was conducted. Upon approval of these agencies, interviews were then conducted in the landing sites. The interview was conducted between August 27 to October 25, 2013 in General Santos Fish Port Complex (GSFPC) and in Mati Port in Davao Oriental (**Figure 1**). The respondents in the two locations were both purse seine and ringnet fishers of various fishing companies based in General Santos City. The interviews were conducted with the fishers at the Port of Mati, at a favorable time when fishers were docked on port as a typhoon was forecasted to be passing their fishing sites. The time of the interview was most appropriate as the fishers are free of their regular duties. Respondents were fishers who were identified to possess detailed information on catch trends, schooling behavior, and movement patterns of fish around anchored FADs. A total of five master fishers, seven master divers, seven master netters, and 27 carrier boat captains from 30 purse seine boats and 16

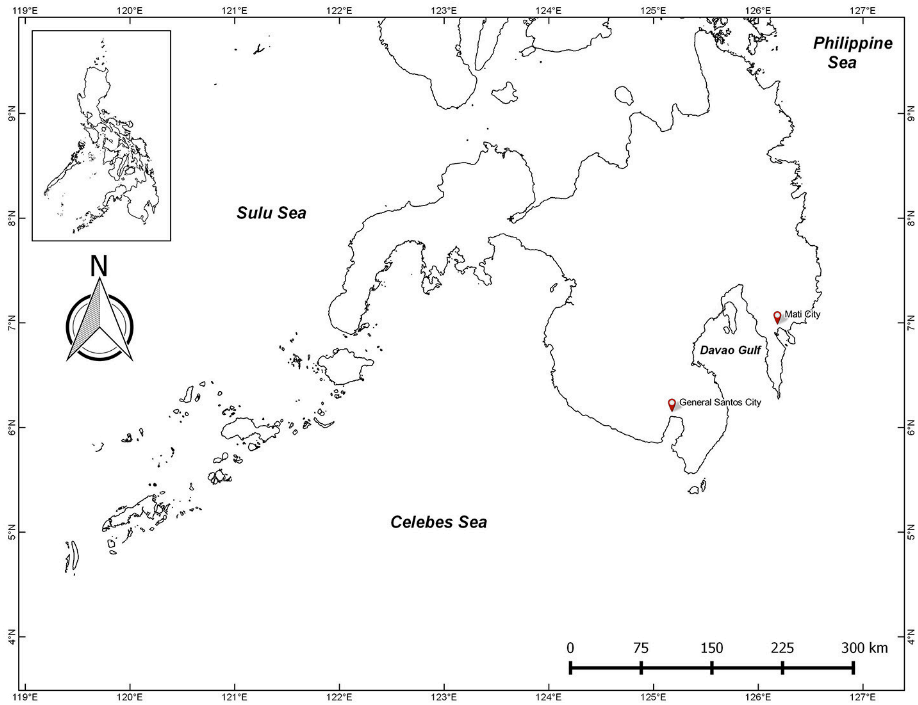

FIGURE 1 | Map of the study sites and the fishing grounds adjacent to them.

ringnet boats were interviewed individually ($n = 46$). Among the respondents, the master fishers who direct fishing operations and FAD deployment were known to have over two decades of working experience at sea.

As the only difference between a purse seine and ringnet boat, is the mechanical and manual hauling of the net during a fishing operation, the respondents are considered to be of the same set. This is particularly in terms of knowledge and exposure to FAD fishing and fish behavior in their fishing ground. Respondents of the study were all purse seine and ringnet fishers from fishing companies based in General Santos City, Philippines. The interviews lasted from 15 to 45 min and interviews were ceased after getting similar answers from the interviewees that corroborated or triangulated interview results.

Interview Design and Strategy

The interview dealt primarily with the respondent's perceptions of the behavior of fishes associated with anchored FADs, specifically on the attraction, retention, and departure behaviors. We also added questions on species distribution and community characteristics below the FAD. The interviews were done in the local *Cebuano* dialect. Questions on the general locations of FADs were asked from respondents but specific locations were withheld to keep this important information from competing fishing companies. Although interviews were done using a semi-structured format, respondents were allowed to answer freely.

The information that fishers provided during the individual interviews was verified through three focused group discussions (FGD) particularly on fish species distribution during day time and night time in the anchored FADs. The three FGDs were conducted on August 27, 2013 ($n = 20$), September 30, 2014 ($n = 11$), and October 1, 2014 ($n = 7$), and with total attendance of $n = 39$ (master fishers, boat captains, and crews). During the FGDs, fishers were shown a drawing of an FAD with fish found at various depths. They were then asked what species were found near the FAD (0–2 m) and at various depths of 0–10, 11–20, 21–50, and >50 m. The question was also repeated for fish species that are far from the FAD (25–50 m) and at various depths of 0–10, 11–20, 21–50, and >50 m.

Data Analysis

The information gathered from the fishers was quantified as percentages of total responses per question. Similar answers were grouped together under themes and these were shown through tables and figures. To examine similarities or differences with scientific research-based information on tuna behavior; answers provided by fishers were compared with the available scientific literature on tuna behavior. Secondary data on fish species characteristics related to anchored FADs also checked. Data was further analyzed using one-way ANOVA after checking normality of distribution and homogeneity of variance using Shapiro-Wilk's test and Levene's test. If the data was not normally distributed, a one-way ANOVA was still used as ANOVAS are robust to slight deviations from normality (Underwood, 1997; Quinn and Keough, 2002). We tested the association of reported school size, whether single or multiple, to attraction distance, normal wait-time for fish, wait-time for the first appearance of tuna, and wait-time for fish after a fishing event (dependent variables). The association of various tuna species to attraction distance and the various wait times were also performed using one-way ANOVA. In addition, a paired sample *t*-test was used to compare the presence and abundance of species during day time and during night time at depths of 0–10 and 11 to 20 m from the semi-structured interviews. All statistical tests were performed at significance level of $P < 0.05$. All statistical analyses were performed using IBM SPSS Statistics for Windows, Version 23 (Armonk, NY: IBM Corp).

Verification and Validation

Information was also gathered using dive survey of FADs to ascertain the species distribution as derived from the semi-structured interview and the FGDs. Although the location of the dive site was in Davao Gulf, the authors assumed that fish species found in the area could be similar to those mentioned by fishers in the interview whose fishing grounds are located in Sulu/Celebes Sea and the Philippine Sea—a site much farther from Davao Gulf. Fish names, comparing local names, and scientific names were confirmed using various local literature (Herre and Umali, 1948; Ganaden and Lavapie-Gonzales, 1999), verification of names from the local market, and the use of fish base published by Froese and Pauly (2017). A diver assessment survey was performed by three professional licensed divers equipped with scuba gears at depths of 0–20 m in ten randomly selected anchored FADs in Davao Gulf. The dives were performed on March 28 to 31, 2016 and lasted from 15 to 44 min on average. The divers went down together to reduce disturbance of the fishes. The visual census was done only in clear waters with a horizontal visibility of 10–20 m. All throughout the 10 dives, one diver performed the fish species identification assessment. Another diver used the video to record and document the fish species in the site. The third one was in charge of the safety of the group. The divers would enter the water scanning the various depths of 5, 10, 15, and 20 m of the FADs. All species found at these depths were recorded and counted, including fish species that are hiding inside the palm fronds. The time and GPS locations of the dives were recorded and the fish species identified during the dive and their behavioral characteristics were observed and summarized in a table.

RESULTS

Interview of Fishers

The mean age of respondents was 42 (±10 s.d.), with 16 years of fishing experience at sea (±11 s.d.) and have a total cumulative year of experience of 653 years. The mean boat length of respondents was 88 feet (±30 s.d.) and their boat have a mean weight of 83 tons (±60 s.d.) with a mean boat power of 342 HP (±146 s.d.) (see **Figure 2** for typical purse seine boats used in the Philippines). The respondents gave estimates of the deployed FADs at an average of 100 FADs (+100s.d.) per company in their respective fishing grounds. There is cumulative total of 4,600 FADs of these various FADs deployed by the different companies as seen in **Figure 3** for offshore FADs. The respondents have also mentioned an average of 40 (±17 s.d.) FADs per catcher vessel or motherboat. Majority of the respondents have also stated that they visited more than 30 FADs per motherboat, and rotated in going to the different FADs a month's time. There were times when FADs could be lost due to vandalism or could get entangled on the lines of other fishers. They can also be removed because of strong currents or wave action that causes its destruction.

FIGURE 2 | Purse seine boats docked side by side at the General Santos City Fish Port Complex preparing for deployment to the High Seas.

Majority of the respondents mentioned five main motivations in selecting their present fishing grounds: fish abundance and bigger fish size (63%), fish abundance only (24%), available area to fish (7%), fish abundance and available area (4%), and bigger fish size (2%). In addition, the respondents described their fishing grounds as either characterized by calm current (30%), or affected by moderate to intense waves (70%). Areas that have strong wave action are described to have rough waves and strong currents. These fishing areas are mostly exposed to typhoons during the rainy season.

The respondents also regularly mentioned their target species: skipjack tuna (*Katsuwonus pelamis*) (27%), roundscad (*Decapterus* spp.) (24%), juvenile yellowfin tuna (*Thunnus albacares*) (22%), bigeye scad (*Selar crumenophthalmus*) (9%), frigate/bullet tuna (*Auxis* spp.) (6%), rainbow runner (*Elagatis bipinnulata*) (5%), triggerfish (*Sufflamen fraenatum*) (2%), mackerel (*Rastrelliger* spp.) (2%), golden trevally (*Gnathanodon speciosus*) (2%) (**Figure 4A**). However, the respondents mentioned that rainbow runner (24%), golden trevally (24%), roundscad (18%), and triggerfish (9%) are the first species to aggregate or gather in the anchored FADs (**Figure 4B**). A few of the respondents also remarked that skipjack tuna (6%), bigeye scad (5%), dolphin fish (*Coryphaena hippurus*) (4%), filefish (*Aluterus monoceros*) (3%), frigate/bullet tuna (*Auxis* spp.) (3%), juvenile yellowfin tuna (3%) and torpedo scad (*Megalaspis cordyla*) (1%) are also observed to arrive first in the anchored FADs. These species were later followed by adult (big) tuna species such as bigeye tuna (*T. obesus*) (16%), skipjack tuna (*K. pelamis*) (26%), and yellowfin tuna (*T. albacares*) (30%) (**Figure 5**).

Attraction, Retention and Departure Behavior of Fish in Anchored FADs

Detailed answers from the respondents concerning the attraction behavior of fish to anchored FADs are summarized in **Table 1**. The respondents noted that tunas were attracted to FADs from 1 to 10 km. This knowledge was based on the perception that tunas transfer from one FAD to another FAD, which was estimated to be 10 km apart from each other, on average. According to the respondents, these tuna movements in between FADs are often noticed because of the flocking of seabirds and fishes leaping out of the water.

Detailed answers related to fish attraction were shown in **Table 1**. On average, the respondents have mentioned that fishers must wait for 11 days after the first deployment of the FAD before checking the biomass contents of their FADs. This waiting time could range from 2 to 30 days. After a fishing event on the FAD, fishers then have to wait for about 10 days on average before the FAD can welcome new settlers or have a new aggregated biomass. The respondents have also proposed that these smaller fishes (e.g., triggerfish and golden trevally) serve as prey in attracting other fishes.

FIGURE 3 | Materials ready for deployment offshore including steel FADs. Note the rocket like steel drum. The nose always points to the direction of the current; the fishers are standing on concrete anchors made of mixed gravel, stones, rocks, and cement.

Furthermore, the waiting time for the first schools of skipjack, yellowfin and bigeye tunas may take 22 days. Sometimes these fish species appeared as early as 5 days or as late as 2 months. Majority of the respondents have suggested that a school of tuna under a FAD is due to aggregation of multiple smaller schools of tuna (89%). Other fish species such as scads and mackerels of similar sizes also form their own schools (96%). Divers of the fishing fleets also observed that various fish species segregate based on sizes, with different size groups of the same species occupying different layers of the water.

Tunas were also observed to exhibit vertical movement behavior during early morning hours (4–8 a.m) (57%) and move away from the FAD at 8 a.m to 4 p.m during day-time (26%). Some respondents observed both behaviors (17%).

Majority of the respondents stated that the main reason for the aggregation of fish under FADs is due to the presence of food and availability of shelter (**Table 2**). The respondents claim that fish feed on algae, shells and barnacles on the ropes and the palm fronds. Other fishes prey on anchovies or smaller-sized schools of frigate/bullet or skipjack tuna or early juveniles of other fish species. The presence of krill-like organisms had also been noticed to attract other fish species toward the FAD. Meanwhile, other respondents stated that social interaction is also a reason for fish aggregation under FADs. Social interaction here is defined as the attraction of fish to other fish because of similar sizes or being conspecifics.

According to interviewed respondents, the length of stay of tunas around anchored FADs takes from less than a week to more than a month, with majority of the interviewees agreeing that tuna stays for 2 weeks (48%) around the FADs (**Table 2**).

As shown in **Table 2**, fish schools of small pelagics such as roundscads (*Decapterus* spp.), bigeye scads (*S. crumenophthalmus*), and other small tunas are mainly disturbed by a passing school of anchovies, visits of marine

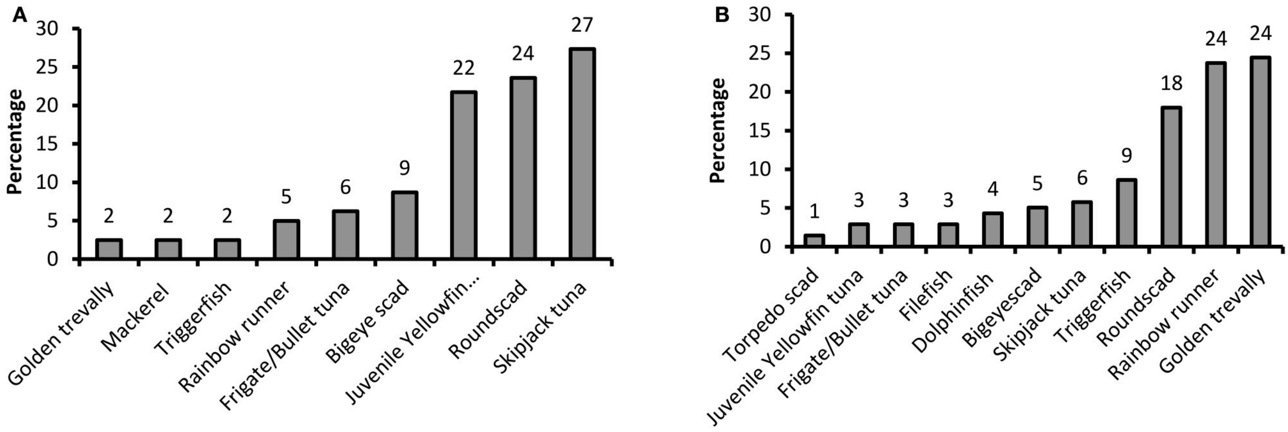

FIGURE 4 | Target fish species mentioned by fishers during interview **(A)** and proportion of occurrence of various fish species as pioneers in anchored FADs according to respondents **(B)**. Numbers are percent of the total interviewees that mentioned given information ($n = 46$).

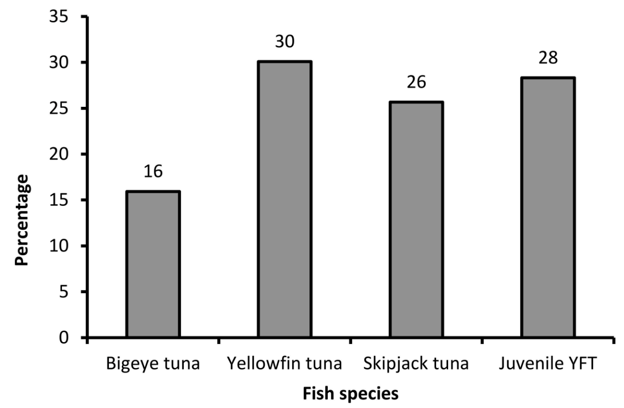

FIGURE 5 | Proportion of occurrence of various tuna species around anchored FADs according to respondents. Numbers are percent of the total interviewees that mentioned given information ($n = 46$).

TABLE 1 | Fishers' responses related to attraction behavior of fish to anchored FADs.

Attraction behavior of fish to anchored FADs		
Attraction distance to FADs	**Meters**	
Average	1000	
Min	20	
Max	9000	
Wait time for fish to aggregate below FADs	Days	
Average	11	
Min	2	
Max	28	
Wait time for fish to aggregate after a fishing event	Days	
Average	9	
Min	3	
Max	21	
Wait time for other fish species to aggregate below FADs	Days	
Average	22	
Min	5	
Max	60	
What are the source of fish school?	Response	%
Single large school	5	11
Multiple school of fish	41	89
How are fish schools organized?	Response	%
Size	2	4
Species and size	44	96
Some observed behavior of tuna fish	Response	%
Fish moves up and aggregate near the FAD (early morning)	26	57
Fish moves away from the FAD (day time)	12	26
Fish moves up and aggregate near the FAD and fish moves away from the FAD	8	17

mammals, and change of current strength and direction of the water either due to a typhoon, undersea earthquake or strong winds (63%). Another reason for this disturbance according to the fishers is the change in sea surface temperature. The presence of cetaceans is known to distract the fish schools in the anchored FAD causing them to leave temporarily. Sea current was also mentioned to affect the fish schools just as a school of anchovies and change in sea surface temperature do. This usually happens when the current direction changes unpredictably due to the meeting of two currents or because of a sudden change of wind direction. Typhoons are also known to change sea current direction because of strong winds, as well as undersea earth quakes that jolt the fishes.

Meantime, there was not a significant result on the ANOVA test on the following: reported school size, whether large or small and the attraction distance to the FAD with the various waiting times for fish to arrive or appear at the FAD (**Table 3**). Consequently, other factors might explain better the association of various school sizes to FADs and not only the attraction distance or school size of tunas, perhaps factors like productivity and sound of the anchored ropes or sea-water temperature.

Fish Species and Fish Behavior through FGD and Diver Assessment

There was little variation of species found at depths of 0–10 m ($t = -0.149$, $df = 6$, $P = 0.887$), and 11–20 m ($t = -0.044$, $df = 9$, $P = 0.966$) in the anchored FAD either during day time or night time. Results of pooled data comparing species at day time vs. night time also showed no difference ($t = -0.117$, $df = 16$, $P = 0.909$). Triggerfish and filefish that are abundant at the surface and are known to inhabit the suspended palm fronds, are also found at lower depths such as at 11 to 20 m (**Table 4**). In terms of fish schools that are abundant at surface depths (0–10 m) as well as at depths of 11–20 m, which was mentioned to occur during day and night time were golden trevally, roundscad, and rainbow runner. Tunas such as skipjack, juvenile yellowfin and frigate tunas were also discussed to appear frequently at 11–20 m and even deeper. Relevant observations by other fishers based on the FGD validate the statements that aggregations of fish under FADs are segregated based on species, sizes, and water depth. For instance, rainbow runner, roundscad, mackerel scad, and bigeye scad are observed to appear near the surface as well as at depths of 20 m. Fish species that occur near the surface are smaller in sizes. Both triggerfishes and filefishes are known to be associated with the floater or the suspended palm fronds and usually stay near the surface. Most of the bigger fish schools of skipjack, juvenile yellowfin tuna, and frigate tuna occur far from the FAD (25–50 m) and swim around. They also stay deeper at 21–50 m. Adult tunas are known to reside in deeper areas from >50 m.

Results from the fish visual census (**Table 5**) show that there are nine species recorded from the 10 FADs visited in Davao Gulf. Most of these fish species observed are like those recorded in

TABLE 2 | Fishers' responses related to retention and departure behavior of fish to anchored FADs.

Retention and departure behavior of tunas		
Reasons why tuna aggregate around FADs	Response	%
Tunas find food around FADs such as algae, shells, barnacles	3	7
Tunas find shelter or protection from other predators	8	17
Combination of food and shelter	26	57
Combination of food and social interaction	3	7
Combination of food, shelter and social interaction	6	7
How long do tunas stay around FADs	Response	%
< 1 week	1	2
1 week	5	11
2 weeks	22	48
3 weeks	1	2
1 month	13	28
> 1 month	4	9
Reasons for tuna to leave a FAD	Response	%
Distraction from passing of anchovies and from visits of marine mammals	10	22
Sudden change of currents due to winds, typhoons and seaquakes	1	2
Distraction from passing of anchovies and from visits of marine mammals and change of sea current	29	63
Distraction from passing of anchovies and from visits of marine mammals and change of sea temperature	1	2
Combination of all of the above reasons	5	11

TABLE 3 | Variables tested for its association with the reported fish school size and various tuna species using one-way ANOVA.

		School size			Tuna species		
Variables	**Source**	***df***	***MS***	***P***	***df***	***MS***	***P***
Attraction distance	Between Groups	1	828017	0.572	7	2111912	0.582
	Within Groups	44	2558600		38	2595343	
	Error	45			45		
Wait time (fish)	Between Groups	1	22	0.431	7	36	0.410
	Within Groups	44	34		38	34	
	Error	45			45		
Wait time (tuna)	Between Groups	1	31	0.696	7	126	0.743
	Within Groups	40	197		34	207	
	Error	41			41		
Wait time (fishing event)	Between Groups	1	19	0.321	7	11	0.792
	Within Groups	44	19		38	20	
	Error	45			45		

the results of the FGD interview. The main difference, however was the absence of skipjack, juvenile yellowfin tuna, frigate/bullet tuna in all the 10 dives although visibility was more than 10–20 m in all the dive sites. About 88% of the fish species recorded can be found at depths of 5, 10, and 15 m and the other remaining species 8 and 4% at depths of 20 m, and >20 m. The juveniles of sergeant fish were observed to associate near the floater of the FAD while the blue sea chub was observed to move at various depths of 10, 15, and 20 m. The schools of trevally, bigeye scad, and roundscad were observed to swim around the anchored FAD.

DISCUSSION

Most of the respondents have mentioned that demersals and small pelagics (trigger fishes, filefishes, dolphin fishes, sergeant fishes, blue sea chubs, golden trevallies, and rainbow runners), are followed by scads and mackerels which then will settle around the anchored FAD. These fishes are then followed by skipjack, frigate, bullet, and juvenile yellowfin tunas a few days or weeks after the non-tuna species have settled in the FAD (Castro et al., 2002). Tunas are known to prey on a wide range of species which

TABLE 4 | Depth distribution of fish species on anchored FADs during day time and night time based on semi-structured interviews ($n = 46$) and based on three FGDs ($n = 39$).

Semi-structured interview				Focus group discussion (FGD)			
Depth (m)	**Species**	**Day time (%)**	**Night time (%)**	**Depth (m)**	**Day time**	**Night time**	**Observations**
0–10	Golden trevally	33	25	0–10	x	x	These are the first species that colonize the FAD
	Roundscad	10	18			x	Fish are segregated by species, schools and size
	Rainbow runner	28	27		x	x	
	Common Dolphinfish	8	8			x	
	Bigeye scad	3	6		x		
	Triggerfish	5	8		x		
	Skipjack tuna	5	2				Fish usually aggregates or moves closer to the anchored FADs during the night and especially during night lighting of the anchored FADs
	Filefish		4				
	Juvenile Yellowfin tuna	8					
	Frigate/Bullet tuna		2				
11–20	Golden trevally	18	13	11 to 20			
	Roundscad	20	12		x	x	
	Rainbow runner	20	10		x	x	
	Skipjack tuna	10	22			x	
	Common Dolphinfish	6	7		x		
	Frigate/Bullet tuna	2	8			x	
	Mackerel scad				x	x	
	Triggerfish	8	4				These are usually found 25 to 50 meters from the anchored FADs and moving around during daytime
	Tripodfish	2	2				
	Bigeye scad	6	6				
	Juvenile Yellowfin tuna	8	17				
21–50	Frigate/Bullet tuna				x	x	These are species found 25 to 50 meters from the anchored FADs and moving around during daytime
	Skipjack tuna				x	x	
	Juvenile yellowfin tuna				x	x	
>50	Yellowfin, Bigeye tunas				x	x	

TABLE 5 | Presence of various fish species at different depths found in 10 anchored FADs examined in Davao Gulf, Philippines.

Species		Depths (m)				
English name	**Scientific name**	**0–5 (%)**	**10 (%)**	**15 (%)**	**20 (%)**	**>20 (%)**
Blenny	*Meiacanthus* spp.	(1) 50	(1) 50			
Blue sea chub	*Kyphosus cinerascens*	(7) 44	(8) 50	(1) 6		
Indo-Pacific sergeant	*Abudefduf vaigiensis*	(12) 86	(2) 14			
Trevally	*Carangoides ferdau*	(4) 31	(7) 54	(1) 8	(1) 8	
Filefish	*Aluterus monoceros*	(2) 18	(9) 82			
Rainbow runner	*Elagatis bipinnulata*	(2) 50	(2) 50			
Bigeye scad	*Selar crumenophthalmus*	(2) 28		(1) 14	(3) 43	(1) 14
Yellowstripe scad	*Selaroides leptolepis*			(1) 100		
Roundscad	*Decapterus spp*		(2) 40	(1) 20	(1) 20	(1) 20

Numbers are record of frequency at different depths.

includes shrimps, squids, stomatopods, other non-tuna species (e.g., lantern fish, scads, mackerels) and other smaller tunas whether juvenile yellowfin, bigeye, skipjack, and frigate and bullet tunas (Barut, 1988; Jaquemet et al., 2011). In relation to this, the association of juvenile tunas to an anchored FAD seems to indicate that they feed primarily on prey species found under the FAD because of their rapid growth, 3.8 mm per day (Mitsunaga et al., 2012). The opportunistic feeding behavior of tunas and its predisposition to social interaction (Robert et al., 2013) may have implications on its movement from one anchored FAD to another (Ménard et al., 2006).

The attraction distance of 10 km which fishers mentioned about tunas is reasonable given that the usual maximum inter-FAD distances between anchored FADs in the Philippines, is of the same distance (Libre et al., 2015; Macusi et al., 2015). In addition, tunas are attracted to floating objects and they associate with FADs for some time. The 10 km distance between FADs enable the small multirole vessels of purse seines and ringnets to navigate and check the fish biomass aggregation underneath the FADs. This attraction distance was also similar to the results of the interview of boat captains and master fishers who use drifting FADs (Moreno et al., 2007b).

Based on previous studies on the results of sonic tracking of juvenile yellowfin tunas, it was found out that tagged individual fish and fish schools associate in a network of FADs with 3 km distance from each FAD (Babaran et al., 2009a,b; Mitsunaga et al., 2012). These tagged juvenile yellowfin tuna forage in a network of anchored FADs as they start to migrate outside the locations of these fishing grounds. Moreover, a follow-up study by the same authors also showed that a tagged juvenile yellowfin tuna was caught 12 km away from the original tagging site which means that juvenile yellowfin tunas can easily move from one FAD to the other (Mitsunaga et al., 2013). In contrast, investigations of adult yellowfin tunas by Ohta and Kakuma (2005) showed that the fish stayed for a maximum of 55 days around a single FAD while Dagorn et al. (2006) reported that they stayed for a maximum of 151 days on a network of FADs.

On the attraction of various fish species to floating objects like anchored FADs, the pioneer species are usually herbivorous and piscivorous such as the Indo-Pacific sergeant fish, the filefish, golden trevally, and trevallies and juvenile tunas. While various reasons are hypothesized to explain this attraction such as sheltering, feeding, meeting point, indicative of productive areas (Freon and Dagorn, 2000; Castro et al., 2002), there is no single accepted explanation for this attraction to floating objects by these fish species. Moreover, it is thought that the biomass of fish around anchored FADs would not be enough to feed the biomass of oceanic tunas swimming around anchored FADs (Olson and Boggs, 1986). Majority of the fishers have reported that the aggregation process of various fish species takes time. This means that there was a gradual build-up of biomass around anchored FADs mainly with pioneer non-tuna species that arrived first in the FAD. These fish species were then followed by the attraction of oceanic tunas to the anchored FADs. In terms of the lack of difference between the fish species present during daytime and at night time, resident fish species seem to utilize FADs as their shelter and foraging area. But for the associated fish species which were loosely attached to the floating objects such as oceanic tunas, they are capable of swimming away to another anchored FAD when distracted.

Based on the reported tuna behavior in this study, there are three conditions involved in the attraction and retention process of oceanic tunas in a FAD fishing area: (1) Number of FADs deployed in the site—the more FADs deployed by fishers, the more choices of FADs for the school of tuna to visit (Aprieto, 1981; Macusi et al., 2015); (2) Level of productivity of FADs can have influence in the area because tunas are thought to visit productive (rich food areas), keeping those FADs located in poor food areas with less fish biomass (Jaquemet et al., 2011); (3) The size of tuna schools that visit a FAD- the size or biomass of fish school that visits a FAD will differ owing to varying level of individual productivity of FADs as well as the loosely associative behavior of tunas. Because of this difference, there is no fixed amount of catch of fishers for every FAD. However, this can be forestalled by the fishers' use of human sonars or divers as well as the use of acoustic fish finders. When fishers set a quota or baseline amount of harvestable biomass of fish per FAD monitored, more or less, their harvest would be similar to that baseline number.

As mentioned earlier, several reasons can distract tunas in the FAD, which means that FAD visits by a school of tuna may last for hours or for days, the visit or association to a FAD is therefore highly variable (Ohta and Kakuma, 2005; Mitsunaga et al., 2012). Moreover, the lack of relationship between the reported school size of tunas and attraction distance, and various waiting times for their arrival in the FADs, could be a motivation to explore other factors that might better explain the aggregation of fishes in FADs. For instance, a more direct assessment might be needed such as using acoustic techniques to relate the size of schools of fish to these waiting times. The production of sounds by anchored FADs may help orient and attract tuna toward the structure (Babaran et al., 2008), since according to Tolimieri et al. (2000), sound can serve as a navigational cue for fishes.

Concerning the results of the actual dives to examine the fish composition of anchored FADs, where there were no skipjack or yellowfin tuna observed in the vicinity of the anchored FADs, the survey was done near the shore, for instance with FADs found <100 km offshore as against the FADs located 500–1,000 km offshore in Mati and in Celebes sea. This was a limitation of the study. Although, before the survey was conducted in Davao Gulf, catch data, and catches were obtained from the local fishing companies with fishing areas in Davao Gulf. It was noted, however, that the local markets in Governor Generoso (a coastal municipality situated near the mouth of the Gulf) shows that juvenile skipjack, frigate, and yellowfin tunas were part of the ringnet catches. Another limitation of this study is the lack of pilot study for the dive assessment of the fish composition of anchored FADs at different times of the day before the actual conduct of the survey. There was also a lack of a chartered vessel dedicated for this purpose to study the FADs used by fishers in their fishing grounds, which could go for more than 500 km from the shore. This study can be extended in the future through an assessment program using fish visual census coupled with acoustics to understand fish schooling and association behavior in anchored FADs. This should be done since acoustics can complement and address the limitations of FVC (fish visual census; e.g., limitations on effective distance of FVC) (Taquet et al., 2007; Moreno et al., 2016). This will examine the various behavioral characteristics of small non-tuna species, and the oceanic tunas (both the juveniles and adult ones).

The implications of this study support the growing literature on overexploitation of marine resources which leads to economic losses. According to Kompas et al. (2010), overharvesting of tuna can incur an economic loss of billions of (US) dollars. This is partly due to excess in fishing effort that places enormous pressure on global marine fisheries (Anticamara et al., 2011). Excessive fishing pressure is a result of the high food needs of a burgeoning global human population (Stobutzki et al., 2006; Béné et al., 2015). Excessive fishing pressure, however, can also be a result of the failure of fishers to capitalize on available information to optimize fisheries yield on harvesting target species and lower non-target species catch, which are often discarded and also incurs economic loss (Patrick and Benaka, 2013). The complexity of the dynamics of marine fisheries is further confounded by the lack of understanding on the role of fish behavior and how it impacts marine fish population and marine fisheries in general. For example, in a model simulation conducted by Railsback and Harvey (2011) on brown trout (*Salmo trutta*) populations, it was shown that individual adaptive behavior (e.g., activity selection) has contradicted the traditional understanding on food limitation and how it regulates populations, accentuating fish behavior as a major factor to consider in formulating conservation and management strategies (Shumway, 1999). In this study, LEK has been proven to provide additional information for further understanding of the complexities of fish association to anchored FADs and how fishes behave.

The knowledge extracted from fishers, for example, in attraction behavior of fishes to FADs can help optimize FAD deployment (e.g., minimal number of FADs while achieving maximum sustainable yield by maximizing spacing between FAD deployments) and can lower operational costs for fishing fleet that will reduce fishing effort and overharvesting. Information generated by this study will be useful in designing policy formulations and management plans, especially in the regulation of FAD deployment in the country.

CONCLUSION

Various studies have shown that the high dependence on marine resources for food and livelihood can lead to excessive fishing. This was done by exploiting the fish behavior of association with floating objects and deploying FADs to increase fish production. FADs have been abundantly deployed in both near shore and offshore areas and their deployments are un-registered and unregulated. Because of the massive deployment of FADs, coupled with illegal, unreported, and unregulated (IUU) fishing, fisheries production has been steadily declining. The target species of purse seine and ringnet fisheries around anchored FADs are large pelagic (e.g., tuna) and small pelagic fish (frigate and bullet tuna, roundscads, and mackerel) while the average time of fish aggregation in FADs vary according to species and fish sizes; larger tuna (skipjack, yellowfin, and bigeye) usually aggregate last.

Moreover, fishers tend to move fishing operations in areas with more abundant and larger fishes to increase prospective revenues. To help conserve our pelagic resources, it is necessary that stricter enforcement of fisheries laws be applied. Alternative jobs for fishers and subsidies for their families for daily survival should also be an option. They also need to be educated in order for them to be less dependent on the fishing industry.

AUTHOR CONTRIBUTIONS

EM wrote, designed and conducted the survey used in the study as well as did the analysis and writing of the manuscript; NA also helped in the conduct of the field survey of the FADs as well as in writing and editing the manuscript. Both NA and RB helped in the analysis and writing of the manuscript.

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History of the Virginia Oyster Fishery, Chesapeake Bay, USA

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Oyster populations in Virginia's waters of Chesapeake Bay were lightly exploited until the early 1800s, when industrial fishery vessels first arrived, driven south from New England due to the collapse of northeastern oyster fisheries. Early signs of overexploitation and habitat degradation were evident by the 1850s. The public fishery, where oyster fishers harvest on state-owned bottom, rapidly developed after the Civil War and peaked in the early 1880s. Declines were noted by the late 1880s and eventually prompted the creation of Virginia's shell-planting and oyster-seed (young-of-the-year, YOY) moving repletion program in the 1920s. Despite management and increasing repletion efforts, the public fishery collapsed (annual landings <10% of peak historical landings) by the early 1960s. The private leasehold fishery, in which individuals rent areas outside the public grounds to plant shells and oysters for their own private use, surpassed the public fishery by the late 1920s, which partly masked this decline due to overfishing, habitat degradation, and diseases until both public and private fisheries completely collapsed in the mid-1980s after a third disease outbreak. This disease outbreak was likely related to warming waters. Overfishing and concomitant habitat loss followed a pattern of sequential population collapses observed in wild oyster fisheries along the Coastlines of the United States and worldwide. In recent years, expanding hatchery-produced seed oysters and aquaculture significantly increased leasehold landings. The wild fishery has also increased as disease resistance is developing naturally in the wild stocks, but remains ~5% of peak landings. Improved management has assisted in this recent limited recovery, improving these efforts further by enhancing stock recovery via large no-take sanctuaries, among other actions, could assist in stock recovery.

Keywords: oyster, history, fishery, Chesapeake Bay, virginia, *Crassostrea virginica*

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BACKGROUND OF THE FISHERY AND MANAGEMENT FROM PRE-COLONIAL TO PRESENT

Early Fishing (Pre-1600)

Native Americans settled in the Chesapeake Bay region, ~9500 years BCE, during the glacial retreat when the Chesapeake Bay as we would recognize it today began to form (Hobbs, 2004). Oysters colonized the Bay ~6500 years BCE as salt water from the Atlantic Ocean, driven by glacial melting, penetrated up-bay, and up-river (Bratton et al., 2003). Reefs grew in elevation and area while expanding upriver(s) and northward as salinity suitable to their survival increased in extent (McCormick-Ray, 1998, 2005; Hargis and Haven, 1999; Smith et al., 2003; Hobbs, 2004).

Native Americans prior to European colonization were few in number relative to the human population living in the Bay watershed today. Estimates of artisanal-level annual harvests from this time period cannot be made. Where Native American settlements were near waters that contained oyster reefs, shell middens consisting of oyster, mussel, and clam shells can often be found. Some middens are sizeable, such as one along the shores of Pope's Creek, Virginia, which covers 12.1 ha (Wennersten, 1981) several meters deep, indicating hundreds to thousands of years of harvesting. At some middens, oyster shells decreased in average size over time, indicating that the Native Americans' sequential harvesting of oysters could have negative impacts on the size-frequency distributions of oysters (Kent, 1988; Jagani, 2011), as observed in middens of other mollusk species (de Boer et al., 2000), though no wide scale decline in size has been observed in the Bay (Rick et al., 2016).

European Colonization and the Early Oyster Fishery (1600s–Early 1864)

The first European settlers colonized Virginia in the early 1600s on the northern bank of the lower James River, the largest Virginia River, located near the confluence of the Bay and Atlantic Ocean (**Figure 1**). Settlers at first collected oyster by hand and/or using primitive tools from shallow, nearshore reefs for food (Tyndall, 1608), similar to Native Americans. Archeological data of colonial middens at Jamestown revealed that a mix of local oysters as well as oysters from the mouth of the James River had been collected for food, indicating local populations may have been depleted by colonists (Harding et al., 2008). The use of oyster shells for lime (CaO, used in agriculture and construction mortar) began in the mid-1600s and became more extensive (Bailey, 1938) as the colonial era in Virginia progressed. There are records of reefs in the James River providing shell for lime, with White Shoal, a reef that remains part of the public fishery today, mentioned as early as 1638; Native Americans middens were also used as a good source of shells. Using shells for lime production continued throughout the colonial period (Ford, 1891). Oyster shells, once shucked of meat, were used in Virginia for road beds, agricultural lime, chicken "grit" (a poultry feed supplement), mortar, a composite form of concrete made of lime, sand, and crushed oyster shells called "tabby," and starting in the mid-1800s, railroad ballast (Hargis and Haven, 1999). Impacts to oyster reefs by early settlers appear to have been limited and local during the seventeenth and eighteenth centuries.

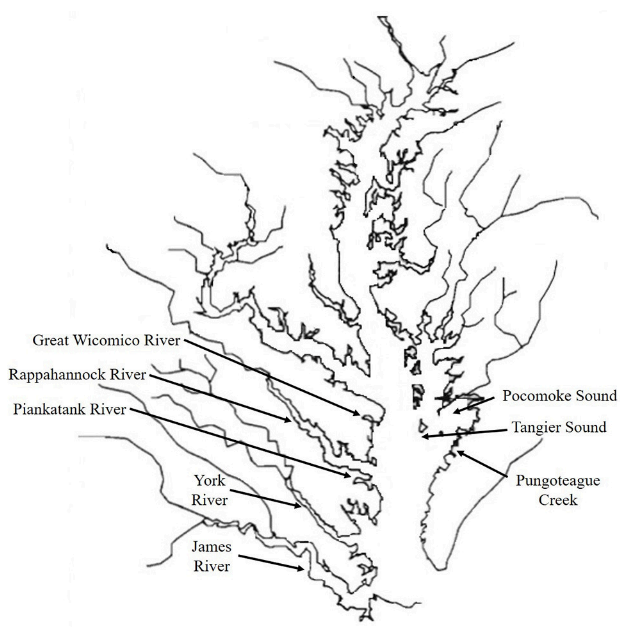

FIGURE 1 | Overview of Chesapeake Bay, key Virginia oyster fishery locations indicated.

The first large-scale commercial fishing was by New England oyster fishers that sailed south to the Chesapeake Bay and began dredging subtidal reefs for oysters in the early 1800s after depletion of their own beds (Kirby, 2004). Dredging continued for several years and the total harvest and dredge-related damage (Winslow, 1881, 1882; Lenihan and Peterson, 1998, 2004) to what had been undisturbed sub-tidal oyster reefs is unknown. Dredging was made illegal in Virginia in 1810, at which time the New England dredgers simply sailed further north into Maryland waters until they were banned there in 1820. These bans did not entirely prevent dredging, due to lack of an organized marine police at the time, as it was noted that New Englanders were occasionally seen as late as the mid-1800s poaching oysters from reefs near the mouth of the James River (Paxton, 1858). Dredging for oysters would remain illegal for decades in Virginia and only hand tongs, a simple tool consisting of two long-handled, hinged, metal-toothed rakes developed in the late 1700s, were permitted.

In the 1850s, the Virginia oyster fishery expanded rapidly (U.S Census, 1850, 1860; De Bow, 1858), concomitant with rail lines that began to link centers of commerce throughout the USA. Harvests increased (**Figure 2**) from 178,000 bushels in 1849 to 2.3 million bushels in 1859 (1 bushel = 0.049225 m^3) (Auditor of Public Accounts, 1776–1928; U.S Census, 1850, 1860). Testimony (Paxton, 1858) suggests that this increase in harvests occurred at a rapid pace: "The oyster trade may be said to have sprung into existence in the last 10 years. Ten years ago, but few persons living away from tidewater ever used oysters. Now the country has been penetrated in every direction by railways, and at this time oysters taken from our Virginia waters are probably used more extensively in the towns and villages of the far West, than they were a few years since in Virginia within fifty miles of tidewater." This increase appears primarily due to growing regional, demand, enabled by more effective means of shipping and preservation. The first large-scale commercial canning operation for oysters, which allowed for shipping oyster meat throughout the USA, began in Baltimore in 1844 (Jarvis, 1988), which would soon become the center of oyster canning in Chesapeake Bay (Maryland Bureau of Statistics and Information, 1903)[1]. By 1858, about 4 million bushels of oysters were being canned annually in Baltimore (Paxton, 1858), the majority processed being fished from Maryland waters though Virginia oysters were also canned here. Small shipments of Virginia oysters to various ports along the North East coast occurred, early records indicate ∼100,000 bushels were being shipped annually during 1846–1857 to Boston, though much

[1] https://www.google.com/search?biw=1167&bih=415&tbm=bks&q=inauthor:%22Maryland.+Bureau+of+Statistics+and+Information%22&sa=X&ved=0ahUKEwjZ38uTwsDTAhVI3mMKHUrzC34Q9AgISTAG

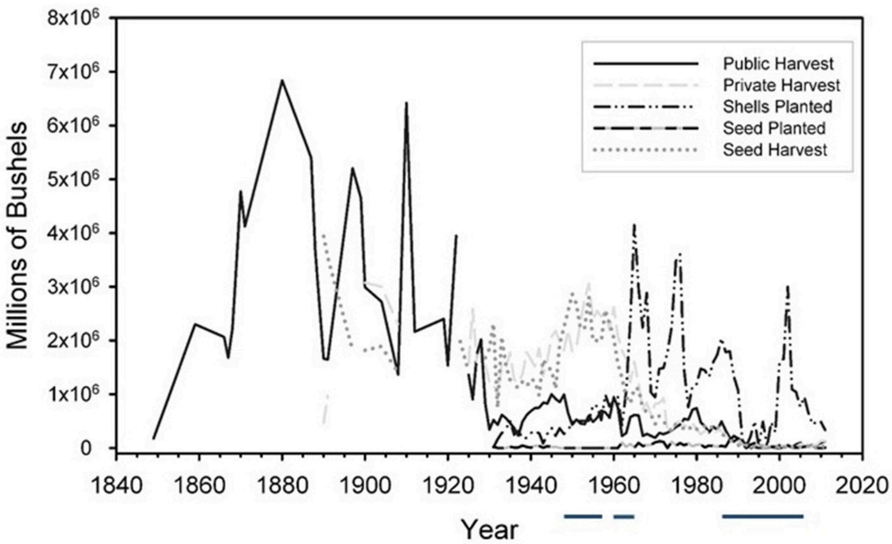

FIGURE 2 | History of the oyster fishery, showing public, private, and seed harvests with repletion activity (shell and seed plants) over time. Data for repletion 2003-14 are based on estimates from VMRC annual work plans. 1 bushel = 0.049225 m^3. Blue lines are years of disease epidemics, first line is the first Dermo epidemic peak years, second line are the peak years of the MSX epidemic, third line is the second Dermo epidemic peak years.

smaller shipments had occurred previously, beginning in 1826, to Boston and other northern cities, including New York City. Smaller and younger sub-market sized (≤76 mm), often YOY (young-of-the-year) oysters, called "seed" were also harvested and sold, primarily to Northern States, for planting and grow out to market size. Records indicate seed oysters from Virginia waters were being shipped as far North as Connecticut as early as 1830 (Goode, 1887) and even overseas (De Broca, 1865). It is unknown how large this seed fishery was, though it may have been comparable in size to the market oyster fishery by the 1850s.

With the advent of the Civil War in 1861, a naval blockade was placed in Virginia waters. Harvests in Virginia declined as local fishermen were often unable to fish during the war (1861–1865). Oyster prices tripled in cities such as Alexandria, Virginia, due to lack of supply (The Alexandria Gazette, 1963–1964). The magnitude of the decline in oyster harvests due to the Civil War remains unclear; the only reliable comparison was between the 1859 harvest of 2.3 million bushels and the first post-war harvest in 1965 at 2 million bushels (**Figure 2**). One source (Brown, 1872) indicates that the harvest during the Civil War may have increased due to harvest by northern dredgers, who, upon payment of a permit fee, were able to dredge Virginia oyster grounds while being protected by the Northern Navy. Virginian watermen could also harvest upon payment of a fee, though few did as many were at war or lacked the money to pay. These dredging activities ceased after the War.

Major Peak of the Virginia Oyster Fishery 1865–1890

In 1860 county courts were authorized to appoint inspectors of oysters to enforce oyster laws, which were first implemented in 1866. A harvesting season for oysters was established, with oyster fishing prohibited during the months of June–August and limited during May and September to no more than 25 bushels/man/day. During other months, there were no harvest limits. Various license fees and taxes were also established for oyster harvesters and related processing activities. There was a rapid expansion of the fishery from 1865 to 1871, which doubled from 2 to 4 million bushels/year (Virginia Auditor of Public Accounts, 1776–1928). The bushel tax was repealed in less than a decade, so records of harvests became intermittent until the 1926–1927 harvest season when a bushel tax on harvested oysters was reinstated Commission of Fisheries of Virginia (1907–1967).

There were two other significant changes in law during this era. One was the codification of the private leasehold system, providing legal protection to "planters" who had been active for some time on a small scale, but who had little legal recourse from pirating fishers tonging their plantings. These leaseholders rented plots that they were given rights of ownership, upon which to plant shells and seed for their own private benefit, permits were granted by oyster inspectors who worked for the State. The second was the permitting of dredges but limiting them to waters over 6.1 m deep. Dredgers worked deeper, sometimes unexplored waters, discovering, and exploiting the last pristine oyster reefs of Tangier and Pocomoke Sounds in the mid-Bay region near the Maryland border in the 1870s. A survey of oyster reefs in the Tangier and Pocomoke Sound region (Winslow, 1882), describes the appearance of such reefs as follows: "These reefs consisted of long, narrow oysters...no single oysters of any (age) class, but all grew in clusters of 3–15. The shells were clean and white, free from mud and sand. The mature oysters were covered and the interstices between them filled with younger oysters," similar to the account made of shallower, unexploited reefs: "In some banks their crowded condition may be inferred from the fact that I counted as many as 40 (live adult) Oysters in an area included by a quadrangle of wire including exactly one square foot (0.0929 m^2); 30 individuals to the square foot was a fair average on one bank examined (Ryder, 1884)." Undisturbed oyster reefs appear to have had up to 320 adult oysters/m^2 of varying sizes up to 23 cm (adults are classed as oysters $\geq$ 35 mm), perhaps larger, and growing in dense, cohesive aggregations that induced an elongate growth form. This elongated architecture of oysters in dense aggregations was a response to competition for space and food, and is similar to adaptations of rain forest trees that compete similarly for light (Poorter et al., 2003).

Little additional change occurred in the laws governing the fishery until the outlawing of dredging of oysters on any public oyster grounds in 1879. Virginia also eliminated its marine police force (created in 1875) due to a perceived lack of need of it, which resulted in pitched battles in many Virginia waters. In the Rappahannock River, dredging boats began to illegally harvest oysters openly during the winter of 1879–1880, using rifle and cannon fire to discourage local hand tong fishermen from fishing (Bulletin of the US Fish Commission, 1880). The marine police force was quickly re-instated to restore order and restore the ability of the state to collect taxes and fees related to the oyster fishery, which had dropped precipitously from $28,169 USD in 1871 ($501,770 in 2013 USD) to a mere $541 USD in 1879 (10,373 in 2013 USD). Illegal harvest by dredgers was estimated to be as high as 2 million bushels/year when the marine police patrol was disbanded (Moore, 1982). Conflicts between Maryland and Virginia oyster fishermen were also commonplace, especially in disputed waters of Tangier and Pocomoke Sounds and the Potomac River; these conflicts were the "Oyster Wars" of Chesapeake Bay (Wennersten, 1981) which at times grew intense enough to force the Governor of Virginia (William Cameron 1882–1885) to intercede (Moore, 1982; Tice, 1982). Oyster harvests peaked in the Chesapeake Bay during this era in 1880 at 6.3 million bushels of market oysters and 1.9 million bushels of "seed" oysters. Harvests remained high at over 5 million bushels/year until the late 1880s, when the first declines were observed. At this time (1890) total harvest was split into public and private ground harvest (**Figure 2**). Seed oysters were mostly planted (~1.4 million bushels) in state on private leased grounds. Seed during the great majority of the productive years of the private leasehold fishery came primarily from what came to be known as "seed beds" in the lower-salinity reaches of the James River. This was a region of high oyster recruitment due to favorable local hydrodynamics coupled with a slow growth rate due to the low salinity. This situation created a desire to move these oysters to enhance production coupled with lots of young oysters available to move and fairly steady rates of replacement, perfect for leaseholders. These reefs also consisted of thick deposits of shells, rising several meters off the bottom which could be harvested for many years before being reduced to footprints (~12 ha out of over 1,000 still have limited relief from the bottom even today) (Woods et al., 2005). The remainder, over 500,000 bushels, was shipped north where it was planted in New York, Rhode Island, and Connecticut waters, sustaining limited output in fisheries that had collapsed due to overharvest and environmental degradation (Kirby, 2004). Later shipments were smaller, being 100,000–150,000 bushels by 1930 and declining thereafter until it virtually ceased in 1950 when legislation was passed that forbid shipment of seed oysters outside the state unless seed demands of in-state oyster planters were met. Due to these demands, shipments of Virginia oyster seed to out-of-state planters became intermittent and quite small (50,000–100,000 bushels/year) (Report of the Commission of Fisheries of Virginia, 1907–1967; Alford, 1973; Mackenzie, 1996).

Varying Fishery Output Years 1887–1912

The first mention of public oyster ground depletion was by Paxton (1858), whose interviews of prominent members of the oyster industry and resulting testimony supported the first legislative attempts to govern the oyster fishery. He described depletion of oyster grounds in the York River and at the Hampton Bars in the lower Bay near the Atlantic Ocean confluence, which had been severely depleted and damaged by oyster dredging by the 1850s. Additionally, large oyster grounds abutting Craney Island, which lies at the confluence of the James and Elizabeth Rivers, had been depleted. Similar damage was noted along the Bayside of Virginia's Eastern Shore region, in addition to the depletion of large oyster beds in the Tangier/Pocomoke Sound region. Oyster rock was, at the time, found as far South as Cherrystone Creek near the mouth of the Bay but were so depleted prior to the first official maps of the public oyster grounds (Battle, 1892; Baylor, 1894, 1895) that the Cherrystone Creek oyster rocks were not included.

The next warning was by Winslow (1882) during his survey of oyster grounds in the James River and the Tangier/Pocomoke Sound region of Virginia in the late 1870s. He noted that market sized oysters were in far lower numbers than expected, finding "one market sized oyster per three square yards of oyster reef, on average." At the time, Winslow noted that failure to enforce oyster cull laws, which returned smaller than market sized oysters and loose shell to the reefs was depleting the oyster beds. These early warnings for Virginia, similar to those being given in Maryland by scientists (Brooks, 1891), went unheeded. It is also during this time that seed oyster harvest peaked at over 3 million bushels/year in the 1890–91 and 1891–92 seasons.

The first significant declines occurred in the late 1880s as harvests of market oysters dropped by several million bushels/year, from the peak of over 6 million bushels in 1879 and 1880 to less than 4 million by 1889. By the 1890s harvests of market oysters declined to less than 2 million bushels/year from the public grounds and the private planters were contributing much more to the overall harvest, which increased in acreage from ~8,000 ha in 1894 to over 24,000 ha by 1904. Private leasehold harvests also increased, from ~0.5 million bushels in 1890 to almost 3 million bushels in 1904. Thus, what should have been viewed as a significant decline in public ground harvest (over 50% in less than 25 years) was, outside of fishery managers occasionally raising an alarm (Report of the Board of Fisheries to the Governor of Virginia, 1900–1907), unnoticed. Private leaseholds continue to expand, peaking at over 52,000 ha by 1960 (Report of the Commission of Fisheries of Virginia, 1907–1967). The private leasehold fishery essentially masked the decline in public ground harvests as it surpassed them in the early 1900s. This would remain the typical condition of the fishery, a smaller public and larger private component, until the final decline and collapse of the fishery in the 1980s (Haven et al., 1978; Virginia Marine Resources Commission, 1985–88; Hargis and Haven, 1999; Kellum, 2008). Maryland's, has a small private leasehold fishery due to political interference by watermen (Kennedy and Breisch, 1983), public harvest have always exceeded private harvests in northern Chesapeake Bay. The private leasehold fishery was entirely (and to a significant degree still is) dependent on wild oyster seed (Haven et al., 1978; Bosch and Shabman, 1989), with a significant positive correlation between the two evident from the time series. The main weakness in this system was its reliance on wild oyster seed. The leasehold system was for most of its history essentially a livestock "finishing" operation where young oysters are moved from wild reefs to privately owned grounds for fattening for market. The relationship between harvested seed and private leasehold production was positive, with a 1-year lag observable between seed harvest and subsequent harvest from the private leaseholds on which it was planted. Seed oysters typically take an additional year to reach market size. Our analysis considered 1-, 2-, and 3-year lags between seed harvest and private lease harvest, with the 1-year lag providing the best fit ($r^2 = 0.85$, **Figure 3**). This is in agreement with a study done at the time (Report of the Virginia Fisheries Laboratory, 1953) that indicated maximum yield of planted oysters was obtained 15 months post-planting. Today, this system of planting and growing young oysters on shelled leased ground is still extensively used, though more modern aquaculture practices are being rapidly adopted by leaseholders with significant success (Murray and Hudson, 2011).

The wild fishery experienced a partial recovery after the early 1890s, when harvest on the public grounds increased from 1.6 million bushels/year to nearly 3 million bushels/year from 1900 to 1904 (Report of the Board of Fisheries to the Governor of Virginia, 1900–1907; McHugh and Bailey, 1957). The total oyster harvest of 1904 (7.6 million bushels) nearly equaled the peak of 1880 (Report of the Board of Fisheries to the Governor of Virginia, 1900–1907).

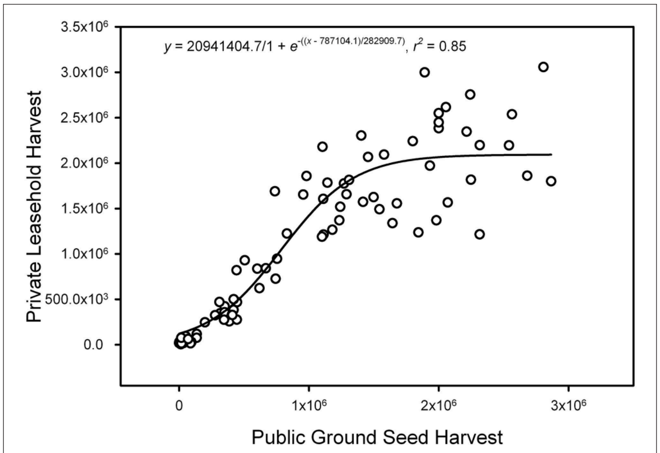

FIGURE 3 | Sigmoid fit of public ground seed oyster harvest to private leasehold harvest (units are VA bushels). 1 bushel = 0.049225 m^3.

Harvests soon declined again, though unlike prior ones this decline appeared to be driven by changes in the market rather than a decline in fishery potential output, which suggests market factors at this time played a significant role in oyster harvest declines (Mackenzie, 1996, 2007). Consumers were concerned about illness due to oyster consumption. This was known in the oyster industry as the "Pure food" scare, which peaked during the 1907–1909 seasons and significantly reduced demand (McHugh and Bailey, 1957). This scare was caused by outbreaks of typhoid fever and other illnesses, some of which were linked to the oyster industry, and resulted in the Pure Food Laws of 1906. These linkages had merit; for example, the U.S. Surgeon General documented that raw sewage was being dumped immediately adjacent to oyster growing beds in Hampton, Virginia, and in Chincoteague, which is part of the Seaside Eastern Shore of Virginia and was, at the time, an important oyster producing area. These oysters were being sold for human consumption (Annual Report of the Surgeon General of the Public Health Service, 1915), some raw in the half-shell. The VA fish commission observed: "as a result of the "panic" and pollution scare in 1906 a large proportion (at least 50%) of VA oyster carried over (left unharvested) on the beds." The Commission also noted that oysters were making the transition in consumption from a staple to a "semi-luxury" food item at this time (Report of the Board of Fisheries to the Governor of Virginia, 1900–1907). The temporary decline in demand caused several laws to be passed in 1908 in Virginia, to restore public confidence (Report of the Commission of Fisheries of Virginia, 1908–1912). Oyster and clam harvesting was prohibited from polluted waters from May 1st to August 15th and required that shellfish harvested in season were to be placed for at least 7 days in waters certified as unpolluted prior to be offered for sale as food. This process of relaying oysters subject from contaminated to clean water, called depuration, allows oysters to purge many contaminants, biological and others, from their tissues given sufficient time (Gardinali et al., 2004; Reboucas do Amaral et al., 2005; Nappier et al., 2008). However, demand for oysters increased in the 1909–1910 season, as the effects of the "panic" wore off and the largest harvest recorded since 1904 was seen, indicating stocks may have recovered during the years of lower demand. The oyster industry was operating at near full capacity by 1910. This is the only instance, other than during World War 1, where there is evidence of market forces significantly depressing the Virginia oyster harvest. Stock declines, concomitant overharvesting and related habitat damage due to harvesting were the primary driver for the decrease in local landings (Hargis and Haven, 1999; Kirby, 2004), as imports of oyster meats and production in other areas of the country rose as harvests in Chesapeake declined. Additionally, locally, prices for oysters rose as harvests have declined, indicating demand has been higher than supply since at least 1970 (National Academy of Sciences, 2004) as well as the fact that Virginia oyster processors had begun importing gulf oysters since shortly after the MSX epidemic began (Murray and Kirkley, 2010), which formed the bulk of the oyster shucking done in Virginia for decades until the Deep Horizon oil spill of 2010.

The "cull law" of 1910 was a measure implemented to maintain the condition of the natural oyster habitat. Oystermen were to cull their catch over the reef from which it was taken and were legally permitted to keep only those oysters exceeding 76 mm in shell length; all other materials, including shells and undersize oysters, were to be returned to the reef. The exception to this rule was the "seed beds" of the James River, which supplied most of the "seed" oysters used by oyster planters throughout the state. Harvests remained high (~6 million bushels/year total, about 1/3 of which were market sized oysters from the public grounds) until World War I, which decreased both the demand for oysters and numbers of fishers to catch them (Report of the Commission of Fisheries of Virginia, 1945).

Soon after World War 1 ended in 1918, harvests on both public and private grounds declined, with the total harvest falling to 4 million bushels/year by 1920 and never recovering. Production on the public grounds dropped below 2 million bushels/year and fell below 1 million by 1929. Unlike prior declines, this one was met with considerable alarm by fishing industry managers and fishers. Conditions of the oyster rock were described as follows (Report of the Commission of Fisheries of Virginia, 1929): "A survey of the natural oyster rocks on the ocean side of Accomac and Northampton Counties shows that thousands of acres of oyster bottoms, as defined by the Baylor Survey, have become entirely barren. On the bay side of the above named counties the only natural rocks which can be called productive area are a few of those lying in Pocomoke Sound. The natural rocks in Virginia tributaries of the Potomac, including the Yeocomico and Coan Rivers, have become depleted to such an extent that, with a few exceptions, they may be said to be now practically exhausted. The same conditions prevail in the Great Wicomico and York Rivers, in Mobjack Bay and its tributaries, and to a modified extent in the James River below the seed line. Some of the rocks in the Rappahannock and Piankatank Rivers are still comparatively productive, but many of the rocks in these rivers have either become much smaller in area or are now totally barren. These conditions easily explain the falling off in the production of the natural rocks." This decline was attributed primarily to constant tonging and dredging without adequate rest or replenishment of the public oyster grounds. A second factor was oyster drills, *Urosalpinx cinerea*, a predatory snail on young oysters, which caused 20–40% mortality on oyster recruits (Report of the Commission of Fisheries of Virginia, 1926–1963, Report of the Virginia Fisheries Laboratory Report, 1953). It is unknown if the snails routinely caused this mortality rate, as this is the first time it was measured, but it is likely they did.

Birth of the Repletion Program

To address the public fishery decline, the commission recommended that a shell planting program to refurbish the public grounds be initiated and funded at the level of \$100,000/year (\$1.39 million in 2015 USD) with a goal of planting at least 500,000 bushels (22,600 m^3) of shells/year on the public grounds in an attempt to halt the decline in productivity. This repletion program began in 1929 with the first shell plantings to attempt to maintain the habitat and seed to more directly augment commercial harvest in specific areas. Seed at this time came from areas of high recruitment, typically the "seed beds" in the James River, the region of the James that had already been providing the majority of the seed oysters to private planters (Report of the Commission of Fisheries of Virginia, 1929). During the first two decades, ~276,000 (12,475 m^3) bushels of shells and 15,000 (678 m^3) bushels of seed were planted/year. During these early years of the repletion program (1931–1947) shell plants, with a 2-year lag to account for the time needed for recruits on fresh shells to grow to market size, did not have a statistically significant impact (ANOVA, $p > 0.05$) on the public oyster ground harvest (**Figure 4**). Seed plantings during this time (1931–1947) were also analyzed with a 1-year time lag being most appropriate considering seed generally took 1 full year post-planting to reach market size. No significant impact (ANOVA, $p > 0.05$) on the harvest due to these seed plantings was observed. Seed plantings were also examined with a 2-year lag and this was also not significant (ANOVA, $p > 0.05$). While it may have had some benefits, and perhaps did in slowing the rate of stock decline, given the limitations of the available data this impact is undetectable. Public ground oyster harvests during this time (1929–1949) averaged 650,000 (29,380 m^3) bushels/year, roughly 10% of what it was during the peak years. Harvests on the public grounds declined further during the 1950s by 9% to 596,000 (26,939 m^3) bushels/year (Report of the Commission of Fisheries of Virginia, 1947–1961). In response, the repletion program was augmented in shell planting volume to 676,000 (30,555 m^3) bushels of shells/year though seed plantings, believed to not be of significant help, were halted (Report of the Commission of Fisheries of Virginia, 1929–1949). State general funds were used to supplement the repletion program funding in 1947, which had prior to this point been funded solely by tax and license fees on the oyster fishery (Commission of Fisheries of Virginia, 1947). The general public therefore began to subsidize the fishery, a 70-year subsidy which continues to this day.

Advent of Oyster Disease and Its Impact on the Fishery and Repletion Program

In the late 1940s, oyster mortalities were being noted in adult oysters that could not be attributed to predation. The cause was identified as a fungus (actually a protistan parasite) that is now known as Dermo, *Perkinsus marinus* (Report of the Virginia Fisheries Laboratory, 1949–1959; Andrews, 1979). Estimates of annual mortality during this time ranged from 10 to 30% of oysters nearing market size in the summer prior to their fall harvest (Report of the Virginia Fisheries Laboratory, 1959). *Perkinsus* remains a problem to this day, becoming much more severe in Chesapeake Bay in the 1980s (Burreson and Andrews, 1988; Ragone and Burreson, 1993; Burreson and Ragone-Calvo, 1996; Ragone Calvo et al., 2003; Wilberg et al., 2011), when mortalities of adults due to Dermo were over 90% of age 2+ adults/year in many areas of the Bay (**Figure 2**). Mortality has since declined from this peak, but it remains a significant impediment to oyster population recovery at present. Shell plantings increased in volume in response to the increasing mortality on market and near-market sized oysters. The benefit of shell plantings occurred 2 years post planting, the time to grow a single year class of oysters to market size on a shell planting (ANOVA, $p < 0.05$), though not at 3 or in later years (ANOVA,

$p > 0.05$). The amount of increased harvest was estimated using the regression equation on the raw data of the era, to be a 41.8% increase in commercial harvest due to the shell plants (time period 1950–59, linear regression, $r^2 = 0.63$), which was the largest positive impact noted for the shell planting program. No seed was planted on the public grounds during this time. The volume of shells relative to the public ground harvest increased significantly to achieve this benefit, with shell plants now amounting to 105.1% of the volume of the commercial harvest, compared to 35.8% by volume in earlier years. Another oyster disease, MSX, *Haplosporidium nelsoni, first* noted in Delaware Bay in the late 1950s, caused significant mortality to Virginia's oysters starting in 1959. Unlike *Perkinsus*, which appears to be a native organism, *Haplosporidium* was introduced into Delaware Bay via importations of non-native Pacific oysters, *Crassostrea gigas*, from Japan (Burreson et al., 2000). The combined Dermo-MSX epidemic caused massive oyster (primarily adults of sub-market and market size) mortalities (90–95%) in high salinity waters (>11 PSU) throughout much of Chesapeake Bay by 1960 (Andrews, 1964, 1968; Andrews and Wood, 1967; Andrews, 1979). Harvests peaked in 1960–61 as oyster fishers try to catch as many oysters as possible before MSX killed them; plummeting to 227,000 bushels in the 1962 harvest, the lowest ever seen on the public grounds. The private leasehold fishery also declined with the advent of MSX, production plummeting from ∼2,500,000 million bushels/year during the 1950s to less than 1 million by 1967. Seed oyster production also declined from 2,300,000 million bushels/year during 1950–1960 to 1,150,000 million by the early 1960s. As disease reduced stocks and drove down seed counts per bushel, the price per seed oyster rose simultaneously as seed quality declined due to increased mortality from disease (Shabman and Capps, 1984; Bosch and Shabman, 1989). The decline in spat counts per bushel after MSX was introduced to Chesapeake Bay were most apparent in the James River, but also occurred in other Virginia waters (**Figure 4**) (Burke, 2010). James River seed oysters were particularly vulnerable to MSX disease due to their origin in low salinity (6–10 PSU) waters, which inhibit natural selection for disease tolerance as MSX does not thrive in such waters (Ford, 1985). After the initial MSX epidemic, oysters in high salinity waters developed some tolerance to the disease (Ewart and Ford, 1993) which appears to have become significant in recent years (Carnegie and Burreson, 2011) though low salinity populations remain naïve and subject to significant mortalities if relocated to high-salinity waters.

The MSX disease epidemic of the 1960s initiated the first of three waves of Federal economic subsidies to the Virginia oyster industry. The response to the James River seed problem was to develop two smaller rivers in higher salinity waters as seed oyster sources for the private leasehold fishery, the Great Wicomico and Piankatank Rivers, which began to receive large scale shell plantings in the early 1960s as part of both state and federal oyster disaster relief effort along the Northeast Coast of the United States. The federal funds were used to support research into disease resistant oysters as well as rehabilitation of oyster beds via shell plantings and through seed purchase and movement (Report 1736, 87th Congress, 1962). This larger scale shell planting effort also involved adding shells obtained by dredging buried shell deposits from local waters to shells bought from shucking houses,. During the peak of the shell planting program in Virginia (1963–1968) 2,600,000 bushels (117,520 m^3) of shells were planted/year. The oyster seed planting program was also re-initiated at this time (1961) in response to the MSX epidemic, to move oysters from high salinity regions where they recruit in good numbers to low salinity areas where MSX mortalities were lower and survival of planted seed to market size (76 mm) more likely. In prior years when seed was moved onto public grounds (1931–1946) an average of 18,700 bushels (845 m^3)/year were moved. From 1962 to 1972, 73,400 bushels of seed oysters were moved, which amounts to 21.5% by volume of the commercial harvest from the public oyster grounds. Considering that planted seed can potentially produce over a bushel of market oysters per bushel planted depending on survival and growth rates, this seed movement could have made a significant contribution to the commercial oyster harvest during the peak years of the MSX epidemic (Report of the Commission of Fisheries of Virginia, 1931–1965).

Post MSX Period (1964–1980)

The large scale shell plantings and seed movement may have exerted a positive effect on the public oyster fishery as harvests, despite ongoing though declining but still significant MSX mortality (Andrews, 1968), which appears to have peaked during the early 1960s (Mackenzie, 1996). However, statistical analysis indicates there was no clear relationship between shell or seed plantings and the public oyster harvest with the exception noted (1950–59). ANOVAs on harvest vs. repletion program (with a 2 year stagger for shell plants and a 1 year stagger for seed plants) from the entire time of the repletion program (1931–2009), and various eras selected for times of more intense shell and/or seed plants after the MSX epidemic: 1960–1985, 1991–2009, 2000–2009, 2005–2009, 1960–1969, 1960–1971, and 1963–1966 revealed no significant relationships, $p > 0.05$). Shell plants and seed plants were factors, considered independent of each other as well as interactively using R software, as were all subsequent ANOVA of various time periods, with harvest as the dependent variable. Harvests from the public oyster rocks vary considerably during this time, from a low of 228,000 bushels in 1962 to just over 600,000 bushels by 1965. Harvests decline again (> 300,000 bushels/year) from 1967 until after Tropical Storm Agnes in 1972 (Report of the Commission of Fisheries of Virginia, 1907–1980).

Tropical Storm Agnes had a significant negative impact on the oyster industry, but it also exerted a positive impact by virtually extirpating the predatory oyster drill from much of Chesapeake Bay, particularly the Rappahannock, Piankatank, and Great Wicomico Rivers, and severely depleting them in the York and James Rivers (Lynch, 2005), allowing for greater survival of young oysters. The heavy freshwater flooding caused by Agnes also inhibited seed oyster production due to the very poor recruitment on seed beds. Mortality due to the storm on private leaseholds (Report of the Commission of Fisheries of Virginia, 1907–1980) was much higher than on natural reefs. The public ground harvest stayed steady while the private ground harvest plummeted to ∼33% of the prior year's harvest. The private leasehold fishery did not recover and production remained <50%

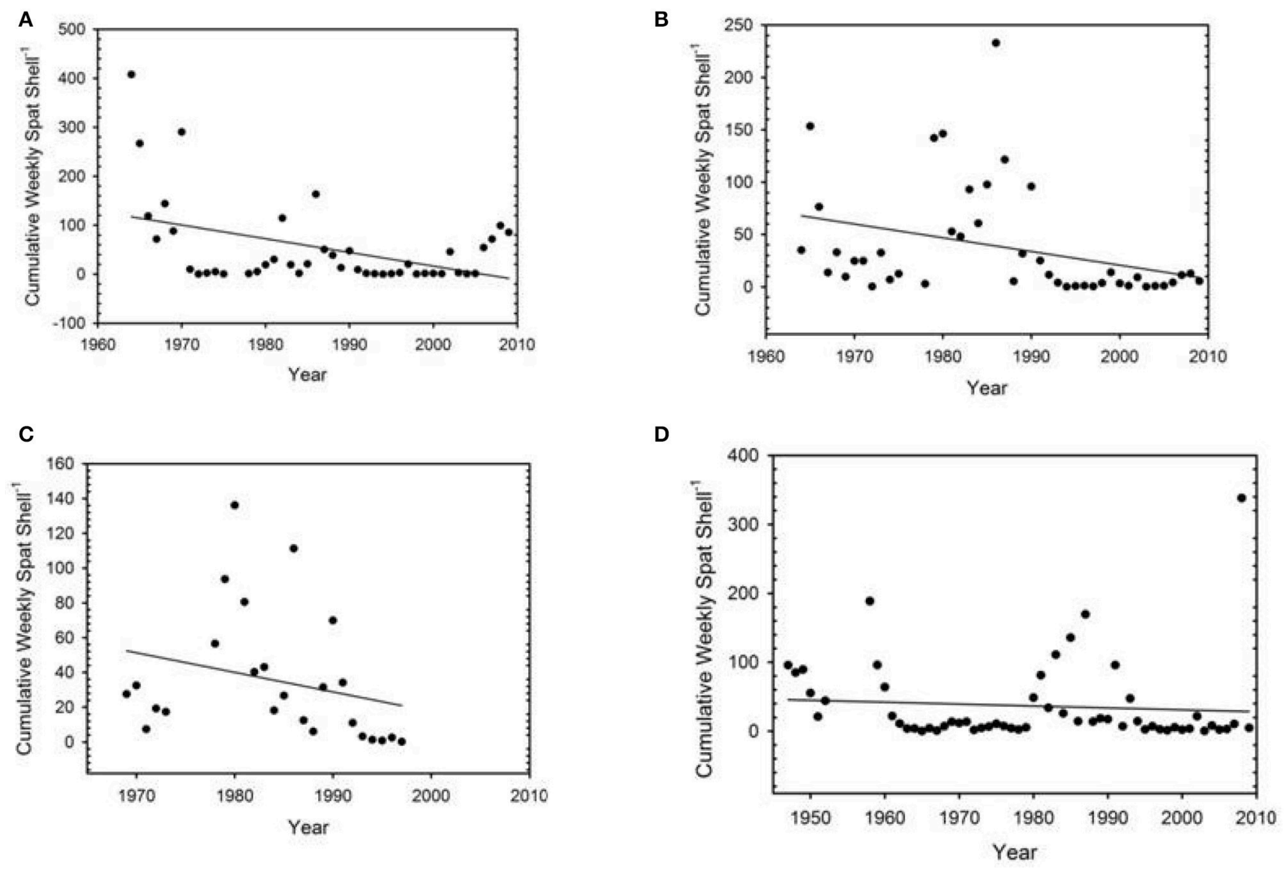

FIGURE 4 | Mean spatfall over time in various Virginia tributary rivers over time. (A) Great Wicomico River, **(B)** Piankatank River, **(C)** Mobjack Bay, and **(D)** James River.

of the decade before. Federal disaster relief funding resulted in massive shell plantings for several years, rapidly increasing after 1972 to a peak of over 3,000,000 bushels (135,600 m^3) of shells planted in 1975 and 1976. Harvests increased from 260,000 in 1972 to over 700,000 bushels of oysters in the 1979–80 harvest seasons. This peak was the highest since 1961, and the last significant peak in production for the public oyster fishery (Report of the Commission of Fisheries of Virginia, 1907–1980).

Final Decline and Collapse with Recent Signs of Recovery (1981–Present)

Seed movement, which had increased to over 100,000 bushels a year in the early to mid-1970s, was reduced to less than 50,000 bushels/year from 1975 to 1986. Large scale shell plantings on public grounds also declined from over 3,000,000 bushels (135,600 m^3)/year in the mid-1970s to less than half that total in the following decade [~1,400,000 bushels (63,280 m^3) shells/year from 1977 to 1986]. Harvests from the public grounds declined along with the shell plantings, falling over 50% from 1980 to 1984. The years 1985–86 were very dry and hot, especially during the time when oysters and their diseases are metabolically active, permitting *Perkinsus* to overwinter at high prevalence. In typical years reduced winter salinity and temperatures promote reductions in disease prevalence and intensity (including MSX). This allowed for an expansion and increased virulence of Dermo throughout most of the Chesapeake Bay causing massive mortalities of adult oysters (Andrews, 1996) in almost all Virginia waters. MSX also played a role in increasing disease mortalities at this time, especially in Maryland, though Dermo was the primary source of disease mortality during this epidemic. As stocks of market sized oysters declined precipitously in almost all Virginia waters, the situation for the oyster industry grew dire. The result was the unprecedented move by fishery managers to open the James River seed beds to harvest for market oysters in 1986. Another action was to allow hand scrapes, which are small oyster dredges, for use in the oyster fishery and the opening up of many regions to their use in 1987 in an attempt to maintain harvests (Virginia Marine Resources Commission 1986–1987). Dredges, pulled over a wide area of reef, catch more oysters per unit time than tongs when oyster densities are low. These management measures enhanced harvests for several years before populations were depleted. It was believed that as disease would soon kill the oysters, it was best to attempt to harvest them. The James River seed beds were managed over much of their former area for market oyster production. Shell and seed plantings to maintain the public grounds continued, shell plantings averaged

~1,500,000 bushels (67,800 m^3)/year planted and 80,000 bushels (3,616 m^3) of seed/year planted from 1981 to 1990 (Virginia Marine Resources Commission, 1981–1990, Hargis and Haven, 1999). Public ground harvests during this time average 322,000 bushels of oysters/year, steadily declining during this time from 475,000 in 1981 to 178,000 in 1990, a 73% drop, and now at 3% of the historic peak. The Dermo outbreak also impacted the private leasehold fishery, which declined from 300,000 bushels/year from 1980–1986 to less than 100,000 by 1990. The state cut its public oyster repletion program drastically (by 81%) in 1991, and remained low until very recently (2013) when much more substantial state funding ($2 M USD) was provided to allow the repletion program to expand again. The Federal government began providing funds in the 1990s. These funds exceeded state funding for a significant period of time (Virginia Marine Resources Commission, 1993–2010) decreasing after 2010. From 1993 to 2011, on average nearly 767,000 bushels (34,668 m^3) of shells have been planted/year on public oyster grounds to maintain the fishery, along with an average of nearly 30,000 bushels (1,356 m^3) of seed oysters (wild and in recent years some hatchery produced) planted annually on these same grounds. At the same time, oyster harvests on the public grounds have been very low, 42,426 bushels/year on average. These repletion numbers do not consider reefs constructed as sanctuaries, which are closed to oyster harvesting, or any oysters planted on these sanctuaries. If these were included, both shell and seed figures would be much higher (Virginia Marine Resources Commission, 1986–2011). Public oyster harvests declined further, recording harvests of less than 10,000 bushels for several years in the 1990s, 2001 and 2006. The only harvest exceeding 100,000 bushels occurred in 2005 when a large sanctuary established in the James River in the 1990's was opened to commercial oyster harvest (Daily Press, 2005). This sanctuary supplied the majority of the 2005 public harvest total of nearly 100,000 bushels. Another large sanctuary in the lower Rappahannock River that had been closed to commercial oyster harvest in 1993 was opened to harvest in 2007, enhancing harvest that year, though. Public ground harvests remained lower than 100,000 bushels/year until recently (post 2010). Further management actions taken at the time of the Rappahannock River sanctuary opening included establishment of a rotational harvest system in the lower Rappahannock River and in the Tangier/Pocomoke Sound region, dividing them up into regions so that individual public grounds are rested for a year between harvests and also to better coordinate repletion activities to maximize commercial harvest (Virginia Marine Resources Commission, 1986–2007). It is believed that this allows for higher stock and harvest levels. It is unknown at this time if this management is having this affect, as there has been developing disease resistance, which has also enabled higher harvests post 2010. Rotational harvest has been used successfully for molluscan species, including sea scallops (Valderrama et al., 2007). Due to the present lack of wild seed resistant to disease, there has been a significant increase in production of oyster seed from hatcheries for aquaculture, either on the bottom or in more managed cage and rack systems (Murray and Hudson, 2011), this trend continues at present. In recent years, hatchery produced seed has significantly augmented the private leasehold productivity, which has out-produced the wild oyster fishery in terms of bushels of market oysters produced/year since 2006 with this gap widening significantly in the past several years. This increase has been primarily due to the development of hatchery produced seed, not increased wild seed production, though wild seed production has increased in recent years as well.

In Virginia, three formerly productive oyster beds of varying size at the confluence of the Nansemond, Elizabeth, and James Rivers (1037.4 ha) and in Tangier Sound (284.6 and 479.4 ha) were permitted for dredging of buried shells that formed the footprint of these large historical reefs. They were denuded of live oysters and surface shell by years of overfishing and covered by ~0.6 m of sediment as of 1960 (Withington, 1965). The largest site had been depleted by 1850 (Paxton, 1858) and the two smaller sites by the 1870s (Winslow, 1882). This dredging of former reef footprints commenced in Virginia in 1963 and continues at present. The three initial sites, which contained unconsolidated deposits of shells up to 4 m thick served for many years of shell dredging (Withington, 1965). These initial three sites were eventually depleted and are no longer used today. Several small sites in the lower James River totaling ~114 ha are permitted for use at this time. The majority of shells planted in Virginia waters in recent years have been dredged shells, with shucking house shells comprising a smaller portion [~500,000 bushels (22,600 m^3)/year]. Most of this shucking house shell was not derived from local harvests but from imported shell stock from the Gulf of Mexico, as the few remaining (161 in 1981, 36 in 2009) oyster shucking and packing houses in Virginia primarily imported and processed live oysters from the Gulf of Mexico until the Deepwater Horizon oil spill in 2010 impacted a significant part of the gulf oyster fishery, causing a wide-scale closure of most of it (Sumaila et al., 2012) and the increasing local harvests in recent years.

Shell Placement

Shells were generally placed to sustain the commercial harvest by repairing damaged habitat. However, there have been significant exceptions. At the commencement of the shell planting program in the late 1920s, a number of experimental shell plantings were conducted to assess the benefits of expanding oyster habitat. The results when compared to planting shells on existing, damaged and depleted habitat were poor. State fishery management developed a position in 1931 (Report of the Commission of Fisheries of Virginia, 1931) as follows: "The planting of shells on barren grounds, and then closing the areas on which they are planted until there is a sufficient catch of oysters of marketable size, as the statute now provides, will not, in the opinion of the Commission, produce satisfactory results for the reasons, that there is frequently a failure to obtain a catch of young oysters on such grounds, and when they are once thrown open to the public, the repleted areas soon become as barren as they were before the shells were planted. Furthermore, the cost of restoring the natural rocks on barren bottoms in Virginia would be too great to be considered. On the other hand with *shells planted on the live, productive rocks*, and the cull law enforced, there is not only a better chance to obtain a catch of young oysters on the shells year by year, but they would afford a continual means of production." However, accuracy of shell placement was limited by navigational technology to locate accurately the bed to be planted, as well as the means to place the shells (typically a water cannon of the type used on marine fire control vessels was used to blow shells off a barge) as well as currents which can displace shells as they settle to the bottom. This had been noted as early as 1950, when the Virginia Fisheries Laboratory "recommends an annual survey of the public oyster rocks in order to determine more accurately the location in which shells should be planted for cultch purposes (Report of the Virginia Fisheries Laboratory, 1949–1959)." Extensive experimental plantings outside typical repletion done on natural oyster rock habitat commenced with the influx of Federal funding in the 1960s that was allocated to Virginia in response to the MSX disease epidemic. However, it remained state fishery management policy to spend the bulk of the repletion efforts on areas of known productivity: "It is our intention to continue planting the largest quantity of shells in the *tried and tested* areas although we expect to make experimental plantings in other rivers where we hope to get enough recruitment to further advance the program" (Report of the Commission of Fisheries of Virginia, 1964–1965). These experimental plantings continued to be part of the repletion program for several years, throughout the late 1960s. They evidently continue to some extent to the present time, as in the Rappahannock River and Tangier/Pocomoke Sound which show that portions of recent repletion projects (year 2000 and more recent) have included significant shell plantings on new areas rather than on natural oyster rock (**Figures 5–7**).

Oyster Fishers

The total number of fishers is considered, and fishermen types are often grouped for the analysis as harvest data by gear type is limited. Two main distinctions in gear type define the type of fisher: tongs, which are large metal-toothed rakes that are worked by hand or hydraulically, and dredges, which are metal-toothed frames with an attached bag that are pulled over the bottom by the boat. Tongs take a discrete, small area of reef per deployment whereas dredges are dragged over an area of reef per deployment. Dredges are more efficient oyster harvest gear both in deeper waters and lower market oyster densities (Tarnowski, 2004). Dredges are more damaging to the reef structure than are tongs, and additionally, over time, spread the remaining reef material over a wider area, expanding it while reducing reef quality (Winslow, 1881; Moore, 1910; Lenihan and Peterson, 1998, 2004). Tongers (hand and patent) dominate the fishing license holders numerically with few exceptions; 1989 and 2004-present, when dredgers dominate. Legislative protection has been provided to tongers throughout the history of the fishery, reserving large areas, typically in rivers and shallower waters, for their exclusive use. This permitted larger numbers of watermen to remain in the fishery at the expense of individual income. This recent dominance by dredgers is largely due to the permitted use of smaller dredges, called "hand scrapes" into the oyster fishery in the late 1980s over much of Virginia's public oyster grounds. Prior to the Dermo epidemic, dredgers constituted 10% or less of the total fishers in Virginia. Maryland reacted similarly to the Dermo disease epidemic, opening up wider and wider areas to oyster dredging as oyster populations collapsed in an attempt to sustain harvests (Tarnowski, 2004). This management action resulted in more rapid and complete population collapse in Maryland. Further, the Dermo induced collapse may have been avoided had fishing mortality been decreased (Rothschild et al., 1994; Jordan and Coakley, 2004) and though this has not been extensively studied in Virginia, it is likely true for the Virginia oyster population as well. For example, in 1978, dredging was declared legal during a short, designated late winter season each year in open waters of Tangier and Pocomoke Sound, Virginia. As a result, landings increased to 208,130 bushels for Pocomoke and Tangier Sounds combined during the 1978–79 season, but this level of production quickly declined to only 27,370 bushels in Pocomoke and Tangier Sounds by the 1983–84 harvest season. The data, and the Maryland experience suggest the accumulated stocks were quickly exhausted by the more efficient (and damaging) dredging over tonging during the height of the Dermo epidemic (Virginia Marine Resources Commission, 1978–2011).

As harvests declined fishermen exited the fishery (**Figure 8**) until stabilizing after the final collapse (1993–2011) at a mean of 481 watermen per year holding active licenses to harvest oysters from the public grounds. Income per license holder also varies considerably (**Figure 8**), and a recent trend toward higher income/fisher can be seen, beginning around 2004. This has been attracting more fishers back into the oyster fishery, with 594 in 2008, increasing to 908 licensed fishers as of the start of the 2011 season. Due to the fact that all licensed fishermen are grouped, the income/license is not truly reflective of the average income/fisher. Dredgers harvest proportionally more oysters/license than do tongers, though their capital outlay is typically higher. Additionally, dredgers typically operate on larger boats with a crew of two (hand scrape fishers) or more, whereas tongers tend to operate with a crew of one (just the license holder) or with a single helper. During the earlier history of the fishery, crew often consisted of unpaid young (<18 year old) sons of adult watermen, forced conscripts (typically recent European immigrants), who were paid poorly if at all (Keiner, 2009), to today's crews where the boat owner will be paid the most with smaller amounts to various crew members, if present.

What can be seen over time is a general downward trend in gross income (adjusted to 2011 dollars) per license-holder over time coupled with a decline in license-holders over time (**Figure 8**). This trend is accompanied by a transition from oyster fishing as providing near full-time occupation to seasonal employment. The early years of the fishery (1880–1928) saw the average license-holder earn $12,277 USD (inflation adjusted for 2011). For the era, this was a below average income (average income from 1913 to 1928 was $16,098 USD in inflation adjusted 2011 dollars (Piketty and Saez, 2003), illustrative of the low income typical of a commercial fishermen in the Bay that continues to this day. For example, at Tangier Island, Virginia, a small, isolated community whose workers largely derive their income from commercial fishing, had a median household income of $28,384 USD in 2011, compared to the US median of $49,445 USD in 2011 (Lebergott, 2017). Today, the oyster fishery provides limited

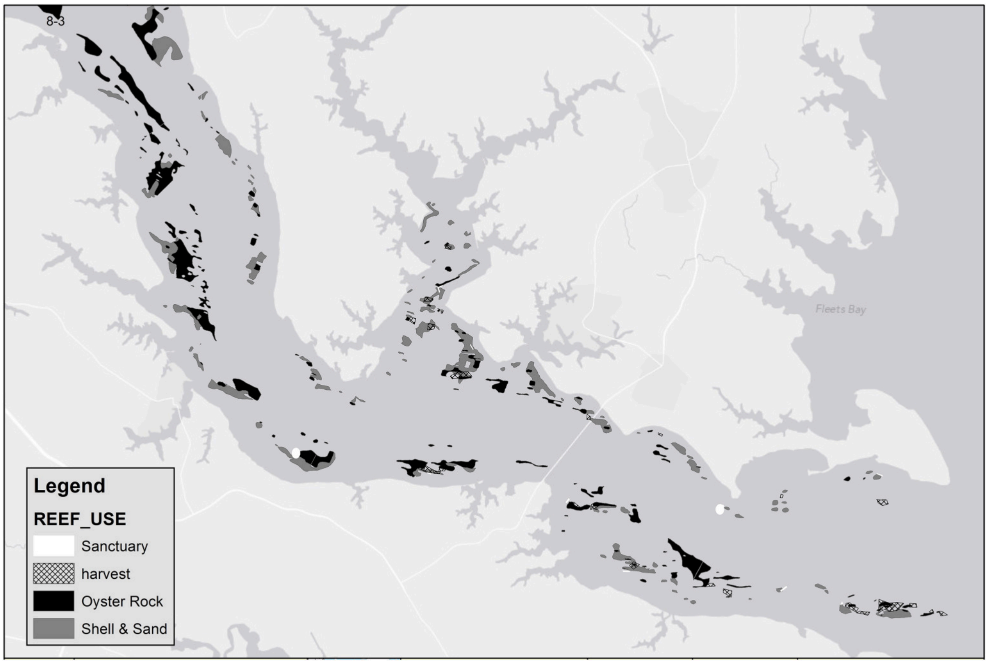

FIGURE 5 | Shell placement in the Rappahanock River, early 2000's. Note a large portion of the shells were not placed on the highest quality "oyster rock" bottom areas.

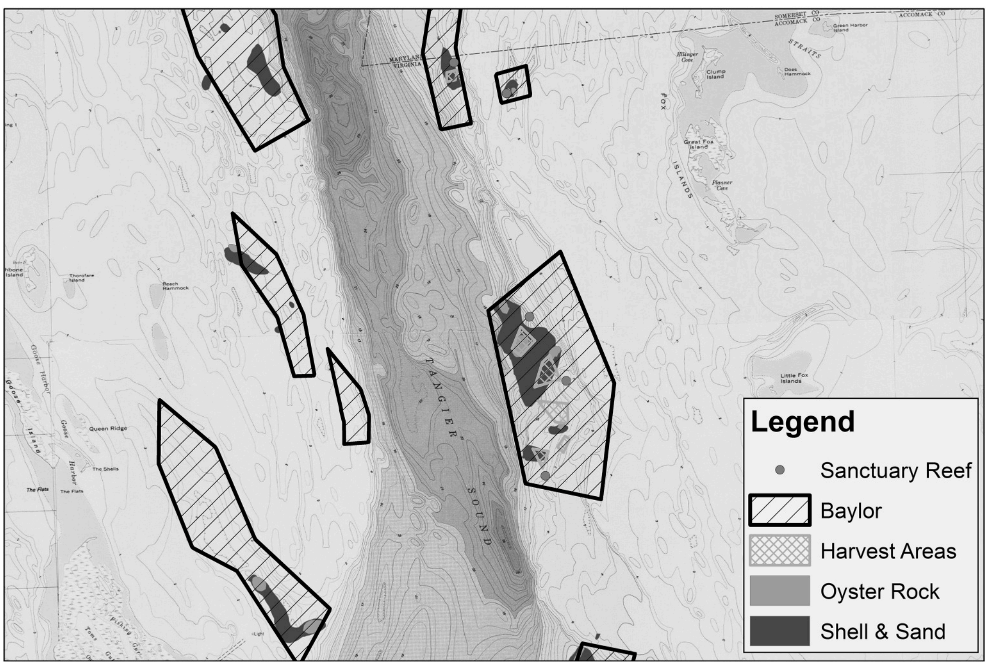

FIGURE 6 | Shell placement in TangierSound, 2002. Note a large portion of the shells were not placed on the highest quality "oyster rock" bottom areas.

seasonal employment to a small number of fishermen, who rely on more destructive fishing practices (dredges) than earlier times, to maintain the small public ground harvests seen today.

Extent of Oyster Habitat and Loss Over Time

The total area originally delimited in Virginia waters of Chesapeake Bay as public oyster grounds was 81,429 ha, with

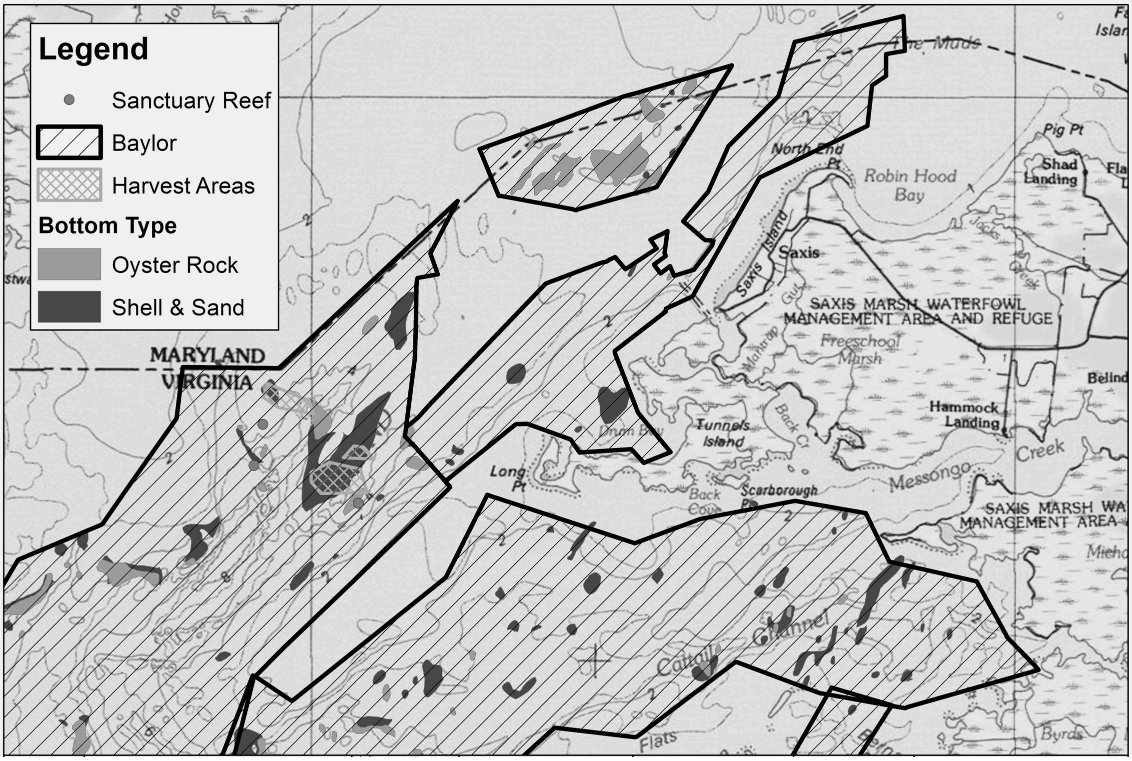

FIGURE 7 | Shell placement in Pocomoke Sound, 2002. Note a large portion of the shells were not placed on the highest quality "oyster rock" bottom areas.

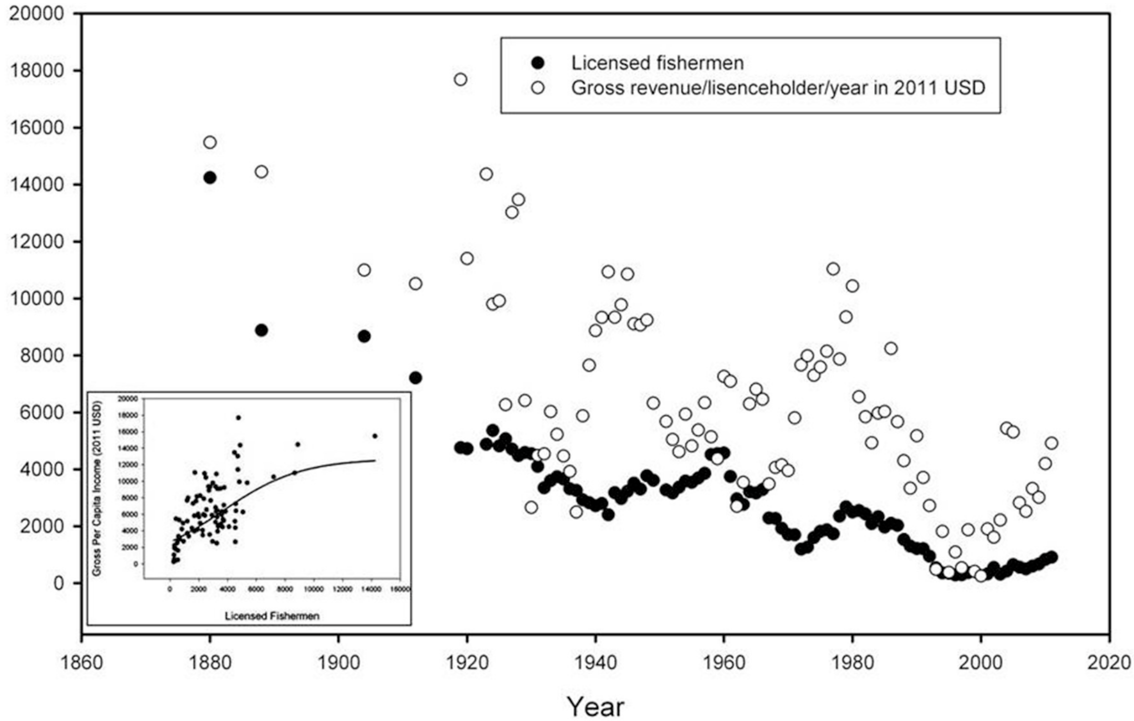

FIGURE 8 | Number of fishers and gross income over time. Embedded graph is a sigmoid fit of the data, y = 12723.3/(1 + e-((x–3623.0)/2717.7), r^2 = 0.43.

18,046 ha of these on the seaside of the Eastern Shore of Virginia (Baylor, 1895). Baylor mapped the beds based solely on the input of the county oyster inspectors, who served as his guides, without any ground truth examinations of the bottom.

This means of delineation resulted in numerous discrepancies between where oyster reefs were actually located and the mapped public grounds, with some reef areas kept out and barren areas included. Perhaps the largest discrepancy was that one entire region, much of the lower Bayside Eastern Shore, was not surveyed by Baylor due to the prior decimation of the reefs in this region (Paxton, 1858). In the Lynnhaven River, Baylor was prohibited by the oyster inspectors from surveying much of the Eastern and Western Branches of the River, due to the inspectors' desire to keep such areas out of the public oyster fishery (Baylor, 1893).

The result of the Baylor survey was a series of polygon maps that can serve as a crude guide of the locations and areal extent of oyster grounds, with extensive reef areas excluded in some cases and barren areas that were not oyster habitat included within them. A schematic of the Baylor Survey vs. an older survey (Winslow, 1882) that was subject to a meticulous bottom survey to determine the extent and quality of oyster habitat within the same area, the Tangier/Pocomoke Sound region of mid Chesapeake Bay, shows significant discrepancies (**Figure 9**). Areas that were undoubtedly oyster habitat were excluded from the survey, based on the borders of a number of oyster reefs that clearly extend off of the Baylor Grounds, and areas that clearly were not oyster habitat were included within the Baylor polygons. To further confound the issue, these surveys (both Winslow, 1882, and Baylor, 1895) were conducted after decades of dredging and it is likely that reef habitat was already lost by this time. Areas covered by ground-truth surveys include the Tangier/Pocomoke Sound region of the Bay main stem (Winslow, 1882), the upper western shore of Virginia waters of Chesapeake Bay (Bradford, 1881), Onancock and Pungoteague Creeks (Bradford, 1881), and the James River (Moore, 1910).

Tonging and dredging damage reefs and can reduce their areal extent as well as reef height (Winslow, 1881; Wennersten, 1981; DeAlteris, 1988; Lenihan and Peterson, 1998; Hargis and Haven, 1999). As an example of tonging impacts, the Moore (1910) survey delineated 2852 ha of high-quality oyster reef habitat (oyster rock) in the James River. Such habitat consists of mostly live and dead oysters and shell, with minimal if any exposed sediments of other types on the reef surface. A more recent survey (Haven et al., 1981) delineated 1,744 ha of oyster rock habitat in the same river, a 38.9% loss largely between 1906 and 1979 (71 years), for an annual loss rate of 0.55%/year (**Figure 10**) due primarily to tonging though sedimentation plays a role by covering depleted beds (Lenihan, 1999), rendering them useless for oyster recruitment. For an example of dredging impacts, Winslow (1882) surveyed the Tangier/Pocomoke area of the Bay main stem. At the time of his survey, there were 2,252 ha of oyster rock habitat in Virginia waters. The Haven et al. (1981) survey documented 630 ha of oyster rock remaining, a 72% loss over the period 1878–1979 (101 years) for an annual rate of 0.71%/year (**Figure 9**). A creek in this region, Pungoteague Creek, also illustrates this damage and resultant habitat loss (**Figure 11**).

Repletion rates were different between the two regions (Reports of the Commission of Fisheries of Virginia 1929–1967; Annual Reports of the Marine Resources Commission, 1968–1978), with the James River oyster rock receiving, on average, 89.7 m^3 of planted shells/ha and Tangier/Pocomoke Sound oyster rock receiving, on average, less at 50.5 ^{3}/ha since the inception of the repletion program to 1978 (the year before the Haven survey was conducted) compared to the original surveyed rock areas. Plantings often occurred in the same areas known to be particularly productive or due to political pressures, so these averages are not truly reflective of what actually occurred—some areas were preferentially maintained, while others may never have had any shell planted. The higher rate of repletion in the James River may have slowed its rate of areal shrinkage compared to the Tangier/Pocomoke region, which may explain the lower rate of habitat loss, though it is more likely due to a combination of higher initial relief of the James River reefs compared to those in Tangier/Pocomoke Sound as well-differences in fishing devices. Overall, these rates of habitat loss are comparable to those estimated for the Maryland portion of Chesapeake Bay's oyster habitat (Rothschild et al., 1994; Smith et al., 2005).

It is also probable that new habitat was formed by the extensive dredging of the reefs, which spread shells over a wider area than the original pre-exploitation reefs covered. Winslow (1882) and Ingersoll (1881) indicated that this was the case. Modern experiments (Lenihan, 1999; Lenihan and Peterson, 2004) demonstrated that oyster dredges spread reef material over a wider area when run over reefs with significant bottom relief, as most early reefs did (DeAlteris, 1988; Woods et al., 2004) in Virginia waters of the Bay. The "scattered" areas in the Winslow survey (1881, 1882) were, in part, new habitat formed by spreading of shells from the original reefs.

DISCUSSION

The public oyster fishery follows the typical pattern of depletion seen for most oyster fisheries worldwide (Kirby, 2004; Beck et al., 2011). Today, the remaining oyster habitat in Virginia waters in the Bay is in generally poor condition and stocks are low. The fishery is defined as collapsed (Worm et al., 2006; Costello et al., 2008), as both public and the linked private leasehold fishery returns are much less than 10% of peak landings (0.5% for the public fishery and 0.8% for the private leasehold fishery since the early 1990's. Most of this loss can be attributed to overfishing compounded in later years by disease (Haven et al., 1978; Hargis and Haven, 1999; Kirby, 2004; Beck et al., 2011), coupled with inadequate stock management during disease epidemics (Jordan and Coakley, 2004). It is possible that diseases increased as stock declined due to allee effects, which have been implicated in fishery collapses, including molluscan fisheries (Gascoigne and Lipcius, 2004) but this has not been confirmed for Chesapeake Bay oysters.

The oyster repletion program, a put-and-take fishery subsidy, operated in the early years with little impact, though it likely

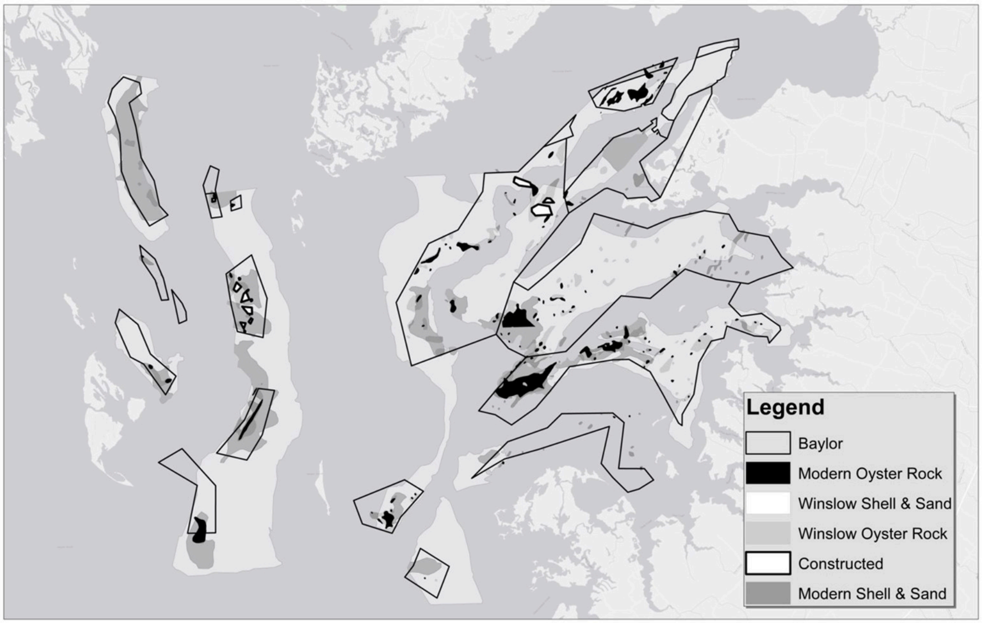

FIGURE 9 | Map showing Baylor (1895) grounds (polygon outlines), Winslow (1882) survey (medium grey = Winslow oyster rock, very pale grey = Winslow shell and sand, and Haven et al. (1981) survey (black = Modern oyster rock, dark grey = Modern shell and sand, bright white polygons are where modern (post 2000) shell plantings have been constructed) of Tangier and Pocomoke Sound waters, VA.

FIGURE 10 | Habitat loss between Moore Survey (1910, gray areas) and Haven et al. Survey (1981, black areas) in the James River.

played a role in sustaining harvests and slowing the rate of the collapse of the public fishery. When the shell-planting program was sufficiently large, a positive benefit of increased harvests on public oyster grounds was observed. Overall, repletion efforts in Virginia increased exponentially over time with increasingly larger efforts (and associated expenditures) needed per bushel of market oysters harvested from the public oyster grounds after each disease outbreak. The dredged shells used for the majority of the shell plantings since the early 1960's currently cost \$2.00/bushel (this price continues to rise) and oyster seed used

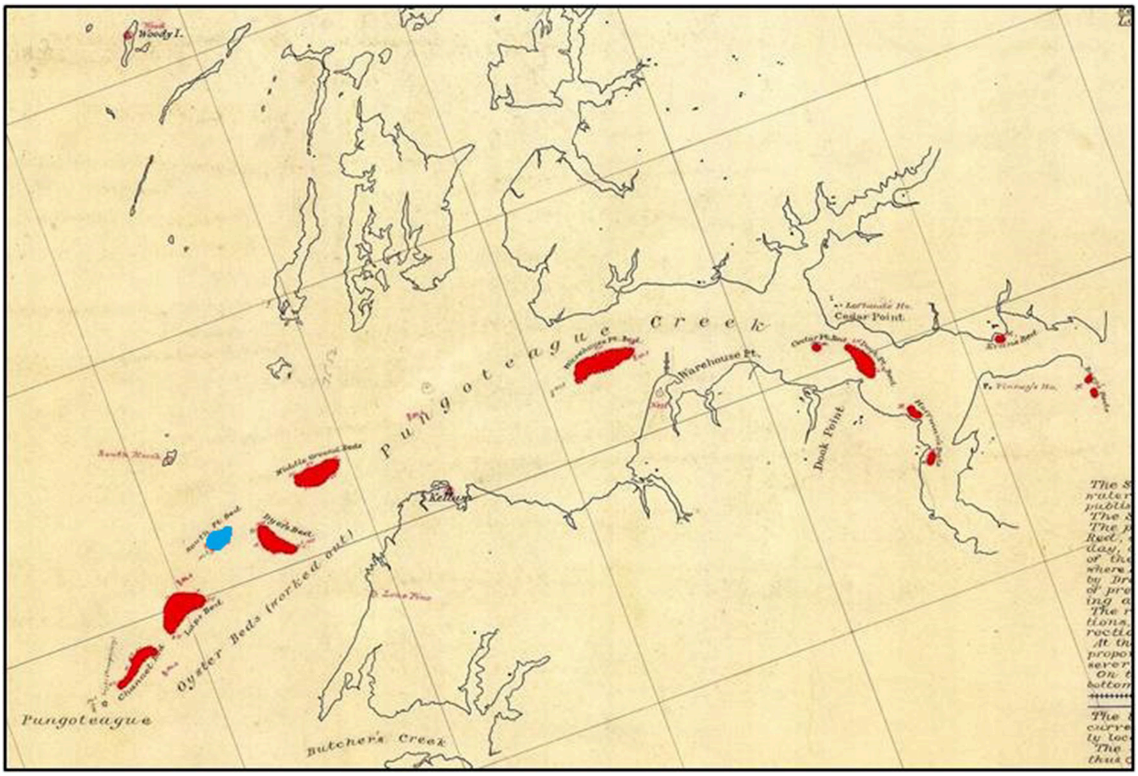

FIGURE 11 | Pungoteague Creek on Bayside Eastern Shore of Chesapeake Bay, showing loss of oyster habitat between 1881 (red areas) and 1981 (blue areas).

for seed plantings costs from \$6–30/bushel with the cheaper seed being produced on public oyster grounds and more expensive varieties produced on private leaseholds (\$12 USD/bushel) or hatchery produced (\$15–30 USD/bushel). The price of hatchery produced seed is falling and will likely continue to fall as hatchery capacity and technology is further developed in the Virginia region of the Bay. These repletion efforts in Chesapeake Bay have been analyzed in both Maryland (Cabraal and Wheaton, 1981; Herberich, 2006; Wieland, 2007) and Virginia (Santopietro et al., 2009) from an economic perspective and returns in recent decades for these subsidies have not been positive. This could change if the public ground harvest continues to increase, prices per bushel hold steady or decrease, and the price of shell remains modest compared to a similar volume of harvested live oysters.

The story of this fishery and associated disease impacts in recent decades are similar to the California abalone fishery (*Haliotis* spp.) where chronic wasting disease completed the decimation of abalone stocks after they were severely overfished (Moore et al., 2002) with water temperature increases (Lafferty and Kuris, 1993) being a driving factor in the initial expression of the disease and subsequent mortality (Chu et al., 1993). Similarly, water temperature increases in the mid-Atlantic have been implicated in oyster disease outbreaks (Soniat et al., 2009,?) as well as extension of oyster diseases northward along the North American coast as waters warm due to climate change (Cook et al., 1998; Hofmann et al., 2001). The disease epidemic plaguing the native oyster in Chesapeake Bay is part of a pattern seen in a wide variety of coastal and marine species in recent decades (Lafferty et al., 2004) and is inhibiting stock recovery of the Chesapeake Bay oyster, though there is evidence (Burke, 2010; Carnegie and Burreson, 2011) that disease mortalities in high-salinity populations of oysters in Virginia waters of Chesapeake Bay are developing resistance. The first Dermo epidemic caused a significant drop in oyster harvests from the public grounds, with a subsequent recovery that peaked at a lower level (**Figure 2**). This pattern repeats itself with MSX, and appears to be occurring again now with respect to the second Dermo epidemic as the public ground harvest is again showing signs of a significant recovery, although it is clear from this pattern that the overall trend is downward and relates to overfishing over time, with significant disease impacts further suppressing the stocks and harvest. Based on the observed pattern, harvests can be expected to increase further, though they will likely not exceed the numbers recorded prior to the MSX epidemic and remain below 500,000 bushels/year.

RECOMMENDATIONS

Considering the 1950–59 time period, the only time period in which the repletion program was shown statistically to augment the public oyster fishery, the following actions are suggested for the repletion program today if it continues. Only large scale efforts (>500,000 bushels/shells/year) have a chance at making a significant impact. Repletion, if done, should at least be this size annually. Current shell sources are being depleted. New sources of shell need to be identified, both from buried former reefs as well as out-of-state sources, such as mined pre-historic shell from terrestrial deposits in the Gulf of Mexico. Currently, rotational harvest schemes are being used in the Rappahannock River and Tangier/Pocomoke Sound, where in general, a harvest ground is only harvested every other year. It is unknown of this rotational method is helping enhance harvest at present, though a study done several years ago to assess the practice in the Rappahannock River (Santopietro et al., 2009) suggest it is not. Further study of the merits of rotational harvest is recommended. Disease dynamics are shifting to favor oyster survival (Carnegie and Burreson, 2011) and it is possible this rotational management may be helpful now. Studies have assessed the shell budget of reefs in Chesapeake Bay (Mann et al., 2009; Waldbusser et al., 2013) and found that current shell budgets on Chesapeake most of Bay oyster habitat are negative. Shell is being lost faster than it is being replaced, resulting in continuing habitat loss and constant maintenance of extant habitat via shell plantings. The abatement of disease, which is allowing for larger harvests in recent years, will be helpful to reverse this trend as older, larger oysters produce more shell. However, these are the same oysters targeted in the fishery. Additionally, recruitment is historically low in most of the Chesapeake Bay. The few exceptions, in the Great Wicomico, Lynnhaven, and Pianktank Rivers have been the target of large-scale restoration efforts with sanctuary reefs, free from fishing pressure (Schulte and Groth, 2005; Schulte et al., 2009; Chesapeake Bay Foundation, 2010; TNC, 2017) and a single area in the lower James River where oyster stocks have remained higher than all other harvested areas of Chesapeake Bay (Mann et al., 2009). Large-scale sanctuary projects have been demonstrated to increase local recruitment (Schulte and Burke, 2014), this suggests that sanctuaries can play a key role in stock restoration. Stock levels, if high enough, produce enough new shell to maintain and/or build habitat. Sanctuary reefs, appropriately placed and scaled to match the region they are meant to influence can greatly assist in reversing negative trends in stocks and shell budgets. Hydrodynamic models coupled with larval behavior should be used to determine distinct hydrologic units where restoration projects can be placed to influence a river or segment of the Bay. Once the size and local circulation is determined for these units, a properly-sized sanctuary, covering 20–40% of the historic public ground area in the unit, depending on the degree of larval retention, with areas of lower retention requiring larger sanctuaries than more retentive regions (USACE, 2012) can be built. Sanctuaries can then increase habitat and harvests, as well as ecological services provided by oyster reefs (Kennedy, 1996; Peterson et al., 2003; Coen et al., 2007; Grabowski and Peterson, 2007; Grabowski et al., 2012). While harvested areas can be built with thin layers of shells and re-shelled as needed, ideally enough oyster shell would be produced to sustain the habitat if harvest management measures, including rotation, allow enough time for shell accretion once recruitment is enhanced sufficiently. Sanctuaries should be built at higher relief from the bottom, at least 0.2 m tall, as this has been shown to enhance reef function, (Schulte et al., 2009) though they cost more to build initially than thin-shelled areas. Sanctuaries should also be protected by placing large stones randomly within them, to discourage poaching. The stocks should be better managed, with a fishery-independent survey sufficient to provide the data necessary to put a TAC (total allowable catch) in place for each sub-unit where fishing occurs. Most fishermen are older (76% age 40+) (Kirkley, 1997) and it is recommended that a cap on the total number of fishing licenses be put in place to partially restrict access to the fishery. Fishermen in isolated fishing communities, such as on Tangier Island, who are more dependent on fishing for income with fewer (if any) other options, should be preferentially offered licenses as other fishers retire, to help sustain these communities. Overall, though, effort should be made to shift as many fishers as possible to sustainable aquaculture, including cage and rack systems as well as floats, which is where most industry growth is now occurring (Murray and Hudson, 2011; Murray, 2013). Fishers can convert to aquaculture practices either as individuals or by forming co-ops where various tasks are divided up between different fishers, depending on skills. The great majority of the world's oyster production is now via aquaculture (NOAA, 2017), which is sustainable, and this should be encouraged in Chesapeake Bay.

Despite its long history and expectations of its continuance, the data suggests that the Virginia repletion program is neither cost-effective nor a reasonable means to restore the public commons wild oyster fishery (Herberich, 2006; Santopietro et al., 2009) to anything resembling prior levels without massive, ongoing financial commitments and extensive and continual use of dredged shell resources, which are not unlimited. Considering growing public awareness and concerns, culminating an executive order (Obama, 2009) and significant changes in Maryland (TNC, 2010), it is highly unlikely that the large subsidies required will be offered or sustained for any length of time and the future of the fishery will almost certainly be driven primarily by increases in sustainable oyster aquaculture output. Most (95%) of the world's demand for oysters is now being met by aquaculture (NOAA, 2017) which does not rely on destructive harvest practices on wild oyster reefs but instead reduces the need for such harvests. The Virginian oyster fishery should consider completing the transition from the hunter-gathering phase of oyster production to oyster farming, a far more efficient and less environmentally damaging means of oyster production. The ecology of Chesapeake Bay will be the better for it.

AUTHOR CONTRIBUTIONS

The author confirms being the sole contributor of this work and approved it for publication.

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Reconstructing the History and the Effects of Mechanization in a Small-Scale Fishery of Flores, Eastern Indonesia (1917–2014)

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The number of studies on small-scale fishing communities has grown considerably over the past 30 years. Evidence on how the process of mechanization and technological expansion has affected traditional small-scale fishers in peripheral regions, however, is less abundant. For areas like Eastern Indonesia that are now facing important challenges in governance and resource degradation, lack of information impairs the design of long-term environmental solutions. This article explores the changes in fishing participation and per capita seafood intake in a small-scale fishery in Flores, Eastern Indonesia over the past 100 years (1917–2014). By combining multiple sources of information (ethnographic, observational, nutritional, and historical) to reconstruct the story of stocks, fishing effort, and consumption of marine products, long-term trajectories, and trends in resource use practices are identified. Findings underline that mechanization and commercialization can have dire repercussions on food security and job stability within small-scale fishing sectors, especially if these processes are not part of comprehensive community development programs. The article concludes that understanding the outcomes of mechanization at the fringes of more centralized systems is essential to navigate the trade-offs among poverty reduction, economic growth, and environmental degradation.

Keywords: small-scale fisheries, development, mechanization, environment, historical ecology, nutrition

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INTRODUCTION

Understanding local patterns of resource use has become a priority for coastal and fishery managers (Staples et al., 2004; Charles, 2011; Bavinck et al., 2015). To identify characteristics that may impede participatory governance, researchers have begun to explore the challenges that fishing communities face as they transition through processes of industrialization, mechanization, and market integration (Andersson and Ngazi, 1998; Bavinck et al., 2013). Historically, the transformation of local fisheries is often a result of intensive technological and capital development

Abbreviations: BPSE, Badan Pusat Statistik Ende; The office for Statistical Information for Ende District. BPSN, Badan Pusat Statistik Nusa Tenggara Timur; The office for Statistical information at the Provincial Level of Nusa Tenggara Timur. DKP, Dinas Kelautan dan Perikanan; Endenese Fishing Commission. CPUE, Catch per Unit of Effort; MSY, Maximum Sustainable Yield; MSE, Maximum Sustainable Effort; REPELITA, Rencana Pembangunan Lima Tahun; Five year development plans introduced by the Indonesian Government.

promoted by government and non-government agencies (MacFadyen and Corcoran, 2002). Yet, mechanization and commercialization can have dire repercussions on food security and job stability within small-scale fishing sectors, especially if these processes are not part of comprehensive community development programs (Ahmed, 1992; De la Cruz Modino and Pascual-Fernández, 2013; Donkersloot and Menzies, 2015). For example, higher capture efficiency through gear substitution, motorization, and the rapid adoption of new fishing devices can deflate market prices, increase competition, and introduce conflicts of access forcing individuals to exit the fishery (Bailey et al., 1987; Muhammad and Susilo, 1995; Andersson and Ngazi, 1998). In order to enhance the understanding of the impacts associated with development and modernization, this article explores the changes in fishing participation and per capita seafood intake in a small-scale fishery in Flores, Eastern Indonesia in the past 100 years (1917–2014).

While the number of studies on fishing communities has grown considerably since the 1980s, evidence on how the process of mechanization has affected traditional small-scale fishers after major industrial and technological fishing expansion is less abundant (Ahmed, 1992; Chuenpagdee, 2011, p. 23; Pascual-Fernández and De la Cruz Modino, 2011). Furthermore, research on subsistence fisheries in tropical regions and the social and environmental trade-offs associated with economic development has concentrated in studying densely populated areas (Cribb and Ford, 2009). Vast productive regions of the Eastern Indian Ocean, such as Eastern Indonesia, being at the fringes of more centralized policies have received little to no attention (Fox, 2005; Fox et al., 2009; Tull, 2009; Christensen and Tull, 2014).

Despite lower demographic densities, dependence on natural resources in these areas can be high as large sections of the population are still engaged in subsistence farming, fishing, and animal husbandry (Barlow and Gondowarsito, 2009; Resosudarmo and Jotzo, 2009; Stacey et al., 2011). These areas are also characterized by widespread poverty, high rates of infant mortality, and low incomes, which has made them a target for state and international aid. The tendency of government and conservation programs to concentrate in a reduced number of hotspots such as Raja Ampat in Papua New Guinea, Komodo National Park in Flores, or Wakatobe National Park in Sulawesi, and the lack of effective enforcement makes Eastern Indonesia an attractive location for illegal fishing, mining, and logging operations (Varkey et al., 2010; Mangubhai et al., 2012; Wright and Lewis, 2012). Unfortunately, limitations in the scope of environmental management efforts have consequences for ecological diversity that transcend the local and provincial scale.

The main goal of this article is to reconstruct the historical trajectories followed by Endenese communities in Eastern Indonesia as a result of development and modernization policies that occurred predominantly in central regions of the archipelago. Building from historical ecology and ethnographic research, this study discusses fishing participation and the consumption of marine products before and after the implementation of provincial plans to incentivize production. Analyzing what causes changes in resource use, the article reflects on the repercussions of capital-intensive fisheries, technological modernization, and alimentary policies for communities on the fringes of economic and political centers.

A study of this nature contributes to the understanding of how practices and behaviors, albeit shaped by local policies, are also a byproduct of both the continuities and discontinuities in national and regional administration. It is contended that different patterns of development take shape as a dynamic expression of these realities and their effects at the household level (Allison and Ellis, 2001; Lenselink, 2002). Their history of resource use should be taken into account to generate new patterns of economic growth that are environmentally sustainable and do not exacerbate poverty (Béné, 2003; Allison and Kelling, 2009; Béné and Allison, 2010; Christensen and Tull, 2014). While considered peripheral in their geographical location, fishing communities like the Endenese are not isolated or disconnected from major economic centers (Wolf and Eriksen, 2010). Failure to capture these interconnections in policies and proposed governance solutions allows for the continuation of non-sustainable and illegal operations that have serious consequences for biodiversity conservation (Heazle and Butcher, 2007). As a consequence, fishery governance policies in Indonesia and other parts of the world will benefit from looking at the periphery to develop solutions across multiple geographical and institutional scales.

HISTORICAL RECONSTRUCTIONS IN DATA POOR FISHERIES

As shown by recent studies (Pauly and Zeller, 2014; Piroddi et al., 2015; Zeller et al., 2015), historical reconstructions can offer important lessons for future management policies seeking to modify local practices or to implement different systems of resource tenure. Rather than a definitive baseline, reconstructions represent an initial characterization of a fishery's production (Jacquet et al., 2010; Blythe et al., 2013; Pauly and Zeller, 2014). While many of these historical projections rely on official statistics, reports, and qualitative data such as interviews and anecdotal sources (Blythe et al., 2013), long-term observational or behavioral evidence is rarely available to correct retrospective estimates in data poor fisheries (Silvestre and Pauly, 1997). Additionally, reconstructions are often based on estimations of effort that do not consider the diversity of gear and capacity that a small-scale fishery might exhibit. This affects both the internal and external validity of findings, and constrains their implications.

In Eastern Indonesia, there are noticeable limitations on the coverage and quality of official statistics (Stacey et al., 2011). In the 1970s, the Indonesian central government imposed a general protocol for collecting fishery's information to address some of these issues (Bailey et al., 1987). The protocol is implemented unevenly at the provincial and regency level. For example, in Ende, the absence or lack of functionality of fishing auction offices has lead researchers to collect most measurements in regional markets. Measurements are then projected to calculate monthly and annual level figures. Estimations of yields often suffer from underreporting or the conflation of results with other regencies. Along with serious problems in consistency and transparency, in many cases the process behind estimations remains unknown.

Complementing historical information with behavioral research, this article has three objectives. First, the evolution of the small-scale fishery from 1917 to 2014 is reconstructed through the generation of time series of landings, fishing effort, labor, and seafood consumption at the district level. Second, annual estimates of landings and per capita fish consumption are formulated from observational, nutritional, and ethnographic data. Proposed estimates, which in the case of fishing households condense prolonged research and track seasonal changes and can help contextualize historical reconstructions from official data. Third, the article explores potential explanations for changes in fishing participation over time.

It is important to acknowledge that, given the lack of comprehensive records, reconstructed figures are preliminary. Suffering from limitations in terms of the measurement of effort and in the consideration of environmental factors, proposed reconstructions are corrected with systematic observations and extensive research on site. They represent an initial attempt at characterizing the production of the fishery and its significance in terms of production that can be of value to resource managers and scholars (Jacquet et al., 2010; Blythe et al., 2013; Pauly and Zeller, 2014).

METHODS

Study Site: The Endenese Fishery

The study area is in the District of Ende, Eastern province of Nusa Tenggara Timur, Indonesia (**Figure 1**). Limited to the south by the Savu oceanic basin and to the north by the Flores Sea, this area is known for its coral reefs and pelagic fishing grounds. In 2014, the population was 280,076 people ascribing to different ethnic groups including Bajau and Bugis immigrants (BPSE, 1984–2014). Small-scale fisheries in Ende operate under the local fishing commission, following district, provincial, and central government management rules. As a consequence of decentralization, fishing rights are defined at the village level for areas that are <2 miles offshore. With the exclusion of trawling (pukat harimau), dynamite, and cyanide, there are virtually no restrictions to total allowed gear or any rules about bycatch. Fishing licenses (surat perikanan) are required if operating beyond the district area (>12 miles) in other regencies like Manggarai or Komodo. Only a small fraction of fishermen (<5%) venture on weeklong trips to other regencies in search for sharks, snappers, or large tunas. Hence, the majority of fishing occurs along the shorelines and relies on canoes, small-motorized plank boats, or medium size purse seiners (<5 tons; Ramenzoni, 2015). In 2011–2012, the local fishing commission reported around 2,500 boats according to a census of fishing effort. Survey data from sampled communities for the same period indicates negligible differences with official reports in the number of active fishermen. According to questionnaires of fishing profile, the most prevalent fishing gear includes small gillnets (mesh size of 2.5–12 cm), troll lines, and hand line fishing. Common captured species comprise Scombridae, Clupeidae, Lutjanidae, Serranidae, and Carangidae families (Ramenzoni, 2013). While bigger fleets out of the ports of Kupang and Benoa, Bali, operate pole and line fishing vessels in the offshore regions of the Savu and Timor Seas and in the Indian Ocean (Stacey et al., 2011), Ende has no medium or large scale fishing industry. There is also no fishing

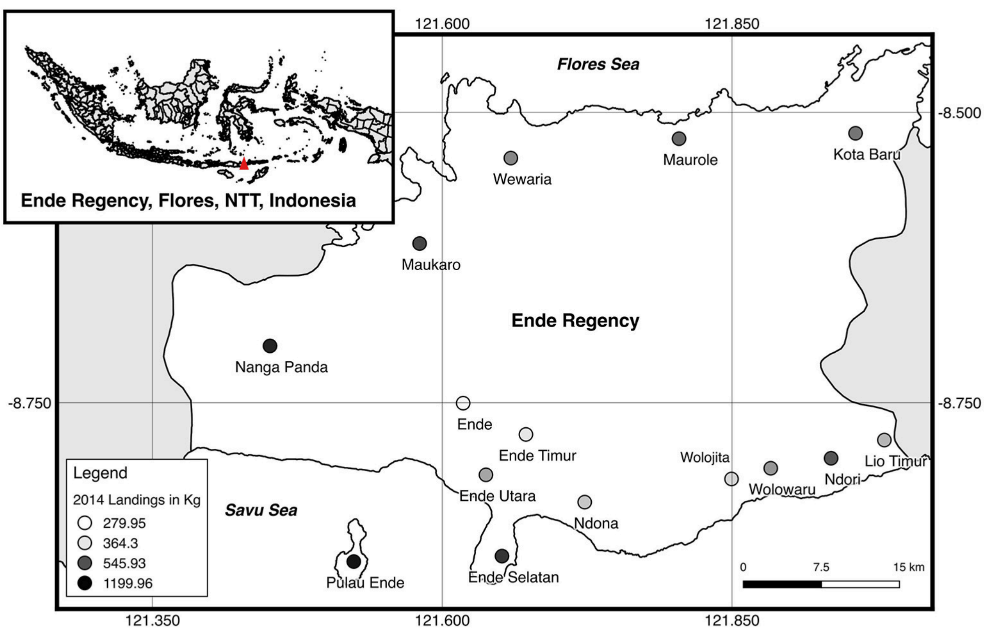

FIGURE 1 | Map of ende regency. This map shows the most important subdistrics in Ende regency and reported landings in 2014. Most productive subdistrics are Pulau Ende and Nanga Panda.

auction in the regency and refrigeration is very limited. Most of the catch is sold at the regional markets.

In the past years, conservation and transnational institutions have called attention to the high level of non-sustainable exploitation and resource degradation in the Savu and Flores Seas (Ingles et al., 2008; Munasik et al., 2011; Achmad et al., 2013). Fishermen have observed sharp reductions of fish populations, with benthic, elasmobranch, and coral species suffering a dramatic decline (Fox, 2005; Blaber et al., 2009; Tull, 2009; Christensen and Tull, 2014). The action of foreign vessels has been reported since the early 2000s, which may further compromise the integrity of marine stocks. In 2013, there were talks and provincial plans for establishing dedicated coastal zones for conservation and ecotourism, and for attracting investment to develop fishing industries and fishing cooperatives (Munasik et al., 2011). More information on the historical context affecting Indonesian small-scale fisheries can be found in **Table 1**. The table shows a transition between an extractive colonial regime mostly concentrated in agricultural development to a nascent democratic republic, a military regime, and finally a neo-liberal democracy. The management of the fisheries reflected the need for economically sustainable food sources in the context of a rapidly growing population, echoing major trends observed in other parts of the developing world.

Catch Reconstructions

Approach 1: Historical Data and Archival Sources

Data were collected during three field seasons in May–August 2009, November 2010–January 2011, and June 2011–January 2013. Research objectives, protocols for data collection, and instruments were reviewed and approved by the Institutional Review Board of the University of Georgia (IRB 2010-10808-2) before any activities begun. Research permits were also procured through RISTEK, the Indonesian government agency that oversees international research and from the proper authorities (Propinsi NTT, Kabupaten Ende). Authors followed strict ethical procedures as outlined by the IRB and have no conflicts of interest to report. Archival research was conducted in Ende and Maumere (Flores, Indonesia), in Yogyakarta and Jakarta (Java, Indonesia), at the Royal Tropical Institute (Koninklijk Instituut voor de Tropen) in Amsterdam and at the Catholic Archives at Radboud University in Nijmegen (The Netherlands). The main sources of district level statistical information were the Bureau of Statistics of Ende (Badan Pusat Statistik Ende or BPSE), the Bureau of Statistics of Nusa Tenggara Timur Ende (Badan Pusat Statistik Nusa Tenggara Timur or BPSN), and the Fishing Commission of Ende District (Dinas Kelautan dan Perikanan or DKP). These offices produce numerous yearbooks and reports that were complemented and consolidated to derive time series.

The processes of reconstruction for population, landings, effort, and labor were completed by adopting a similar approach to Palomares and Heymans (2006) (Zeller et al., 2006, 2007, 2015), Piroddi et al. (2015), and Pauly and Zeller (2014). Reconstructions were informed by archival research, literature reviews, and the combination of multiple data sets from local and provincial agencies and FAO FISHSTATJ. Anchor points extracted from sources, were used to interpolate missing data when information was not available. When assumptions were required, proposed values were highly conservative and corrected by consulting at least two historical sources. See **Tables 2, 3** for a description of data sources, anchor points, and estimations. Specifications are provided for particular years when calculations required adjustments. For example, **Table 2** presents information on demographic reconstructions while **Table 3** gives consideration to landings, effort, and number of active fishermen. In both cases, retrospective estimations are derived from anecdotal and colonial sources for the first half of the twentieth century; therefore, values should be considered as approximations. Information from neighboring districts such as Sikka and Kupang is used to control and extrapolate missing values. It is only at the beginning 1961 that official census data, local and regional statistics, and FAO reports become available. Figures from national, provincial, and district level sources such as BPSE and BPSN are reconciled by corroborating captures with yearbooks for other provinces. For more detail consult methodological annex.

Weights and transformations for reconstructions of landings, effort, and number of active fishermen.

To report landings and captures, the total amount of kilograms in tons is used without disaggregating by type of species or family. Capture is considered to be determined only by the level of fishing effort. Paucity of reliable meteorological datasets for the period before 1971 prevented the systematic consideration of environmental factors in reconstructions.

To standardize effort defined as number of boats, the different types of boats were weighted on the basis on their tonnage and potential optimal catch (Widodo et al., 2004). The estimation of catchability was very conservative and responded to observations of returns at the port of Ende (see Methodological Annex). To establish the effort for a year, weights were multiplied by the number and types of boats. The Catch per Unit of Effort or CPUE was calculated annually as the ratio between landings and effort.

Labor was operationalized as the number of fishermen including individuals with and without boats. To calculate the number of individuals fishing with boats (owners or crew members) the average sizes of crew by type of boat were used. Estimations of crew sizes derived from observations and historical sources (consult methodological annex and **Table 3** for more details). For fishermen operating without gear, a ratio of 0.60 to the total number of individuals operating with boats was initially implemented. This proportion reflected an estimate of gear (nets) to boats, and was adjusted throughout the series to reflect changes brought by military conflicts, mechanization, and intensification of effort.

Approach 2: Field Observations

From June 2011 until January 2013, the author resided in Ende and Pulau Ende where she conducted intensive ethnographic, observational, and ecological research with the aid of two local field assistants. In total 132 surveys and about 120 semi-structured interviews were carried out among active fishermen in the village of Ipy in Ende, and in Rendo Rate Rua, Ekoreko, and Meti Numba in Pulau Ende following purposive sampling techniques. During interviews, fishermen provided

TABLE 1 | Main historical events affecting a small-scale fishery through economic development programs and institutional policies in Ende, Nusa Tenggara Timur.

Period	Historical context and repercussions
1917–1929	• Colonial policies concentrate on agricultural development of coconut tree plantations. • Fishing activities in Ende are mainly for subsistence and at a lower scale than in other regions. Use of traditional gear.
1930–1940	• The1929's economic crisis inaugurates a period of famines. Decreases of 50% of 1,928 export volumes are reached in 1933. 1937 shows recoveries of exports to 80% of 1,928 volumes (Jones, 1966).
1941–1950	• Occupation from Japanese Army. • Japanese soldiers provided advice and taught local fishers how to use explosives. • Shipping was strictly controlled in the Timor seas. • General widespread shortage of boats after end of World War II. • Independence from Dutch government in 1945. Sukarno becames president and establishes the "guided democracy."
1951–1975	• Indonesia began reporting fish landings to the Food and Agriculture Organization of the United Nations (FAO) in 1950. • Important growth in effort, labor, and landings in late 1950s. Number of boats climbed 28% by 1955, and fishermen increased 40% by 1958 at national level (Krisnandhi, 1969). • Change dominated by "Static expansion," intensification of fishing mostly through traditional practices. • Beginning of large-scale trawling and purse seine operations in Western region of the archipelago. • 1967 military coup inaugurates the transition to the "New Order" with Suharto. • First REPELITA quinquennial economic development plan (1969–1974).
1976–1983	• Plans REPELITA II and III. • 1980 Trawling Ban. • Agricultural Ministerial Decree 607/1976 on fishing zones grants small-scale fisheries access to reserved coastal areas. • National Fishery Service develops plan to induce small-scale fishermen to motorize and modernize units (1975–1985). • In 1977 the fishing port of Kupang is built.
1984–1998	• REPELITA IV, V, and VI implemented. Efforts to increase seafood consumption and employment by creating subsidies and credit programs to fisheries, commercialization, distribution channels, and training. Mass credit programs in 1982 for mini purse seiners and gillnets in Wester Indonesia reach Eastern provinces in 1988. • Movement of exploitation toward the Eastern provinces of the archipelago. Fishing fleets based off Kupang began operating in the Savu Sea in 1991. • In 1985, the government opens the fisheries of the Indonesian EZZ to the participation of foreign vessels.
1999–2014	• Important policy changes. Decentralization of fisheries through Law No. 22/1999 (Local Autonomy Law) and later Law No. 32/2004. Agricultural Ministerial Decree 392/1999 establishes zones of exploitation based on vessel size and type. Inconsistencies emerge between these decentralization and licensing laws. • Use of large purse seine nets to capture large pelagic stocks in Flores and Savu seas is forbidden. • Fishermen and market vendors mentioned that about 15% of the catch sold at the market originates in other regencies. Inflows began around 2002. • Creation of a National Medium-term Development 2004–2009 plan aims at increasing and revitalizing fisheries, especially tuna, seaweed, and shrimp. • 2009–2014 Strategic Plan is passed. To empower fishermen, ensure food security, and to support the increase in marine capture at the level 0.5%/year until 2014.

information on fishing activities, seasonality, and historical and environmental changes in the fishery. Surveys allowed for a more systematic collection of data in relation to activity hours, gear used, average catch per season, catch sharing practices, income, and government or private support. In addition to fishing questionnaires and interviews, 113 households (adults) from two villages (Ipy and Rendo Rate Rua) were surveyed regarding their patterns of consumption of marine products. Weighing of portions and special foods was done with a 3,840 BLTBL™ Digital Nutritional Scale in Pulau Ende.

To monitor household fishing effort (the number of trips to capture fish) observations and voluntary diary logs were used at two villages (Ekoreko and Rendo Rate Rua) in Pulau Ende from September 2011 until July 2012 (10 months). The sample was balanced according to type of gear and data collection methods, with 20 fishermen being monitored daily by the main researcher and 20 individuals completing daily self-reports. Participants for self-reports were recruited after 8 months of residence, based on informally observed fishing frequency. Incentives for completing the logs were offered weekly during control visits and included fishing hooks, line, coffee, rice, and sugar. A total of 1,515 (766 canoe, 749 motorboat) fishing trips were recorded, including hour of departure, return, type of boat and gear, and total number of fish caught by species. Fish could not be weighted, as the catch would be sold at sea or right after return to port. In all cases, species were recorded in the local name and then identified with Reef Fish Identification Guides during focus groups and interviews with fishermen (Allen, 1999; Allen et al., 2005).

TABLE 2 | Anchor points and main sources used for estimating population figures from 1917 to 2014.

Period	Anchor points	Main sources
1915–1930	1915, 1917, 1924, 1930	Suchtelen and Leroux, 1921; Metzner, 1982; Dietrich, 1989; Ardhana, 2005; Nakagawa, 2006
1931–1950		Broek, 1940; Jones, 1966; Metzner, 1982; Nakagawa, 2006
1950–1960	1952, 1954	Nakagawa, 2006
1961–1971	1961, 1971, 1975	SUSENAS, 1984
1972–2014	1980, 1983, 1984, 1990, 1993–2000, 2001–2014	BPSE, BPSN annual reports (*Ende Dalam Angka* and *NTT Dalam Angka*) and subject reports (*BPSN-SP, 1984–2014; BPSN-SSK, 1984, 2002; SUSENAS, 1984*)

In addition to fishermen, 33 full time vendors were interviewed at the regional market to explore inflow of fish from other regencies and relations between offer and demand for seafood. Participants were recruited following purposive sampling techniques. It is estimated that this represents about 75% of vendors operating at any given time. The semi-structured interview tool included questions about the daily averages of fish sold according to size and species. Averages were requested in terms of units of fish and not in kg, and for small pelagic individuals vendors were asked about the approximate number of buckets commercialized daily. Other questions included fluctuations in catches, the presence of vendors from other regencies, and prices.

Finally, ecological research involved the monitoring of meteorological conditions. Two weather Davis Vantage Pro stations were placed in Ende and Pulau Ende by the main researcher. Measurements included temperature max and minimums, humidity, barometric pressure, wind direction and intensity, and lunar cycle and were taken from August 2011 to December 2012 every half hour. This information was used to reconcile effort data and to explain phases with no activity or low catches.

Projecting resource extraction

To estimate resource extraction for the district, primary data obtained through household surveys was combined with observations of fishing effort (1,515 events). It is assumed that fishing observations and survey results were representative of the whole fishing population (~7.000 fishing households; BPSE) in the area of study; and that fisheries were mostly artisanal and subsistence based. Because returns of observed fishing expeditions were in number of fish and not in kilograms, catch was disaggregated according to species and the units of fish captured were multiplied by each species average weight. In 2011–2012, 9% of the catch composed by varied demersal and benthic organisms, and 91% small pelagic and coral reef individuals. *Kembung*, also known as short or Indian mackerel (*Rastrelliger brachysoma*) was the most frequent species captured. A scombrid that inhabits shallow areas, *kembung* has an average weight that oscillates between 100 and 300 grams. A value of 200 grams was used as the standard weight per unit of fish. Also in 2011–2012, the mean CPUE estimated for small canoes was about 27.1 units of fish trip^{-1} day^{-1}. This brings about a mean estimate of 7 kg trip^{-1} day^{-1}. For motorboats, the mean CPUE was 49.8 units of fish trip^{-1} day^{-1}, or approximately a mean of 12 kg trip^{-1} day^{-1}. Results are very similar to estimates reported for Banggi subsistence and artisanal fisheries of Banggi, Malaysia (Teh et al., 2007, 2011). Annual captures are calculated by multiplying the mean observed CPUE of 2011–2012, 8.5 kg trip^{-1} day^{-1}, by the reported number of days fishing (19 days a month, with 9 months of operation, totaling 171 days a year). This figure was then, multiplied by the number of active fishermen for a particular year to obtain the total amount of catches in kg. The estimate provided a second measure to qualify historical reconstructions.

Projecting consumption of marine products

To approximate of the amount of marine resources consumed by Ende, annual estimates of fish consumption were generated for both fishing and farming households (**Table 4**). Per capita annual consumption in fishing households was estimated through observations from nutritional surveys conducted in 2011–2012 among Endenese fishing households. Surveys assessed the frequency of fish consumption by main species per week and season and fish portion sizes. For farming households, estimates were derived from the 1984 national social survey (*SUSENAS*; BPSN, 1984–2014) and from nutritional research conducted in the regency in the early 1990s (Reinhard, 1997). In order to back cast rates to 1917, estimates were calculated with national per capita fish intake indices from FAO as well as academic and anecdotal sources. To elevate these values to the population level, intake estimates were multiplied by the number of farming and fishing households present in the area (see Annex).

Projected reconstructions have several limitations. For example, lack of reliable data of catch compositions from 1917 to 1984 prevented the inclusion of changes in consumption levels of different fish species that probably affected overall consumption patterns. In addition, changes in annual per capita intake and other measures were modeled in a linear way. Finally, surveys with vendors from the regional fish market of Mbongawani, Ende, were used to provide context on the offer and demand of fish products. All datasets supporting the conclusions of this article are included within the article and its additional files.

Data Analyses

All statistical analyses were conducted in JMPro 11. Simple correlation, regression, and exploratory cluster analyses were used to approximate the relation between changes in landings, effort, labor, seafood consumption levels, and population figures for the period 1951–2014. The years between 1917 and 1950 were not included in these analyses as reconstructions were based on extrapolations of numbers of fishermen and demography. Landings were log- transformed to reduce skewness in the

TABLE 3 | List of estimations and evidence used to reconstruct effort, landings, and number of active fishers from 1917 to 2014.

Period	Factors	Anchor points	Estimations and adjustments	Sources
1917–1929	Labor force	1917	• Labor or the number of active fishermen, is estimated in relation to type of gear and vessel size. • Projected increase of effort and labor force of 1.5% annually from 1917 to 1929[a,b].	• Suchtelen and Leroux, 1921; Dietrich, 1989; Ardhana, 2005; Koloniaal Verslag van 1908, 2015 • Roos, 1872, 1877; Koloniaal Verslag van 1921, 2017; Koloniaal Verslag van 1908, 2015 • Broek, 1940
	Landings	No	• Landings are estimated using annual average capture per fisher multiplied by labor force. Annual average is the mean of three rates: 547 kg (Pekalongan in1880s and early 1950s); 510 kg (Molukas, 1960s); and 460 kg (Nusa Tenggara 1950s).	• Veth, 1855; Roos, 1877; Weber, 1890, 1903; Suchtelen and Leroux, 1921 • Burhamzah, 1970; Partadireja and Makaliwe, 1974; Semedi, 2003
1930–1940	Labor force and Effort	No	• Number of fishermen estimated in relation to type of gear and vessel size. • A general 3% annual increment in the labor force is projected for the decennial, with an additional 2.5% increment in effort for the period 1930–1933.	• Ardhana, 2005; Kartika, 2009 • Broek, 1940 • Jones, 1966
	Landings	No	• Landings are estimated through labor force and average annual capture.	
1941–1950.	Labor force and Landings	No	• Landings are estimated through the labor force and average annual capture. Number of fishermen estimated in relation to type of gear and vessel size. • Decrements of 50% from 1941 to 1945 given WWII. • Progressive recovery to pre-war levels in 1951.	• Krisnandhi, 1969; Bailey et al., 1987; Roch et al., 1995; Butcher, 2004 • Krisnandhi, 1969; Dick, 1987; Stacey et al., 2011
1951–1975	Labor force	1961	• Labor force and effort derived from landings (1951–1960). • Increase of 28% in 1961 is projected to accommodate changes in landings and national labor and demographic trends. • After 1961, increases in the labor force account for changes in landings, effort, and changes in average capture by gear type.	• Kennedy, 1955; Brand, 1968, 1969; Krisnandhi, 1969; Burhamzah, 1970; U.S. Department of Commerce, 1977; FAO, 2015b • Roch et al., 1995 • Partadireja and Makaliwe, 1974 • Jones, 1966
	Landings	No	• Introduction of new technologies in Indonesia is accommodated with a lag of 5 years[c]. • Captures showed significant increments in 1961, 1966, 1969, and 1975. • Improvements in landings and changes in technology are incorporated gradually to reach an annual capture per fisherman of 750 kg in 1975[d].	
1976–1983	Labor force and Effort	1984–1988	• Rate of growth in number of boats and number of fishermen is derived from 1984 to 1988 by type of boat. Rate is applied backwards to estimate number of boats and the amount of fishermen operating without gear. • Decreases in the number of younger members of the population engaged in fishing are expected due to cohort effects and migration[e]. • Estimates are also adjusted to reflect incipient mechanization and changes in average capture by gear type[f]. Important changes are observed in annual capture per fisherman (mean for the period is 2.2 tons).	• BPSE, BPSN annual reports, and subject reports. • Burhamzah, 1970; Partadireja and Makaliwe, 1974; Bailey et al., 1987; Roch et al., 1995; Satria and Matsuda, 2004; Satria, 2009 • Jones, 1966

(Continued)

TABLE 3 | Continued

Period	Factors	Anchor points	Estimations and adjustments	Sources
	Landings	1975–1983	• Numbers of Total Fishing Domestic Product fixed at constant prices for 1975 are used to reconstruct landings from 1975 to 1983.	
1984–1998	Labor force and Landings	No	• Statistical information from the local district and the provincial level are harmonized to recreate the number of boats and landings in Ende from 1984 to 1999.	• BPSE, BPSN annual reports, and subject reports. • Bailey, 1987; Susilowati, 1996; Heazle and Butcher, 2007; Sunoko and Huang, 2014
1999–2014			• Statistical information from the local district and the provincial level are harmonized to recreate the number of boats and landings in Ende from 1999 to 2014.	• BPSE, BPSN annual reports, and subject reports. • Satria and Matsuda, 2004; Barlow and Gondowarsito, 2009; Resosudarmo and Jotzo, 2009; Satria, 2009; Stacey et al., 2011

[a]*Rate of increase in effort is approximated given the changes in agricultural production and exports and demographic growth for the period.*

[b]*Changes in subsistence practices to minimize risks is a common strategy among fishermen and foragers around the world (Cashdan, 1990; Andersson and Ngazi, 1998; Tucker, 2007; Tucker et al., 2011).*

[c]*To reflect delays in the introduction of new initiatives in Eastern Indonesia, the change in fishery inputs is lagged 5 years (Butcher, 2004; Zeller et al., 2015).*

[d]*Around 1970, East Nusa Tenggara reaches 22,900 fishermen; 460 kg annual capture. West Nusa Tenggara reaches 15,900 fishermen; 1.28 kg annual capture. These two figures are averaged to estimate improvements in annual capture rates in Ende.*

[e]*Cohort effects are demographic effects resulting from changes in the age structure of the population. In this case, effects respond to an increase in babies born after WWII and conflicts of Independence. By 1975, a steady rise in the share of middle aged (25–44 years of age) in the working population is a natural effect of the changes of the previous decennials (Jones, 1966, p. 66).*

[f]*Although no evidence is available in district level documents, the years in between 1975 and 1983 showed important increases in landings suggesting the introduction of new gear. Individual capture rates were modified to reflect changes in technology (Bailey et al., 1987, p. 83).*

TABLE 4 | List of parameters, weights, and evidence used to reconstruct consumption of marine products from 1917 to 2014.

Period	Parameters and estimations	Weights	Anchor points	Main sources
1917–1940	Per capita annual intake of fish in Java and relation to Outer Islands[a].	1.88	1917	Krisnandhi, 1969; Creutzberg et al., 1987
		Average change of −0.03 per year	1927–1930	
		Average change of +0.02 per year	1931–1939	
		Average change of −0.01 per year	1940–1945	
		Average change of +0.05 per year	1946–1950	
	Number of fishing households.	20.395	1924	
1950–2013	Per capita annual intake of fish products in faming households[b].	∼9.5 kg for farming households in 1993–1994	1993–1994	SUSENAS, 1984 (BPSN); Reinhard, 1997; FAO, 2015a
	Per capita annual intake of fish products in fishing households.	∼46.2 kg	2011–2012	Own observations
	Number of fishing households.	45.436	2006	Nakagawa, 2006; BPS Ende; BPSE
		45.973	2010	

[a]*Anecdotal information and nutritional publications were used to approximate values for the years 1917–1940.*

[b]*For the period 1950–2013, per capita rates provided by FAO Food Sheets were used (FAO, 2015a) and adjusted according to population changes.*

data. To further study behavior and accuracy of reconstructions, paired-samples *t*-tests were used. First, the changes in the number of fishermen through time were evaluated through point analysis. Moving averages were calculated to smooth changes between individual data points, and the data series was partitioned into two periods for comparison (1951–1964 and 1965–1984). Second, the similarity between historical reconstructions of landings based on sources and official statistics and projections derived from observational data was assessed. In this second comparison, the series was also divided into two smaller temporal levels (1975–2014 and 1951–1975) to compare the performance of different individual annual catch rates.

The Maximum Sustainable Yield (MSY) and Maximum Sustainable Effort (MSE) for the period between 1975 and 2014 were calculated to evaluate the state of stocks and potential excesses in effort. The time period chosen responds to the quality and reliability of data. Information about landings was obtained from provincial and district level reports and no historical reconstructions or projections were included. In order to approximate demersal and neritic productivity to evaluate the state of the stocks, Dalzell and Pauly's log-linear models (Dalzell and Pauly, 1990; Tomascik et al., 1997) were applied. Through spatial statistical analysis primary productivity from 2011 to 2012 and bathymetry values were extracted for an area of 45 km from the port of Ende. The threshold of 45 km was selected as the maximum distance fishing boats might travel in one single trip given technological limitations (Semedi, 2003). It is assumed that, if oceanographic conditions were the same or better, MSY and MSE figures might reflect the potential productivity of fishing grounds in the early 1900s. Equation parameters can be found in Methodological Annex.

RESULTS

Historical Reconstructions: Changes in Landings, Effort, and Labor

Total capture by Endenese fishermen from 1917 to 2014 was estimated at 342,561 ± 2,573 tons. The values for the reconstructed time series can be found in **Table 5**.

Estimations of Ende's productivity for demersal and pelagic species, and including only Savu's fishing grounds, are placed around 5,900 tons a year at best biological levels. Considering this figure as a proxy measuring the sustainability of the fishery, it is possible to hypothesize that exploitation was not intense from the first decades of the 1900s and into the early 1980s. Annual mean captures fell between 2,290 ± 1,600 tons. In 1989 reconstructions indicate that stocks might have been intensively exploited or exploited beyond sustainable limits. Effort and capture numbers exceed the parameters recommended by the Schaeffer MSY model (**Figure 2**). Through the mid-1990s and early 2000s, catches showed important oscillations reflecting an overall mild increasing trend. The increment, however, is not proportional to the changes in effort, which might suggest an overall excess of boats. The decrease in catch per unit of effort between 1990 and 1985 is about two and a half times.

Observations of decreases in productivity are also supported by conversations and interviews with fishermen and market vendors. While changes in captures and landings were often discussed, fishermen also mentioned a modification in targeted species in the 1990s and 2000s. This shift was toward small pelagic stocks like mackerel tuna (*Euthynnus affinis*), skipjacks (*Katsuwonus pelamis*), sardines and anchovies (Clupeidae families), and scads (Carangidae families), and responded to the reduction of captures of large tunas and elasmobranchs, along with oscillations in the capture of reef and demersal species.

Concerning efficiency in captures, the reconstructed series of annual catch rates shows that individual productivity was relatively low until the beginning of the 1970s (**Figure 3**). The peak in fishing catch rates occurs in 1984, when the number of boats is 851 and the number of active fishermen is smaller in comparison to previous decades (BPSE). In 1989, the number of boats increases several orders along with the number of fishers. Individual productivity, however, falls back to early 1970s' values. The following years bring a steep increase in catch rates, that peaks in 2003 and decreases again toward 2014, when annual individual productivity is 1,134 kg. The catch per unit of effort

TABLE 5 | Reconstructed time series of effort, landings, population, and number of active fishers at the regency of Ende, Flores, province of Nusa Tenggara Timur, Eastern Indonesia.

Year	Effort[a]	Landings[b]	Population	Fishers
1917	216	717,035	68,653	1,418
1918	219	751,930	69,771	1,487
1919	222	786,814	70,890	1,556
1920	226	821,709	72,008	1,625
1921	229	856,593	73,127	1,694
1922	233	891,487	74,245	1,763
1923	236	926,382	75,364	1,832
1924	240	961,266	76,482	1,901
1925	243	996,160	77,601	1,970
1926	247	1,031,044	78,719	2,039
1927	251	1,065,939	88,314	2,108
1928	254	1,100,834	97,910	2,177
1929	258	1,135,718	107,505	2,246
1930	265	1,169,789	117,100	2,313
1931	271	1,210,732	117,639	2,394
1932	278	1,253,107	118,177	2,478
1933	285	1,296,966	118,716	2,565
1934	289	1,302,844	119,254	2,576
1935	294	1,308,732	119,793	2,588
1936	298	1,314,621	120,332	2,600
1937	302	1,320,498	120,870	2,611
1938	307	1,326,387	121,409	2,623
1939	312	1,332,265	121,947	2,635
1940	316	1,338,153	122,486	2,646
1941	291	1,231,101	123,025	2,435
1942	265	1,120,302	122,486	2,215
1943	238	1,006,942	122,688	1,994
1944	214	906,248	122,890	1,795
1945	187	788,436	123,092	1,561
1946	200	843,626	123,294	1,671
1947	214	902,680	123,496	1,787
1948	229	965,868	123,698	1,913
1949	245	1,033,479	123,900	2,046
1950	262	1,105,822	129,807	2,190
1951	279	1,271,300	135,713	2,332
1952	286	1,437,900	141,620	2,397
1953	295	1,480,400	143,712	2,467
1954	307	1,591,000	145,804	2,566
1955	313	1,623,800	146,322	2,619
1956	318	1,651,200	146,841	2,663
1957	310	1,605,900	147,359	2,590
1958	320	1,660,400	147,878	2,678
1959	307	1,592,600	148,396	2,569
1960	315	1,636,900	148,915	2,640
1961	404	2,083,800	149,433	2,977
1962	420	2,145,700	152,423	3,065
1963	449	2,208,300	155,413	3,155
1964	503	2,334,100	158,402	3,334
1965	574	2,637,800	161,392	3,768

(Continued)

TABLE 5 | Continued

Year	Effort[a]	Landings[b]	Population	Fishers
1966	551	2,980,100	164,382	4,257
1967	557	2,732,300	167,372	4,120
1968	563	2,906,000	170,362	3,983
1969	570	3,143,400	173,351	3,845
1970	576	3,251,500	176,341	3,708
1971	582	3,291,800	179,331	3,571
1972	589	3,345,400	179,755	3,434
1973	595	3,527,000	180,179	3,296
1974	601	3,762,100	180,602	3,159
1975	608	3,814,700	181,026	3,022
1976	614	4,148,200	192,113	2,884
1977	620	4,630,100	202,613	2,747
1978	627	4,883,700	198,593	2,610
1979	633	5,514,000	202,752	2,472
1980	639	5,456,300	201,609	2,335
1981	646	6,081,100	204,090	2,198
1982	652	6,191,800	206,571	2,061
1983	658	4,856,100	209,053	1,923
1984	665	6,183,500	214,015	1,786
1985	670	4,958,600	214,605	1,803
1986	674	5,320,400	215,213	1,816
1987	679	5,432,800	215,820	1,839
1988	650	5,447,700	216,428	1,685
1989	2,696	5,715,100	217,635	6,211
1990	2,629	6,483,400	218,841	5,921
1991	2,638	6,126,000	221,000	5,930
1992	2,405	6,457,800	222,012	5,307
1993	1,406	5,241,600	224,900	3,424
1994	1,453	6,790,100	226,500	3,700
1995	1,619	6,049,800	228,000	4,022
1996	1,213	6,032,700	229,400	3,173
1997	1,335	6,120,200	230,700	3,504
1998	1,722	7,060,400	231,800	4,276
1999	1,730	7,200,100	232,600	4,305
2000	1,638	7,250,200	232,270	4,127
2001	1,638	7,345,100	237,156	4,127
2002	2,271	10,974,700	234,579	5,633
2003	1,251	10,603,800	238,486	3,463
2004	1,262	4,174,000	241,826	3,442
2005	1,256	5,357,000	241,929	3,441
2006	1,667	6,102,000	237,555	4,431
2007	1,243	5,669,700	238,040	3,183
2008	1,797	5,801,300	238,127	4,825
2009	1,945	6,305,300	238,195	4,882
2010	2,443	7,125,900	260,605	6,466
2011	2,496	7,565,500	265,761	6,578
2012	2,496	7,868,500	267,262	6,578
2013	2,719	7,988,700	278,538	6,932
2014	2,800	8,210,940	280,076	7,178

[a] *Effort is a standardized measure representing here the number of active boats. The figure is weighted to reflect differences in types of boats based on tonnage and potential optimal catch. See **Table 2** for specifications.*
[b] *Calculated in kilograms.*

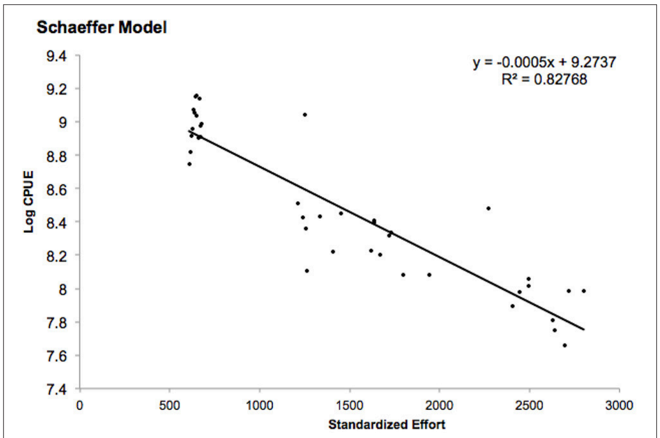

FIGURE 2 | Schaeffer model. The regression line explains the association between the log of catch per unit of effort (CPUE) and effort. As effort increases, the log of CPUE decreases. The linear fit is highly significant, with an Adjusted R^2 of 0.82. The recommended maximum effort is 1,843 units of boats. The Maximum Sustainable Yield is estimated at 7,223 tons.

shows a similar behavior, with steeper increments in 1984 and more pronounced declines in the 2000s (**Figure 3**). Overall, both measures indicate a decreasing trend for the past 30 years and provide further evidence of intensive exploitation of stocks.

The number of active fishers, or the labor force (**Figure 4**), exhibits a somewhat linear increase in reconstructions from 1917 to the early 1940s, and then from 1945 to the mid-1960s. In 1965 the working force averages 4,000. This figure reflects important increases in the number of fishermen at the national level as well as the impacts of population recovery and higher fertility rates after the war. The inference is substantiated in government documents, reports, and academic articles from the 1950 and 1960s that indicate important changes in the structure of age cohorts, mechanization, and landings in the country. The first year for which official statistics are available on labor composition in the district is 1984. Then, about 1,800 people seem to be participating in the fishery.

If comparing the two temporal markers, between 1966 and 1984, a 60% reduction in the working force seems to occur. As it will be discussed later, this sharp contraction can be an effect of overestimation errors given the use of anchor points, extrapolations from other regencies, and anecdotal evidence during the reconstruction. It can also be a factor of source accuracy and of changes on how statistics were reported at the district, provincial, and national levels. Another hypothesis that will be presented later is that the contraction of the labor force can be explained by the nature of the mechanization process in Ende. This speaks of a lack of policies directed at small-scale sectors of the fishery, of the instability in the job market, and of a complex scenario of demographic changes and migration.

After 1989, marked oscillations occur in the number of individuals participating in the fishery. Data points for this period are derived from official reports at the district and provincial levels with few inconsistencies (BPSE). When comparing the most recent decades against the reconstructions for the decennials 1950s, 1960s, and 1970s and for the early years of

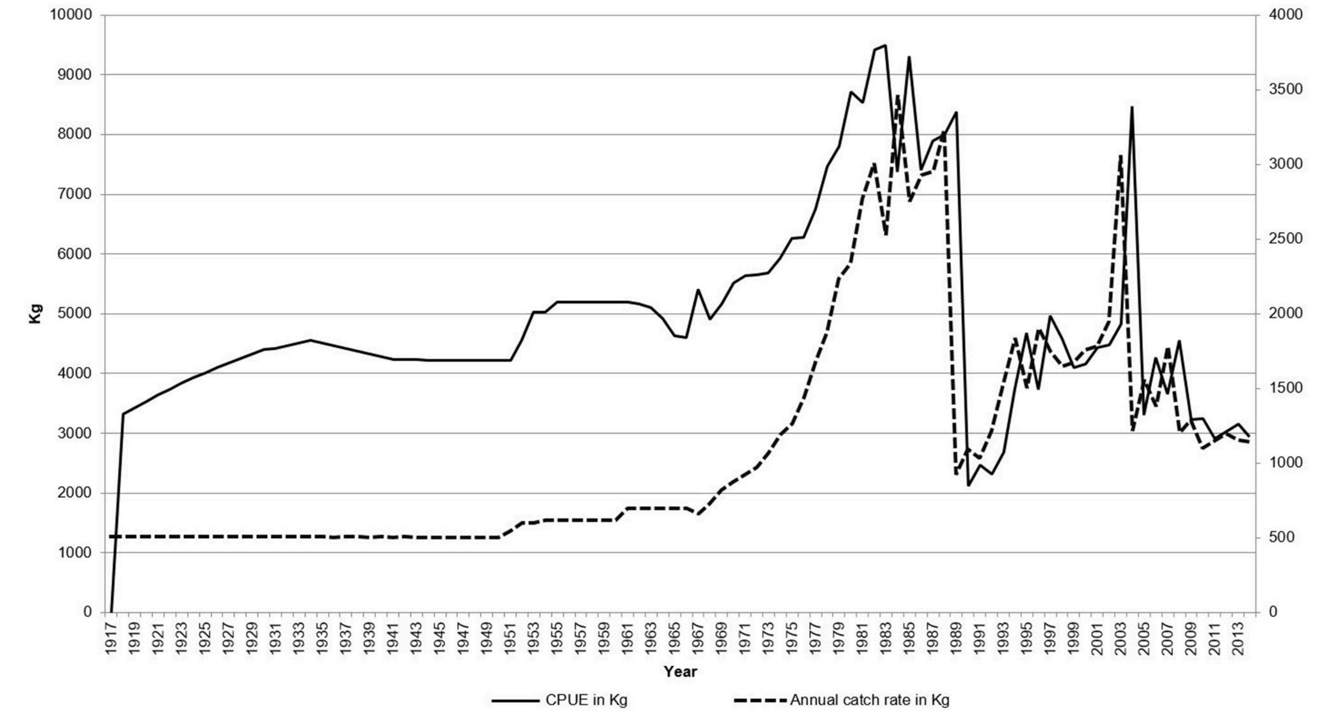

FIGURE 3 | Time series of annual catch rates and CPUE. Chart shows the evolution of catch rates (annual landings divided by number of fishermen) and CPUE (catch-per-unit of effort; landings divided by standardized number of boats) for the period 1917–2014. Observe that both reconstructed measures peak in the mid-1980s, to decline in early 1990s. A second peak occurs in early 2000s.

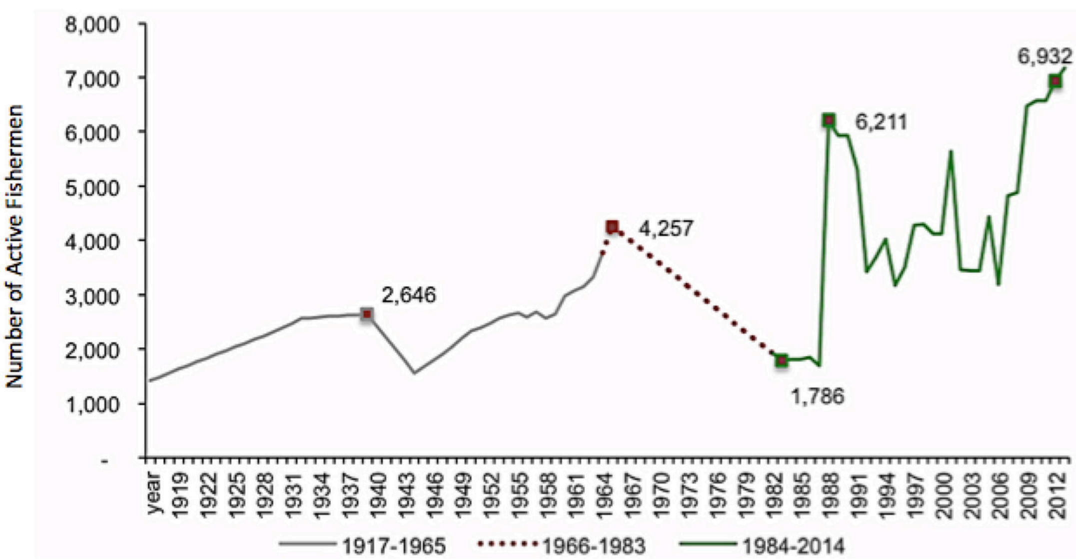

FIGURE 4 | Time series of numbers of active fishers as reconstructed by historical data. The curve shows a bimodal distribution (Normal Mixture), with a potential change in moving averages occurring in the mid-1980s.

1980s, a change can be observed in how the number of fishermen evolves over time. If the period is divided into two smaller equal sections (1955–1984, 1985–2014), and moving averages for each section are analyzed with a T-test for paired samples, differences are found to be significant ($T = 4.00$; $p = 0.0004$). Barring problems with accuracies in the reconstruction, the differences between the two temporal sections indicate that the number of jobs became even more unstable or variable after 1989.

TABLE 6 | Reconstructed time series of Per Capita seafood consumption and total consumption for Ende regency, Flores, province of Nusa Tenggara Timur, Eastern Indonesia.

Year	Per capita[a]	District consumption[a]
1917	9.39	644,585
1918	9.39	655,201
1919	9.39	665,825
1920	9.39	676,441
1921	9.4	687,065
1922	9.4	697,681
1923	9.4	708,305
1924	9.4	718,921
1925	9.4	729,545
1926	9.4	740,157
1927	8.9	785,997
1928	8.61	842,932
1929	8.27	889,384
1930	8.15	953,795
1931	9.49	1,116,966
1932	9.64	1,138,927
1933	9.78	1,161,586
1934	9.78	1,166,706
1935	9.78	1,172,061
1936	9.78	1,177,417
1937	9.91	1,197,319
1938	9.91	1,202,741
1939	10.09	1,230,532
1940	9.78	1,198,369
1941	8.78	1,080,260
1942	7.01	858,544
1943	5.88	721,133
1944	5.62	690,237
1945	5.31	653,789
1946	6.19	763,526
1947	6.61	816,598
1948	7.06	873,350
1949	7.53	933,393
1950	7.58	984,450
1951	7.24	982,261
1952	7.71	1,092,026
1953	7.64	1,098,441
1954	7.73	1,127,129
1955	7.79	1,139,967
1956	8.2	1,203,765
1957	7.96	1,173,268
1958	7.59	1,122,956
1959	7.67	1,138,589
1960	7.7	1,146,228
1961	10.03	1,498,521
1962	9.98	1,521,606
1963	9.73	1,511,546
1964	10.14	1,606,040
1965	10.83	1,747,288
1966	12.04	1,979,532
1967	11.45	1,915,874
1968	10.81	1,841,859
1969	10.71	1,855,965
1970	10.36	1,826,338
1971	10.01	1,795,684
1972	9.74	1,751,344
1973	9.5	1,710,832
1974	9.52	1,719,806
1975	9.38	1,698,843
1976	9.4	1,805,438
1977	9.39	1,903,164
1978	9.38	1,862,101
1979	9.36	1,898,101
1980	9.53	1,921,606
1981	9.48	1,933,851
1982	9.36	1,933,606
1983	9.69	2,024,990
1984	9.67	2,069,873
1985	9.79	2,100,599
1986	9.97	2,145,309
1987	10.09	2,177,977
1988	10.2	2,207,287
1989	15.33	3,337,032
1990	14.81	3,241,646
1991	14.92	3,297,868
1992	14.82	3,289,607
1993	12.98	2,919,815
1994	13.81	3,127,402
1995	14.5	3,305,200
1996	13.95	3,201,045
1997	14.66	3,381,087
1998	15.84	3,672,613
1999	16.29	3,789,700
2000	16.61	3,858,001
2001	17.03	4,038,502
2002	19.13	4,487,259
2003	16.51	3,936,972
2004	16.73	4,046,620
2005	17.2	4,160,337
2006	18.97	4,507,339
2007	17.92	4,265,946
2008	19.34	4,605,329
2009	19.77	4,708,673
2010	20.81	5,422,489
2011	20.03	5,321,903
2012	20.65	5,517,740
2013	21.38	5,955,905
2014	22.27	6,237,529

[a]*Calculated in kilograms.*

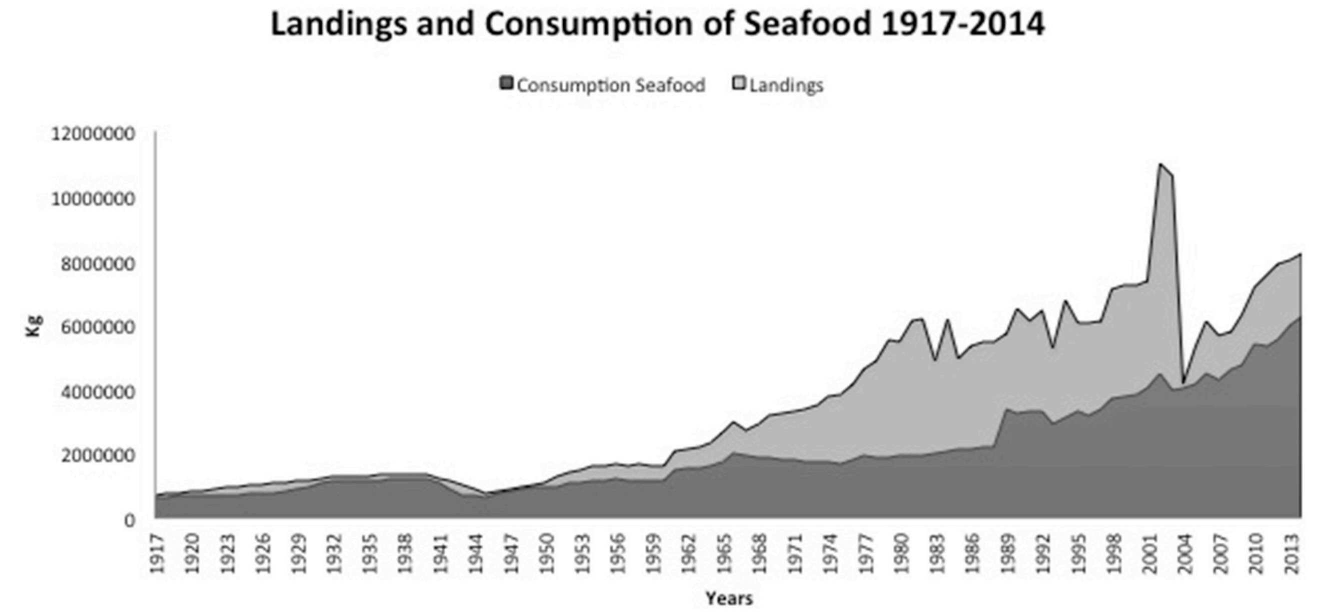

FIGURE 5 | Landings and Consumption of Seafood from 1917 to 2014. Consumption of seafood and fish derived products increased in a continuous trend from early 1960s and reached 22 kg in the 2010s (see **Table 4** for details).

Reconstructions of consumption of marine products: changes in per capita intake of seafood and market demand

Total consumption of seafood for the district is estimated at 201,300 ± 1,400 tons from 1917 to 2014 with average per capita fish consumption of 11.2 ± 4 kg per year (**Table 6**, **Figure 5**). The average is slightly inferior to estimates reported for Pacific Island countries (Zeller et al., 2006, 2007). This is not unusual, as Endenese fisheries have remained at subsistence levels. Only a much-reduced proportion of captures is destined to exports and this includes demersal and coral fisheries as well as elasmobranch products. Changes in fish intake have most likely occurred with modifications in catch per unit of effort over time and economic programs. The most critical developments influencing fishing households seem to have taken place after the 1960s and 1970s with the intensification of effort, increases in catch rates and landings, and the reduction of prices for fish products (BPSN). Farming households also began to incorporate seafood regularly into their diets with changes in roads and infrastructure along with health and nutritional programs.

Interviews with market vendors showed that, on any given day, the demand for seafood was capable of absorbing, and sometimes exceeded, offer. The market brings together about 125 vendors a day, a large fraction of which depends on partners from other towns to obtain fish. On average, five trucks a day (load of 350 kgs) come from the neighboring regencies of Sika (Sika and Maumere) and Nanga Keo (Bajawa). A conservative approach suggests that ∼15% of what is reported as sold could have originated in other regencies. This inflow of fish started about 10–12 years ago and may correspond to the high levels of fluctuation in landings experienced in that period. Finally, it should be noted that even when total captures are growing, landings for some species have declined. For example, market vendors mentioned that small tuna and sardine are among the species most frequently sold, while on average, only 1 unit and a half of large size fish is commercialized per vendor per day.

Historical reconstructions vs. observed effort

To evaluate how historical reconstructions of landings matched retrospective projections for 1950–2014 based on observed effort, T-tests for paired samples were used (**Table 7**). Comparisons did not include the period between 1917 and 1949 as both reconstructed series relied on number of active fishermen to calculate landings. However, starting 1950, historical reconstructions built from FAO datasets and provincial or local statistics, while retrospective projections interpolated captures by multiplying observed annual capture by number of fishers per year (see Section Methods). For the most recent period spanning from 1975 to 2014, no differences were found between historical and observed reconstructions relying on an average capture of 8.5 kg trip^{-1} day^{-1}. While there is an absolute difference of 81,826 kg between the means of both groups, the T-test reports a non-significant difference and a 0.54 correlation. For 1950 to 1975, the comparison of historically reconstructed landings and observed landings with an annual capture average of 4.75 kg trip^{-1} day^{-1} has a correlation of 0.73. The T-test is also non-significant (DF: 24) and the absolute difference between the two means is 152,589 kg. Overall, these results seem to indicate that a change of annual average captures per fisher per trip occurred in the late 1960s, early 1970s. The lower correlation in 1975–2014 between the two series could be a reflection of the oscillation in landings as shown in the data, as well as instability in individual capture rates.

TABLE 7 | Comparisons between reconstructions and observed effort.

Period	Mean reconstructed	Mean observed	Statistics
1950–1975	2,388,616	2,541,205* *at 4.5 kg $trip^{-1}$ day^{-1}	*T*-test is non-significant DF: 24 Correlation: 0.73
1975–2014	6,263,471	6,345,297* *at 4.5 kg $trip^{-1}$ day^{-1}	*T*-test is non-significant DF: 39 Correlation: 0.54

To explore the associations between factors, simple regressions with landings as the dependent variable and population numbers, projected effort, and consumption as explanatory variables (**Figure 6**) were used. In all cases, polynomial fits modeled associations better with respective R^2 of 0.93, 0.76, and 0.86. Changes in the relation between variables happen at different temporal times, mostly around the mid-1970, the 1980s, or the 1990s. For example, while landings and population numbers seem to increase somewhat proportionally until 1975, in 1976 data points become more dispersed. The relation between consumption and landings for the period 1951–2014 also shows higher dispersion in the 1980s and 1990s and some clustering. Regarding effort, the distribution of observations is more clearly clustered around three groups of data points (2200, 1200, and 680 units of standardized effort). Clusters capture the transitions and oscillations in variables occurring from the 1970s to the 2000s.

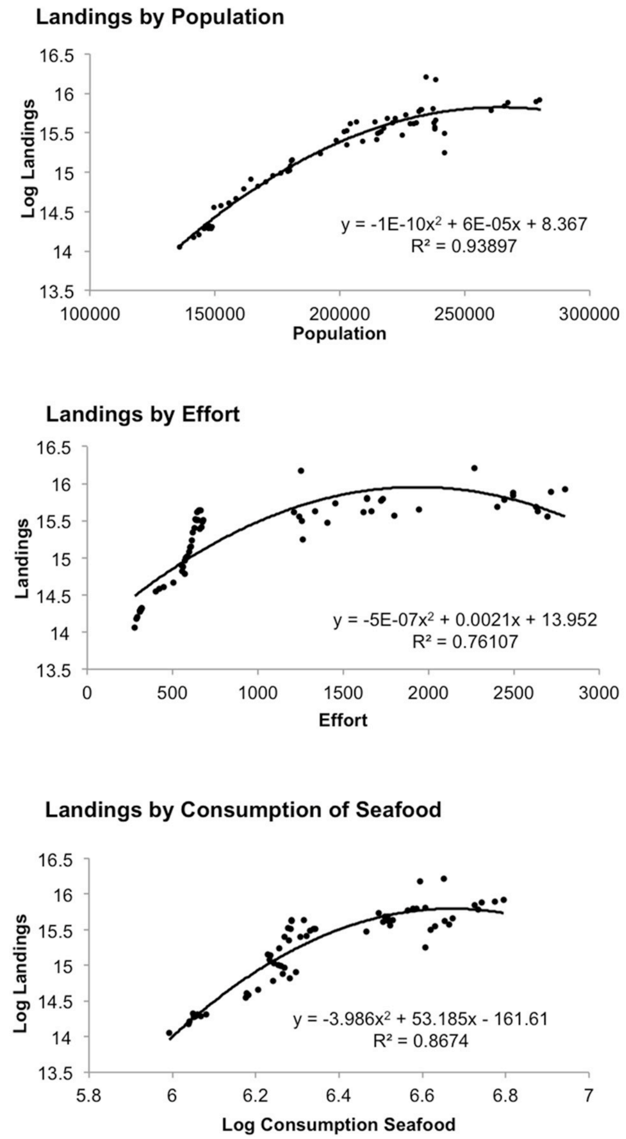

FIGURE 6 | Associations. Graphs interpret the relations among reconstructed landings, effort, and consumption. Changes in the relation between variables occur at around the mid-1970, the 1980s, and through the 1990s and 2000s.

DISCUSSION

Historical reconstructions complemented by observational and nutritional information provide evidence of the singular trajectory followed by Endenese fishing communities over the past 100 years. At the local level, Ende transitioned from a cash crop economy with marginal use of marine resources, to a society that consistently relies on fish as a source of protein and is intensively exploiting its stocks. This transition is seen in the reconstructions as a 10-fold increase in total landings and a five times increase in per capital fish consumption among farming sectors. Moreover, the fishery quadrupled the number of active fishers throughout the years. But, while the district's landings, marine products consumption, and population show increasing figures over time, this growth is not uniform. For example, the number of active fishermen, CPUE and annual capture rates, or standardized effort, do not seem to follow a simple linear trend, and show changes in mean values over time. To understand how these variables fluctuate, it is important to consider the larger historical context in which changes occurred. Ende embodies the case of a fishery that, because of its peripheral location, was exposed to discontinuous development and modernization policies. In tandem with the modifications in effort and consumption patterns instituted by the policies themselves, this characteristic probably exacerbated non-sustainable outcomes and had important effects within communities.

The germ of modernization and mechanization policies can be historically placed in the new economic direction adopted by post-Independence Indonesia during the late 1960s. Emerging from centuries of colonial domination, the new Indonesian state concentrated its efforts to boost the local economy and reduce staggering rates of poverty. In fisheries, actions were directed at achieving self-sufficiency in seafood production and the substitution of imports. These actions took place, initially, in the Western provinces of the archipelago. From 1951 to 1968 a sharp rise in the number of fishermen and fishing boats was experienced (Yamamoto, 1980). As a consequence, the amount of fish landed doubled by the end of 1960s (Krisnandhi, 1969). In 1967, with a change in government and the beginning of the New Order, a new economic direction was introduced. A set of quinquennial development programs, named REPELITA (*Rencana Pembangunan Lima Tahun*), run from 1969 to1999 and oriented efforts predominantly to the development of the agricultural industry and food production. New regulations created an inflow of foreign investment that was directed at the modernization of fishing sectors (U.S. Department of Commerce, 1977). The growth of offshore fishing was encouraged, giving impetus to the creation of new fishing fleets and the industrialization of operations. With the introduction of trawlers and large purse seiners, exports rose from USD $2 million in 1969 to $85 million in 1975 (U.S. Department of Commerce, 1977, p. 96). Modifications in productivity and gear had dire consequences to both fishermen and fisheries alike (Bailey, 1987; Bailey et al., 1987; Roch et al., 1995).

In Eastern Indonesia and particularly in Nusa Tenggara Timur, systematic changes associated to the development of productive sectors began to occur in the 1970s (Partadireja and Makaliwe, 1974). The implementation of the first REPELITA economic programs initially focused on communication, transportation, and infrastructure. Although it was recognized that development had to start by cementing the local economies, agricultural sectors only received 5% of the total budget. Within this distribution, most funds were allocated to animal husbandry and improvement of agricultural crops like cotton and coffee. In 1970, fishery contributions to the GDP of the province were almost three times the amount reported for 1969 suggesting important advances in captures (Partadireja and Makaliwe, 1974, p. 35). What created these increases remains uncertain. However, the allocation for fishery expenditures rose in 1972/1973 budgets (Partadireja and Makaliwe, 1974, p. 38). This was similar to what happened in the provinces of Bali, Moluccas, and Irian Jaya (Bailey et al., 1987). In these regions, captures of demersal and pelagic stocks improvemed with the introduction of large-scale gear. Increases in capture, however, should not be considered as an indication that modernization was taking place uniformly and across all fishery subsectors (Bailey et al., 1987, p. 42). In many locations, and especially in the eastern regions, practices still continued to rely on traditional boats (Partadireja and Makaliwe, 1974, p. 47; Butcher, 2004).

Mechanization of small-scale fisheries in the Nusa Tenggara province was very limited until the 1980s. The adoption of new technologies was constrained by a general lack of credits and government policies directed at facilitating technological transfer (Cribb and Ford, 2009). Other limitations were the availability of new equipment and gear, and the distance to centers of technological dissemination. With changes in infrastructure and communication brought by REPELITA plans in the 1970s and early 1980s, and the operation of large scale fishing fleets in the Eastern regions, exposure to technology gradually increased. As it has been observed for other small-scale fisheries in Southeast Asia and in Africa, the assimilation of new technologies probably modified the composition of fishing effort within communities and created competition between modernized and traditional fishermen (Ahmed, 1992; Andersson and Ngazi, 1998). Higher capture efficiency through gear substitution and motorization can deflate market prices, forcing households to invest in new technologies or to exit the fishery altogether (Bailey et al., 1987; Muhammad and Susilo, 1995). While this reservoir of labor could be absorbed by other sectors in the fishing industry, such as seafood processing or commercialization, in Eastern Indonesia there were very few industries, even less so directed at fisheries (Resosudarmo and Jotzo, 2009). Most likely, additional work effort engrossed the lines of infrastructure, commercial, and government service employment. But, where motorization outpaced both industrial and economic growth or effort concentrated in the hands of few, local fishing communities were most likely becoming poorer (Semedi, 2003).

The process of labor contraction was anticipated in the Western provinces by the evaluation of results from the 1973 national fishing survey by the FAO (Yamamoto, 1980). For example, it was noted that in early 1970s there was an excessive number of small-scale fishermen in the northern coasts of Java, and in other regions like Riau in Sumatra. Increases in efficiency of the fisheries in these regions were to be attained by reducing the numbers of individuals directly engaged in fishing (Yamamoto, 1980). While the creation of a middle fishing sector through technological development was highly desirable as a means to reduce poverty and to improve productivity of non-industrialized areas, it was also recognized that mechanization alone was not an adequate solution (Muhammad and Susilo, 1995). If the process was not accompanied by the introduction of economic alternatives at the community level, it could exacerbate economic deficiencies and be the "cause of serious social problems" (Yamamoto, 1980, p. 6.1.5; De la Cruz Modino and Pascual-Fernández, 2013; Donkersloot and Menzies, 2015). In fact, dramatic conflicts arose between trawlers and small-scale fishermen in the immediate years throughout the Western Provinces and Irian Jaya (Bailey, 1987; Roch et al., 1995).

In the case of Ende, historical reconstructions showed that the number of active fishermen experienced gradual increases until the1940s, when labor fell due to military conflicts. Activities recovered after the cease of hostilities, and continued to grow steadily into the 1960s. After 1965, a marked decrease of almost 60% in the working force occurred in the lapse of 20 years. High instability and posterior recovery of the number of individuals engaged in the fishery happened between 1987 and 2014. The particular trajectory followed by the labor force in the years in between 1965 and 1984 could be a result of inaccuracies in the process of reconstruction. For example, they may reflect errors in anchoring values due to underestimation of earlier figures. However, it could also be interpreted as evidencing an economic contraction of the number of individuals operating in the fishery given the introduction of technological innovation and mechanization. Additionally, demographic effects might explain a reduction of available labor as the age structure of the population pyramid shifted. While statistical information is scant, there are several pieces of evidence that may support this conclusion.

- For instance, fishermen mentioned that nylon nets began to substitute heavier traditional materials such as cotton or vegetal fibers by the late 1960s. Sailboats remained in use until the mid-1980s, when access to outboard engines became more common. Older fishermen did not recall any government aid directly supporting their activities, but emphasized that improvements were based on individual initiative. Traditional shipping and trade between Ende, Bima, and Ujung Padang, made the circulation of these innovations possible. However, not all fishermen had the means to mechanize, and credits were infrequent. The first mention of provincial support and an increase in fishing effort occurs in 1989 (BPSE). This is not surprising, as REPELITA programs seem to have focused on aquaculture and the development of infrastructure such as ports.

- Secondly, considering that no trawling or industrial fishing has ever been established or operated off Ende, observed increases in landings in 1976 might point to an improvement in the efficiency within the small-scale sector. The composition of effort in 1984 shows the existence of 62 motorboats (<5 tons) and of 6 larger-scale motorized vessels (>5 tons). This is markedly different from 1917, where the number of ships of similar tonnage totaled 14.
- Thirdly, whereas close to 1970, the number of fishermen in East Nusa Tenggara was roughly placed at 23,000 (Partadireja and Makaliwe, 1974, 47), in 1983 there were 15,611 fishing households, or ∼18,000 fishermen (BPSE, vi). Hence, indicating reduction of 22% of the number of individuals engaged in the fishery. The report also mentioned that while productivity was kept high, the contraction in manpower in all agricultural sectors was compensated by a migration of workers to areas of commerce and infrastructure.
- Finally, the impacts of demographic changes and inter-island migration should not be overlooked. After WWII, population numbers experienced significant rates of growth (Jones, 1966). As a result, by late 1950s, an inflow of younger individuals was available to join the active work force. By 1965, a renewed emphasis of migration programs, and the creation of jobs in other spheres of the local and regional administration could have meant a reduction of individuals willing to engage in fishing. By 1975, the number of people in the age bracket between 25 and 44 years of age probably tied or surpassed the younger cohorts. Combined to low life expectancy rates (Resosudarmo and Jotzo, 2009) the effect of an older population of workers may have also contributed to lower levels of active engagement in the fishery.

In addition to changes in the composition of the labor force, with the expansion in mechanization in 1970s–1980s, the sustainability of marine resources in the archipelago at large started to decline. In the western Indonesian seas, the central government responded by introducing several measures that sought to protect small-scale fisheries, such as a general ban on all trawling operations. Moreover, during the mid-1980s the general government began to pursue the rationalization and fair allocation of economic growth in the sector by passing several pieces of legislation to protect smaller sectors. This direction took an important role in the quinquennial economic plans, REPELITA V (1989–1994) and REPELITA VI (1994–1999). In 1985, however, the central government modified licensing processes and allowed for the creation of joint ventures. As a result, the fisheries of the Indonesian EZZ became open to the participation of foreign vessels (Sunoko and Huang, 2014).

In Eastern Indonesia, where degradation was not perceived as a threat, the central and the regional government pursued an increase in the number of large vessels fishing for skipjack and tunas operating off ports such as Benoa, Bali and Kupang, Timor. In Ende, modernization continued to prosper with rapid growth in the number of motorized boats. In 1989, through provincial programs, effort quadrupled (BPSE). However, by 1993, the number of boats and landings declined almost 30% suggesting a reduction of fish stocks. Evidence from reconstructions and interviews suggests as signs of overfishing or overexploitation (Reitz, 2004; Carder et al., 2007). It is also in 1992 that Flores suffered a devastating earthquake and tsunami that may also account for the changes in effort. In the following years, landings recovered showing a slow increasing trend due to provincial aid (BPSE). But, this trend was not stable. Throughout the mid-1990s and early 2000s, the level of effort oscillated given new decentralization policies and repercussions of the 1997/1999 El Niño-La Niña events. For example, changes in landings and catch compositions were experienced in other fisheries in Eastern Indonesia in the years before and after 1997 that may have influenced active participation in the fishery (Blaber et al., 2005; Stacey et al., 2011). Tied to success in landings and sustainable aid, the labor force also experienced fluctuations. It is also at this time that immigration to Malaysia and neighboring countries began to rise (Barlow and Gondowarsito, 2009).

At the general level, REPELITA VI marked the beginning of decentralization efforts in natural resource management of fisheries, forestry, and irrigation to provincial and local authorities (Susilowati, 1996). However, the implementation of decentralization policies run into several impediments that include lack of personnel trained in fisheries and lack of trust among different institutions (Satria and Matsuda, 2004; Barlow and Gondowarsito, 2009). All of these limitations seemed to be true in the case of Ende. In 2002, another influx of boats increased effort with landings reaching unprecedented numbers for 2002 and 2003. In 2004, yields fell to 60% of previous reported numbers, remaining at similar or lower levels in comparison to the previous decade. This result may reflect the conflation of incentivization policies with environmental pressures introduced by 2002–2004 El Niño-La Niña events. Changes in ecological conditions probably created new stressors to threatened fishing stocks. The level of effort was incentivized to counterbalance diminishing yields and thus, leading to the 2004 decline.

By 2005, a presidential regulation enacted the National Medium-term Development 2004–2009 plan. The program included an improvement in provision and data accuracy, the development of fishing facilities and handling systems, and the empowerment of the tuna, seaweed, and shrimp fisheries. None of these measures, however, created significant changes in the district of Ende. While informants mentioned the introduction of seaweed programs and training, only a few fishermen were selected to participate and efforts where hindered by favoritism and corruption. When this research was carried out (2009–2012), support from the regional fishery was scant and irregular and mostly directed at intensification through the introduction of *lampara* boats (middle purse seiners). Going against the long-standing independent and individualistic character of the fishery, fishermen that wanted to access gear or engines needed to form smaller groups of three to four to receive any support. Nowadays, the fishery remains at large of subsistence scale. Lampara boats are growing and encroaching into coastal fishing grounds. With a tonnage that averages 4 of sardines, anchovies, and small pelagic fish, the proliferation of these boats are favoring the concentration of the fishery into a few hands. Ende may be at the brink of a new transition that could mean once again the contraction of the working force and the loss of operational independence by the smallest fishermen.

The future remains unknown for small-scale fishermen in Ende. With the establishment of marine protected areas in the Savu through a presidential decree in 2009, local district offices have taken new steps into addressing environmental concerns (Munasik et al., 2011; Achmad et al., 2013). Whether these new guidelines will be at odds with the pressures toward intensifying the fishery and achieving sufficiency in food production or whether they may be successfully reconciled, remains to be seen.

CONCLUSION

Through historical ecology and ethnography, this article explored the impact of development and modernization policies among small-scale fisheries in Ende, Eastern Indonesia. Within fishery management, the transformation of local fisheries has often been seen as a result of intensive technological and capital development promoted by government and non-government agencies (MacFadyen and Corcoran, 2002). While true in other contexts, modernization is a relatively recent undertaking in Ende and has followed a rather fragmented and discontinuous process leaving a particular set of tracks. Endenese fisheries have experienced different gradients of transformation that speak of diverse and complex trajectories in the adoption of technological innovation (Ahmed, 1992). Understanding these trajectories is central to advancing fair regimes of resource use.

For example, when mechanization had not been properly regulated, the increasing competition by more efficient boats has resulted in the concentration of resources, the use of damaging fishing practices, and environmental degradation. The opportunistic nature in which policies were implemented has also meant that benefits from advancements were not equally shared among the parts, creating instability in the labor market and further eroding households' economic sufficiency. At present times, the situation has become more critical due continuous pressure toward modernization and stocks experiencing important changes in composition and stability.

As new regimes of governance are being proposed at the provincial level to address resource depletion and damaging fishing practices, it is important to see how small-scale fisheries are not isolated relicts of tradition. Even when considered peripheral in their geographical location, fishing communities like Ende are not disconnected from trade or technological centers (Wolf and Eriksen, 2010). And while they have been relegated in government priorities, they have become very attractive to illegal fishing operations that include shark finning (Christensen and Tull, 2014). In these cases, is through Chinese middlemen that fishermen acquire much desired technological innovations and new fishing gear. Not accounting for these interconnections within policy and governance mechanisms has serious consequences for biodiversity conservation. Ultimately, environmental degradation reverts to the long-term sustainability of local livelihoods within the community and contributes to exacerbate poverty.

Almost 10 years ago, Heazle and Butcher proposed that to prevent further depletion of marine resources, we should pursued management solutions as "integral parts of a broader regional strategy that takes into account the political and economic circumstances of the region" (2007, 282). Historical reconstructions can help us elucidate how different patterns of development take shape. Understanding the outcomes of mechanization at the fringes of more centralized systems is essential to navigate the tradeoffs among poverty reduction, economic growth, and environmental degradation.

LIMITATIONS OF THE CURRENT STUDY

There are several limitations with the current study. Like other historical reconstructions of small-scale fisheries, this article relies on effort data that may provide an incomplete characterization of the intensity of resource harvesting activities. Given the nature of small-scale fisheries, the large diversity of gears and equipment used makes the systematic consideration of effort an arduous task. Direct monitoring of fishing behavior and landed captures is also difficult due to the flexibility of practices and schedules among individual fishermen. This creates some issues in the estimation procedures that should be acknowledged. Second, while observations and extensive archival and participant observation research were used to contextualized estimates, there are also risks of underestimation given the lack of information in terms of illegal operations in this particular region of the Savu. In addition, it is important to observe that the MSY model suffers from limitations for no biological estimations of growth or survival are available to correct inferences. Calculations might be reflecting thus the intensity of effort instead of real biomass numbers. Finally, environmental fluctuations affecting stocks have not been considered in the projections. The absence of meteorological datasets makes the assessment of the role of environmental fluctuations challenging. Future studies will address these shortcomings.

ETHICS STATEMENT

Institutional Review Board from The University of Georgia. Verbal informed consent was used to collect data for this study.

(a) Interviews/Short Interviews/Surveys:

    (1) Participants were provided with a prior informed consent document informing them of the purpose of the

(2) The content of the prior informed consent document was discussed verbally with each participant for their approval.
(3) Participants were asked to give consent to their participation in the study.

investigation, the data collection process, benefits, and potential risks.

(b) Time Allocation (Scans, focal follows, fishing logs):

Observations of actions conducted by individuals were registered by the researcher. Previous authorization to conduct such observations was solicited with the consent document.

AVAILABILITY OF DATA AND MATERIALS

The datasets supporting the conclusions of this article are included within the article (and its additional files). All datasets and sources used if not included in the document are available upon additional request to the author.

AUTHOR CONTRIBUTIONS

The author confirms being the sole contributor of this work and approved it for publication.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: http://journal.frontiersin.org/article/10.3389/fmars.2017.00065/full#supplementary-material

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Assessing the Effectiveness of Monitoring Control and Surveillance of Illegal Fishing: The Case of West Africa

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This paper assesses illegal fishing in West Africa, one of the regions most affected by Illegal, Unreported, and Unregulated fishing (IUU) in the world. The catch, the economic loss and the amount recovered through Monitoring, Control, and Surveillance (MCS) are calculated based on a reconstruction method, and the information made available through national MCS units, between 2010 and 2016 in an effort to assess the effectiveness of surveillance efforts in the region. Results show considerable loss of revenues for Mauritania, Senegal, The Gambia, Guinea Bissau, Guinea, and Sierra Leone, estimated at 2.3 billion USD annually, while a minimal amount of 13 million USD is recovered through MCS. In addition, this paper finds that countries touched by the Ebola crisis (Guinea and Sierra Leone) drive a tremendous increase in the loss generated by illegal fishing. However, further analysis shows that the overall severity of illegal fishing, as defined by a range of types investigated here, declines as the fines against the most severe forms of IUU fishing increase. Finally this study finds that Sierra Leone and The Gambia have the highest scoring MCS systems, and were the countries where the most offenders are caught and charged with the highest fines, while Senegal's new legislations which improved MCS during 2015 does not appear to show on the scoring results. This study finds that illegal fishing amounts the equivalent of 65% of the legal reported catch from West Africa and poses serious concern for food security, and the economy in the region.

Keywords: illegal fishing, IUU, catches, West Africa, economic values, sanctions, offenses, Monitoring Control and Surveillance

INTRODUCTION

There is growing concern with regards to the health of global fish stocks and the repercussions of their depletion on food security and the economy of most vulnerable countries (FAO, 2016). West African countries rely heavily on fish as a one of the principal sources of protein, but also as a source of income and employment for nearly 7 million people (Belhabib et al., 2015c). This region has seen its fish stocks decline, driven by over-exploitation, overcapacity, and illegal fishing (Daniels et al., 2016). Previous work assessed illegal fishing in the region (Belhabib et al., 2012c, 2016; Belhabib and Pauly, 2015) to nearly 40 per cent of all the fish caught—the highest level worldwide (Agnew et al., 2009). Not only the economy of vulnerable countries is threatened, illegal fishing is estimated to reduce the number of jobs in artisanal sectors by 300,000 (Daniels et al., 2016). Illegal fishing conducted by industrial vessels is very difficult to assess and existing estimates are bound with a high degree of uncertainty, as illegal fishing vessels are highly mobile and develop tedious techniques to escape surveillance, particularly that monitoring is limited in the region.

There are different drivers of illegal fishing, as we look at industrial fishing, we argue that economic gain is the most significant incentive (Le Gallic and Cox, 2006; Sumaila et al., 2006), alongside with the ability of simply doing so (Andrews-Chouicha and Gray, 2005). This is mainly the case in the national waters or exclusive economic zones (EEZs) of the 6 West African countries (The Gambia, Guinea, Guinea-Bissau, Mauritania, Senegal, and Sierra Leone), whose Monitoring Control and Surveillance (MCS) systems are relatively weak.

MCS is often bound with country's indicators such as governance and corruption (Standing, 2006), which are very weak in the region. Poor governance and high corruption combined with high monitoring costs pose a serious concern on the sustainability of West African countries' efforts to combat illegal fishing. Examples in the region show that the presence of international funders helps combatting illegal fishing by adding transparency and increasing surveillance activities. This raises the question of the effectiveness of these systems, and how much of the loss to illegal, unreported, and unregulated fishing is recovered through MCS (fines and sanctions).

MCS efforts are further jeopardized by the use of "detection escape" techniques such as interfering with electronic monitoring systems, the use of different flags to hide vessel identity and escape prosecution, use of multiple boat names, and forgery of registration certificates in the region (J.M. pers. obs.). Several cases illustrate multiple violations of fishery laws within West Africa, and raised important attention on the issue of cost recovery, to allow MCS efforts to become sustainable and independent from foreign "funding" (MRAG, 2005; Greenpeace, 2006). Multiple infractions and low capability of prosecution given high rates of detection escape render MCS particularly vulnerable to lower budgets. This vulnerability limits the ability of West African countries to deter IUU fishing. In addition, losses generated by illegal fishing in the region are barely known which limits knowledge on real economic losses generated by such activity.

This paper seeks to assess economic loss caused by illegal fishing in West Africa and the effectiveness of enforcement in the period between 2010 and 2016. It builds, for the first time, a sanctions and illegal fishing database, and analyses the relationship between sanctions and severity of IUU and draws conclusions on the efforts to make to reduce illegal fishing in the region. It also discusses the implication of illegal fishing on the artisanal fisheries sector, food security, and the economy.

METHODS

Study Area

The study area covers six countries (Mauritania, Senegal, The Gambia, Guinea-Bissau, Guinea, and Sierra Leone). These countries are members of the West African Sub Regional Fisheries Commission (SRFC)[1] and lay within the Canary Current Large Marine Ecosystem (CCLME) in the North and the Guinean Current Large Marine Ecosystem (GCLME) in the South. This makes West African waters particularly productive. The coastal zone of West Africa is an area of strategic interest for the socio-economic development and livelihood of 1.4 million people living along the coast, and fisheries therein can contribute up to 38% of the GDP (Belhabib et al., 2015c).

Building a Comprehensive Database of Illegal Fishing Vessels, Offenses, and Sanctions

We investigate illegal fishing occurrences in West Africa and cover multiple indicators between 2010 and 2016. These are: Vessel name, gear type, country where illegal fishing occurred (or country where a fine was issued), origin of the vessel (flag), amount of the fine paid (or otherwise issued, if not yet paid) converted into USD_{2015}, year of illegal activity, offenses committed per vessel, other sanctions in addition to the fine (such as confiscation of vessel, catch, gear, etc.), and whether a sanction was issued at all. The main data were gathered from various media sources, and observations from various organizations (Environmental Justice Foundation, 2012; INTERPOL, 2014; Greenpeace, 2016a,b), complemented by information from the Department of Surveillance and Protection of Fisheries for Senegal, The MCS units of The Gambia, Sierra Leone and Guinea, and the Ministry of Fisheries of Guinea Bissau, while information for Mauritania were not available. In cases where sanctions were not reported (notably the case of Guinea and Guinea Bissau), the amount of the sanction was assumed to equate the minimum amount that is given under the Fisheries Act of the country for that offense, or the average based on the most recent historical fine amounts available for similar cases.

Estimation of Illegal Catches

We estimated illegal catches, i.e., catches by foreign fleets as per the definition of illegal fishing (Belhabib et al., 2014a) for each country following different approaches depending on data availability.

Senegal

Illegal catches for Senegal for the years 2010 and 2011 were extracted from Belhabib et al. (2014a) and were estimated based on the number of observed illegal fishing boats, their size and a modeled catch per unit of effort (Belhabib et al., 2014b). Given similar MCS efforts between 2011 and 2012, we assumed illegal catches were constant then, and they increased by 20% between 2012 and 2013 after the dismissal of the Russian vessels from Senegalese waters (Belhabib et al., 2014a, 2015a). This particularly applied after Russian vessels obtained licenses in other countries

[1] Cape Verde, also a member, is not included in this analysis.

in the sub-region (notably, Guinea Bissau and Mauritania), as incursions to Senegalese waters at night were common (A.G. pers. observation). We then multiplied the illegal catch of 2013 by the variation between 2013 and 2014, and between 2014 and 2015 to estimate the illegal catch for 2014 and 2015. Variation rates were derived from the percentage of infractions (compared to the total observed vessels) found in the World Bank monitoring report (The World Bank, 2016). Fishing vessels observed by aerial/surface patrol or by radar and satellite monitoring that are committing a serious infraction in targeted fisheries represented 86% of the total in 2013, 60% in 2014, and 60% in 2015 (The World Bank, 2016).

Guinea Bissau

Two data points were available for Guinea Bissau. Surveillance activities found eight vessels fishing illegally during 1 week in 2014 (Caopa and Rejprao, 2016). Given the conservative nature of this estimate, we extrapolated year long and estimated a number of 52 vessels in 2014. This number was multiplied by a CPUE of 1,200 t•boat^{-1}•year^{-1}, which is the minimum an illegal trawler catches to cover its operation costs (Pauly et al., 2014; Belhabib et al., 2015b). We assumed the illegal catch was constant between 2014 and 2015 and interpolated linearly between the estimate in 2010 (18,000 t), provided by Belhabib and Pauly (2015) for Guinea Bissau.

Guinea

Illegal fishing in Guinea represents the equivalent of 64% of legal reported catches (Belhabib et al., 2012a). We first extracted the estimated illegal catch for Guinea from Belhabib et al. (2012a), and then multiplied the reported catch extracted from the Food and Agriculture Organization (FAO) FishStat database, by 64%. Then we extrapolated the trend forwards to 2015.

Sierra Leone

The number of vessels spotted fishing illegally, or estimated, was reported at 30 for 2011[2], 10 in 2012[3] (Finch, 2016), 7 in 2014 (NOAA, 2015), and 80 in 2015[4] associated with the Ebola crisis. The Ebola crisis along with governance issues related to the cancelation of the World Bank project, a major contributor to the increase in MCS in 2012 and 2013, prompted low to virtually no monitoring after 2014. We interpolated the number of boats between 2012 and 2014 and then multiplied by a minimum CPUE of 446 t•boat^{-1}•year^{-1} for the industrial fleet operating in Sierra Leone (Seto et al., 2015).

We note that the number of arrests does not imply the total number of illegal fishing vessels. Given that 10 vessels were reported as committing 252 acts of illegal fishing, these numbers are likely very conservative.

Mauritania and the Gambia

The baseline illegal catch for Mauritania and The Gambia was extracted from Belhabib et al. (2012b) and Belhabib et al. (2016), respectively. These were then multiplied by the regional trend estimated using the total catch for Senegal, Guinea, Guinea Bissau, and Sierra Leone.

Estimation of Unreported Foreign Catches

To estimate unreported catches by the foreign fleets legally operating in West Africa, we first estimated the total catch based on the product of the fishing effort (defined as the number of vessels, their GRT, the number of fishing days and their nationality and gear type), and the catch corresponding to that unit of effort (Belhabib et al., 2014a). The number of foreign vessels operating in Senegal, The Gambia, Sierra Leone, Guinea Bissau, and Mauritania were obtained from national governmental organizations during a workshop in 2016, verified and/or complemented with the number of foreign vessels legally operating in the region obtained from official records (e.g., FAO global fishing vessel database[5]) whenever available completed by a literature review (Anon, 2015). The foreign catch from Guinea was extracted as a sub-set of the total catch, to which an under-reporting rate of 20% was applied (Belhabib et al., 2012c). The difference between the reported foreign catch (extracted from official statistics provided by MCS units whenever available) and the total estimated catch represents the unreported foreign catch, which is obtained by flag for Senegal, Guinea Bissau, Sierra Leone, and Mauritania.

Economic Loss

The annual economic loss caused by illegal and unreported fishing was estimated by multiplying the estimated illegal and unreported catch by the ex-vessel price. Ex-vessel prices were obtained from the *Sea Around Us* ex-vessel price database for 2010 (Swartz et al., 2013) and converted to 2015 USD using Consumer Price Index extracted from the World Bank database (www.worldbank.org).

Although conservative, the values of unregulated catches were also added. The unregulated catch was estimated using the number of vessels that were caught while committing an unregulated fishing act such as illegal transshipment, fishing in a prohibited zone, using illegal mesh size, etc. multiplied by the minimum regional CPUE of 446 t•boat^{-1}•year^{-1} (Seto et al., 2015). This provides a rather highly conservative estimate since only those who were caught are taken into consideration in the analysis.

Assessing the Effectiveness of MCS Using a Scoring System

Sumaila et al. (2006) describe expected penalty drivers (or cheating drivers) as closely related to the effectiveness and efficiency of the surveillance system, the level of non-governmental or private organizations involvement in detecting offenses, which relate to the likelihood of vessels of being detected; avoidance activities of offenders; and the severity of the penalty which disincentivises illegal fishing when it is accompanied by effective enforcement. Herein, we look at these drivers which are the likelihood of vessels of being detected through the number of offenses and sanctions, the avoidance activities which are represented by the number of offenses

[2] http://slconcordtimes.com/60-illegal-fishing-in-salone-waters/

[3] http://blogs.ubc.ca/jdmayer/2014/11/20/from-cannons-to-canon-sinking-pirate-fishing-in-sierra-leone/

[4] http://cocorioko.info/now-it-is-time-for-sierra-leone-to-turn-attention

[5] http://www.fao.org/figis/vrmf/finder/search/#.V9BNKfkrKM9

that escape sanctions and the severity of the penalty. We add availability of information as a proxy for transparency and develop a scoring system based on the indicators below:

1) Average fine amount: The weighted average fine amount was calculated for every country and normalized by the maximum amount (The Gambia) to a scale of 5, where 5 is the best score and 1 the worst. This indicator illustrates the severity of the sanction.
2) Number of fined offenders in contrast to the number of total offenders: This indicates the number of vessels that get effectively fined over the total. This indicator is normalized to a scale of 5, where 5 is the best score and 1 is the worst. This indicator illustrates avoidance.
3) Categories of offenses effectively fined: This indicator illustrates the frequency of vessels of being detected and fined, and ranges between 0 and 23.
4) Catch value per shelf unit: This indicator represents the concentration of the illegal catch, i.e., the amount of fish caught illegally per square km of continental shelf area. This indicator is a proxy for the severity of illegal fishing per country. This was calculated by first dividing the average value of the illegal catch (2010–2014) by the shelf area for each country, transformed to a log scale then reversed. We then normalized the value to a scale of 5.
5) Availability of information: This parameter captures transparency while dealing with illegal fishing, as high transparency reduced bribing and corruption. This indicator is calculated as the sum of 6 sub-parameters scored with 1 for good and 0 for bad: (1) Names of offenders (vessels) available from government records, (2) fines available from government or any other sources, (3) offense category or type available from government or any other sources, (4) information is not aggregated in such a way that masks paid fines and offenses, (5) information is easy to obtain upon request and finally, (6) information is publically available. The scale of this indicator is between 0 and 6.

The total score is then calculated as the sum of the previous scores, where the maximum score is 44 (based on the sum of the maximum of each score).

RESULTS

Illegal Fishing Activities and Sanctions

Overall, there were 230[6] observed offenses which spread over 23 offense categories, or observed offenses that have been detected and mostly sanctioned in the region (**Table 1**). Around one third of the offenses observed were not sanctioned. Under-reporting of fishing effort (associated with GRT) represents the most recurrent offense. However, this offense is only sanctioned 19% of the time, while it remains undetected by the governments of West Africa the rest of the time. Only Senegal applied sanctions on 12 vessels of Chinese origin of around $1,000 US each. Gear related offenses (associated with illegal mesh size, illegal gear, improper stowage of fishing gear, etc.) were caught 44 times overall and were sanctioned entirely, with an average fine of $137,000 US ranging between $835 US (Senegal) and $812,000 US (The Gambia). Fishing in a prohibited zone ranks third with 43 instances and sanctioned 50% of the time only, with an average fine of $134,000 US, driven by high sanctions in Sierra Leone. Registered vessels fishing without a license were caught 19 times and were fined $179,260 US on average, with an average fine of $45,000 US in Senegal (the minimum) and a maximum in The Gambia ($1.1 million US). Forgery of documents, vessel names and marking fault were severely sanctioned in Sierra Leone with an average fine of $302,000 US per offense in comparison with Guinea's average ($30,000 US) and Senegal ($800 US). Unauthorized entry to or exit from the EEZ of Sierra Leone constituted the sixth offense that was most caught in the region, and was sanctioned with a fine of $55,100 US on average. Fishing without an authorization ranks seventh and was caught 14 times. Sanctions for this offense vary greatly from withdrawal of fishing license and a fine of $800 US (Senegal) to around $2.3 million US (Senegal). The next most recurrent categories of offenses consist of mistreatment (of fishing observers), attempted corruption and/or failure to comply with 14 vessels and an average fine of $95,600 US per sanction driven by high sanctions in Sierra Leone.

TABLE 1 | Summary of observed offenses in West Africa, 2009–2016.

Offense	Number
Under-reporting of fishing effort	63
Gear related offense	44
Fishing in a prohibited zone	43
Fishing without a license	19
Forgery-marking default	17
Unauthorized entry or exit to or from EEZ	16
Fishing without an authorization	14
Mistreatment- corruption-failure to comply	14
Absence of an observer onboard	9
Under-reporting of fishing catch	9
Administrative delays caused arrest	8
Illegal trans-shipment	8
Absence of national crew onboard	7
Technical negligence	6
Absence of proper documentation onboard	5
Change of target species	3
VMS-AIS default	3
Prohibited species or juveniles	2
Failure to land catch	2
Illegal discard	1
Failure to pay fees	1
Sanitary and health issues	1
Violating fishing regulations/unspecified	41

Value Recovered through MCS (Total Sanctions)

Over the period between 2009 and mid-2016, around $29 million US were collected or sanctioned in fines.

[6] We don't obtained information from all countries.

Total fines collected or to be collected have increased overall from less than $370,000 US in 2009 to a projected $13.8 million US in 2016 (**Figure 1**). In contrast, the average fine per sanction has decreased, from the first peak in 2010 ($362,000 US) to $137,000 US in 2016 (**Figure 1**). This corresponds to the increase in the number of offenses (**Figure 2**). However, the number of offenses not related to fishing without authorization, such as entry or exit to or from EEZ without authorization, or gear type related offenses have increased which contributed to decrease the average sanction amount per sanction (**Figure 1**).

Overall, the number of caught offenses increased prompting an increase in the total amount recovered, from as low as 2 observed offenses in 2009 to 78 in 2014, declined to 43 observed offenses in 2015, caused by the low MCS in Sierra Leone and Guinea during the Ebola crisis (**Figure 2**), and then increased to a projected 98 caught offenders in 2016[7] (**Figure 2**).

Comparing the profile of fines per offense in each country allows a better understanding of the effectiveness of the legislative background allowing MCS to recover its operating costs. Hence, both the number of sanctions (or caught offenders) and the average sanction amount are important. The highest number of offenses occurred in Guinea Bissau and Guinea, however the sanction is either low or not enforced (when observed by an NGO for example) with on average $24,900 US per offense in Guinea and $81,800 US in Guinea Bissau and a cumulated number of offenses of 109 and 72, respectively. In comparison, The Gambia has the lowest number of caught offenders (11), however charges the highest amount per offense ($395,000 US), and more efforts need to focus on MCS to effectively sanction the offenders. Senegal and Sierra Leone have both a high number of offenders with 50 and 78 caught offenders, respectively, and a high average sanction per offense ($181,000 and $168,000 US, respectively). In addition to high fines and a relatively high number of caught offenders, Sierra Leone MCS detects and fines most categories of offenses (in constraints to detecting the offenders themselves), with the exception of prohibited species, which tends to be merged in the last category, i.e., unspecified violation of fisheries regulations, followed by Senegal (**Figure 3**).

Total Reconstructed Illegal Catches

Illegal catches, i.e., catches taken illegally by foreign fleets, were overall constant at around an average of 690,000 t•year^{-1} between 2010 and 2015. Country estimates vary widely (**Figure 4**). Illegal catches were the highest in Mauritania and Senegal with 268,000 and 261,000 t•year^{-1} respectively, due to the presence of Eastern European pelagic trawlers targeting small-pelagic fish in high quantities (**Figure 4**). However, improving success of MCS due to the availability of funding (The World Bank, 2016), has prompted illegal catches to decline from around 350,000 to 250,000 t•year^{-1} between 2010 and 2015 for both countries. Illegal catches in Sierra Leone declined at first from 10,000 t•year^{-1} in 2010 to less than 3,500 t•year^{-1} in 2014,

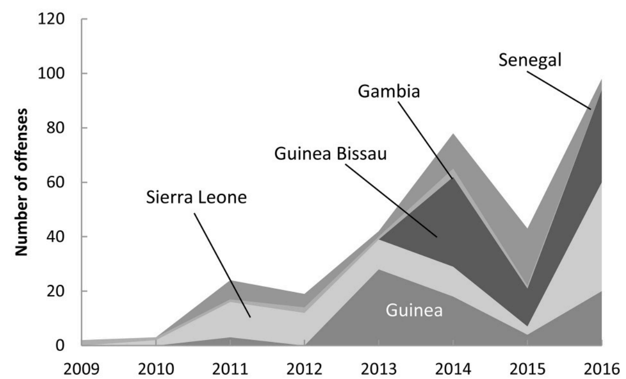

FIGURE 2 | Evolution of the number of caught offenders in West Africa between 2009 and 2016, per EEZ.

[7] For Buinea Bissau, 14 and 17 vessels were sanctioned in 2015 and 2016 (January to August), respectively. However, given the lack of information on the nature of the offense, it was not possible to fill in the gap in the fines using the Bissau Guinean legislation. Multiple cases in 2004 illustrate that fines revolve around an average of $151,611 US (Tribunal International De La Lois Pour La Mer., 2010).

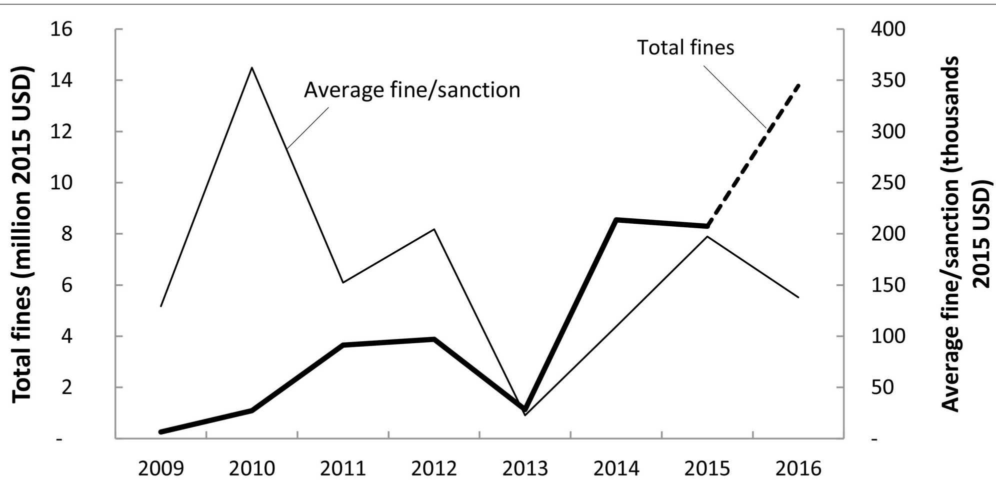

FIGURE 1 | Total (thick line) and average (thin line) fine amounts in West Africa, 2009–2016.

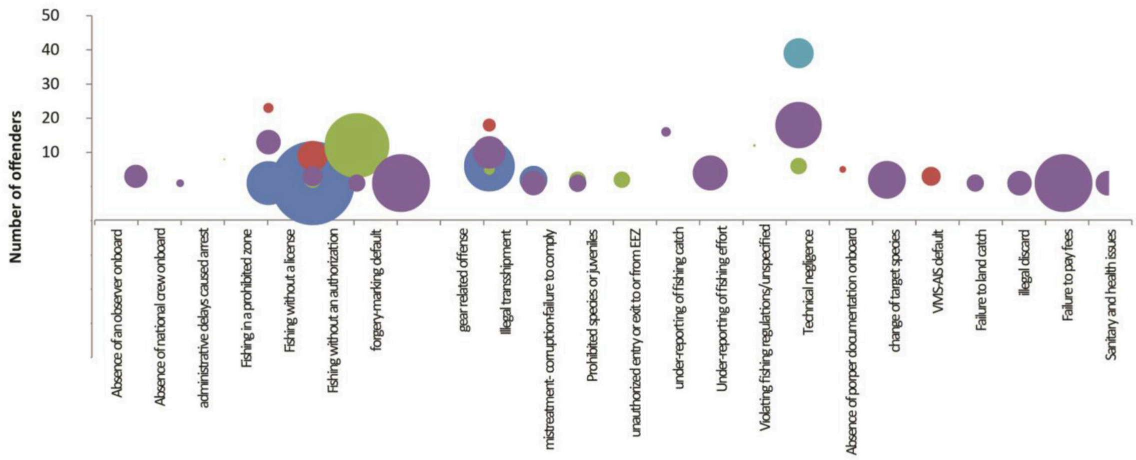

FIGURE 3 | Profile of fine and number of caught offenders by type of offense in Sierra Leone (purple), Senegal (green), Guinea (red), Guinea Bissau (light blue), and The Gambia (dark blue), 2010–2016. The size of circles represents to the amount of the (average) fine for the offense by country.

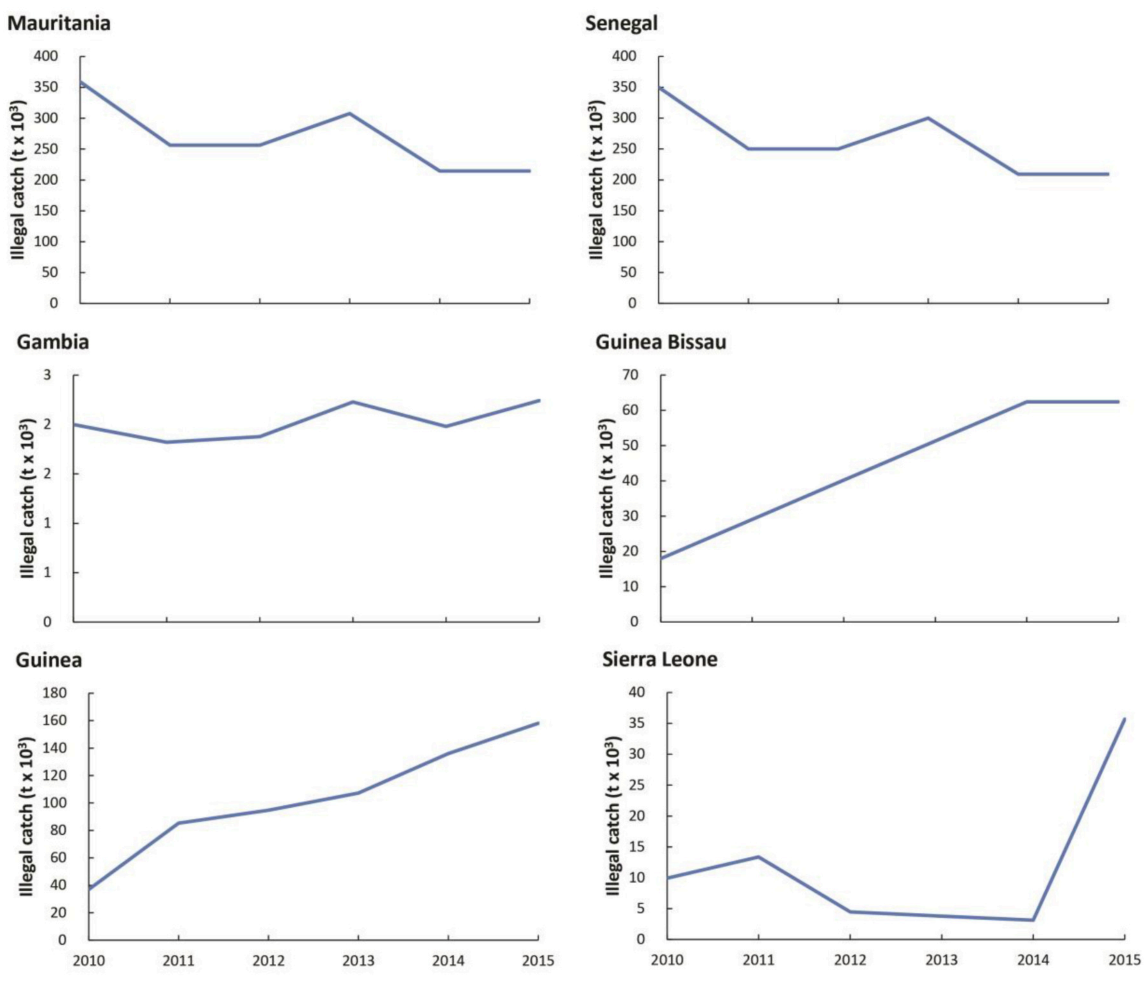

FIGURE 4 | Reconstructed illegal catches from West Africa, 2010–2015. Note that the scale differs.

after which they increased drastically due to the Ebola crisis, to reach 35,000 t•year^{-1} in 2015 (**Figure 4**). Illegal catches in Guinea increased from 40,000 t•year^{-1} in 2010 to over 150,000 t•year^{-1} in 2015 (**Figure 4**). Similarly, illegal catches in Guinea Bissau increased from less than 20,000 t•year^{-1} in 2010 to over 60,000 t•year^{-1} in 2015 (**Figure 4**). Illegal catches in The Gambia remained overall constant with slight variation, at 2,000 t•year^{-1} on average between 2010 and 2015 (**Figure 4**).

Economic Value of IUU Catches

IUU in the waters of west Africa induced, at least, a loss of $2.3 billion US annually, most of which is caused by illegal fishing, or fishing without an authorization and under-reporting by fleets that are otherwise authorized to fish in West Africa (**Table 2**). IUU losses increased from $1.8 billion in 2010 (with $1.1 million recovered through fines) to $2.2 billion in 2012 ($0.2 million recovered through fines), decreased to $2 billion between 2013 ($0.02 million USD recovered through fines) and 2014 ($8.5 million recovered through fines), after which they increased to a maximum of $2.3 billion in 2015 (**Table 2**) during and after the Ebola crisis in Sierra Leone and Guinea, and after the departure of the World Bank and Environmental Justice Foundation from Sierra Leone, whose programs were key in increased monitoring in the country.

Overall, under-reporting alone contributed to a loss of value of $2 billion over the period from 2010 to 2015, of which 30% is contributed by East European countries and Russia, 20% by Western European countries, which is at the same level than China, and 9% by flag of convenience countries, and 21% by unknown/unidentified countries. This illustrates that the lack of monitoring also reflects upon fleets that are legally entitled to fish in the waters of the West African sub-region. Over a period of 6 years, between 2010 and 2015, West African countries lost a total of $ 24.6 billion US to IUU fishing, around half of which is taken by vessels that are not authorized to operate in their waters.

Assessing the Effectiveness of MCS

Using a set of indicators allows to assessing the effectiveness of MCS in West Africa within the regional standard of capabilities. A similar analysis at the global level would warrant a more effective assessment of MCS in the sub-region. This assessment hence takes into account realities of the region, such as governance, human and financial means, corruption, etc. This aims at learning from regional trends lessons that are realistically implementable within a limited means framework. Of a maximum score of 44, Sierra Leone scores 33.5, followed by The Gambia with 24, Guinea with 23.3, Senegal with 22.7, and Guinea Bissau with 13.4, respectively (**Table 3**). It appears from this ranking that Sierra Leone's MCS ranks first in the region, despite an increased illegal catch during the Ebola crisis. Senegal does not appear to be scoring the highest despite clear efforts at the end of 2015 with the adoption of new historical fine legislations, and a new Fisheries Act. The time series used here may affect the scoring with most vessels being caught during a relatively recent time period.

TABLE 2 | Loss induced by illegal, unregulated, and unreported fishing in West Africa, 2010–2015 in million $ US$_{2015}$.

Year	Illegal value	Unreported value	Unregulated value	Total IUU
2010	1,459	376	0.1	1,836
2011	1,669	376	6.2	2,052
2012	1,608	543	4.6	2,155
2013	1,831	177	3.8	2,011
2014	1,704	285	11.4	2,000
2015	1,996	263	4.1	2,263
Total	10,267	2,020	30.2	12,317

DISCUSSIONS

This study estimates that illegal fishing in West Africa is responsible for a loss of over $2.3 billion US a year, of which only $13.8 million US/year (2016 baseline) are recovered through MCS. It also sheds light on the types of offenses that are prevalent in the region and the sanctions therein, and through a cross country comparison, illustrates gaps in monitoring. This gap is further illustrated herein by the total economic loss generated by IUU activities amounted 1.8 billion USD in 2010 (<0.1%), when only 1.1 million USD were recovered through fines. The IUU losses then increased to 2.3 billion USD in 2015, when 8.2 million USD was recovered through fines (0.4%).

This study documents 230 observed offenses and ranks them based on the most prevalent ones in the West African sub-region. Over the 23 offense categories, 22 are committed by vessels authorized to fish in the waters of Senegal, The Gambia, Guinea Bissau, Guinea, and Sierra Leone. Under-reporting of the fishing effort is the most prevalent offense, which remains mostly unsanctioned. This offense relates to the fact that fishing fees are paid, mainly, based on the total Gross Registered Tonnage (GRT), and vessels from Asia were found under-reporting their GRT (Greenpeace, 2016b) to reduce their fishing fees. This offense alone could add another 520,000 $ of non-paid GRT fees (Greenpeace, 2016b) to the loss incurred due to IUU fishing. This study also finds that offenses that have a severe impact on small-scale communities were also prevalent with gear related offenses (catching juvenile and prohibited species and fishing in prohibited zones such as artisanal areas). These offense types rank second and third and were more likely to be detected and sanctioned than other offenses. The presence of non-governmental organizations working with small-scale communities enhances the detection of such infractions (Sumaila et al., 2006).

Illegal catches are based on a reconstruction method whose uncertainty is discussed in previous analyses (Belhabib et al., 2016). Over the $2.3 billion US lost to IUU, only $13.8 million were recovered through MCS, in 2016. However, encouraging signs illustrate that while the number of detected offenses is increasing, the average sanction per offense is decreasing, alongside with a change in the profile of offenses to less severe offenses (according to national regulations). The rise of the Ebola crisis has slowed down the ability of MCS units in Guinea and Sierra Leone, and hence the total recovered fine, however, this total continues to increase. By developing the first regional database for offenses and sanctions, this study introduces the first scoring system that ranks MCS in West Africa, by looking at the

TABLE 3 | Scoring of the MCS system in West Africa[8].

Country	Amount (normalized by the maximum average fine)	Number of Fined offenders weighted by maximum in Guinea (max = 5)	Categories fined	log of catch value per shelf km^2	Availability of information	Total score
Senegal	2.29	5.00	9	4.45	2	22.7
Gambia	5.00	5.00	5	5.00	4	24.0
Guinea Bissau	1.03	3.25	3	4.15	2	13.4
Guinea	0.30	3.47	12	3.56	4	23.3
Sierra Leone	2.08	5.00	17	3.43	6	33.5

fine amounts, the number of detected offenders, the categories of offenses that are effectively fined, the illegal catch value and the transparency of the information system, which could be reproduced in other regions of the world, and could be adjusted for data availability. Scoring analysis indicates that despite the Ebola crisis, Sierra Leone was the most effective in detecting and sanctioning (with considerably higher fines) illegal fishing both in number and amounts. This is, however, to be taken with caution, as data on the number of offenses relative to the number of operating vessels were not available at the time of this study. Further, such database could serve as a benchmark for fining and sanctioning, particularly with repeat offenders. Examples show that when information with regards to previous offenses by a vessel is available, the fine is inflated, which is in the advantage of the fining country[9,10].

Illegal catches decreased in Senegal, Mauritania, and Guinea Bissau and increased by 3-fold in Guinea and by 4-fold in Sierra Leone, due mainly to the Ebola crisis, and despite drastic measures such as red cards emitted by the EU. In addition, the suspension of the West Africa Regional Fisheries Programme funded by the World Bank which assured major funding for MCS activities, and Environmental Justice Foundation, which played a major role in both training and enhancing MCS capabilities in Sierra Leone, prompted a major increase in illegal catches in the country. These increases drive the trend of illegal fishing upwards, and hence the value from \$1.8 billion in 2010 to \$2.3 billion in 2015, which cumulates to \$12.3 billion during the same time period. Vessels legally operating in the region are under-reporting the equivalent of 13% of this value.

Overall, the results of this study show that countries of West Africa are vulnerable to IUU fishing, which is not news. The contrast in MCS capacity between Mauritania (Beibou, 2015) and Senegal in the north and Guinea to Sierra Leone in south is evident through the trends in illegal catches. However, Sierra Leone scoring highest for MCS is an indicator that—in the absence of major constraints such as Ebola-, encouraging signs of increased efforts to combat illegal fishing are shown. Even though all these countries are part of the Sub-Regional Fisheries Commission which has joint surveillance capabilities, investment in MCS has been much higher in the northern countries whose wide continental shelves and rich waters are more targeted by illegal fishing fleets, than in the south. This study further reveals that most detected offenses escaping sanctions occurs in countries such as Guinea and Guinea Bissau, where the rate of sanction is very low. Hence, it calls for the implementation of regional measures such as the right of pursuit which allows an offended country to pursuit the illegal fishing boat and to catch it in the EEZ of its neighboring country. Other efforts post-detection of offense should also be used, such as AIS tracing of vessel activities, as a proof of infringement in court, increased fines to disincentivize illegal fishing, and increased regional cooperation.

This study also finds that IUU fishing poses a serious threat to populations dependent on fish stocks and to the very safety of artisanal fishers. Among the most common infractions are incursions by trawlers into the zones reserved for artisanal fishers and these tend to occur at night, regularly causing fishers to lose their fishing gear and canoes, and has even resulted in the loss of lives (Doumbouya et al., 2004). In addition, recent analysis indicate that tackling illegal fishing in the region may result in regaining back 300,000 jobs (Daniels et al., 2016).

This analysis shows an important gap between the value of the loss generated by IUU fishing and the amount IUU vessels are effectively fined. It also shows that higher fines contribute into reducing incentives of illegal fishing through a higher capability of catching offenders (increased resources for MCS), and providing higher incentives to avoid being caught. This study recommends, beyond addressing the lack of human and financial resources for MCS efforts:

- Increased sanctions against e.g., repeat offenders and foreign illegal fishing: This can be done through strengthening the legal system.

Indeed, this study further illustrates that this legal framework exists in some countries of the sub-region, and whenever possible is applied appropriately. Both Guinea and Senegal's new Fisheries Acts inflict historically high sanctions for illegal fishing (Daniels et al., 2016).

- Issues of transparency, low governance and high corruption, and hence effective prosecution need to be addressed in the region: This region of the world is particularly targeted by major external funding for its MCS operations (The World Bank, 2016), capacity is focused on building the MCS network,

[8]Due to the absence of information the Mauritanian MSC was nor considered in this analysis. We note however that this study was done after Mauritania joined the Fisheries Transparency Initiative and hope that similar analysis could be performed for Mauritania in the near future.
[9]http://www.bbc.com/news/world-africa-25621864
[10]http://researcherdiaries.com/2016/07/busted-the-gotland-to-pay-1-5-million-euros-in-fines-to-the-government-of-senegal/

while prosecution for higher fines, or the legislative system that allows for appropriate sanctions may be weak.

Perpetuating lower sanctions and fines makes MCS vulnerable to the availability of funding through external party contributions.

- It is hence very important to use low cost tools such as Automatic Identification System and Vessel Monitoring Systems for effective monitoring, to implement pre-existing legislations, such as the regional right of pursuit that allows countries to either follow or follow up on illegal fishing vessels regionally as illegal fishing takes a form of transnational activity and does not respect national boundaries.

AUTHOR CONTRIBUTIONS

AD, OC, and DB gathered, analyzed and interpreted data, discussed the results and co-wrote the manuscript. EB and AP edited the manuscript and discussed the results, JM, JI, SC, AJ, AG, and DN gathered data and discussed the results.

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The Marine Fisheries in Bulgaria's Exclusive Economic Zone, 1950–2013

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This study presents a reconstruction of the total catch of Bulgarian marine fisheries in the Bulgarian Exclusive Economic Zone for the time period 1950–2013, including previously unreported landings, discards, recreational and subsistence catches. The landings data officially reported by Bulgaria to the Food and Agriculture Organization of the United Nations for the Mediterranean and Black Seas (FAO Area 37) were revised in line with all available information. The reconstructed total catch for 1950–2013 was 1.7 times the (adjusted) baseline data reported by Bulgaria to FAO and 1.5 times the unadjusted data as reported by FAO. This study revealed major deficiencies in the officially reported Bulgarian catch data, foremost the large amount of unreported industrial catches, especially for the last two decades. The exclusion of some fisheries sectors, notably the absence of data on the subsistence and recreational fisheries in reported data are also noteworthy.

Keywords: Black Sea, invasive species, landing, overfishing, small pelagics, unreported catches

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INTRODUCTION

Global fisheries catches have been decreasing in recent decades (Pauly and Zeller, 2016), which has not only impacted the populations of target species (i.e., population size, demographic and genetic characteristics), but has also changed community structure (biodiversity) and the function of the other components of ecosystems (i.e., trophic levels, Pauly et al., 1998, 2002; Daskalov, 2002; Tsikliras et al., 2015).

The impact fishing has on marine ecosystems can be demonstrated at the broadest scale by initially examining the data documenting extractions of the marine resources. Based on this concept, reconstructing the national fisheries catch data set can provide insights into the historical catch time-series and create a more detailed, comprehensive regional dataset (Pauly and Zeller, 2016 and references therein). The aim of this study is to assemble the total reconstructed catch of Bulgaria in the Black Sea, and to provide a comprehensive dataset which includes all marine fisheries removals, such as landings and unreported catches (discards, subsistence and recreational catches) from the Bulgarian component of the Black Sea ecosystem as a baseline for future studies.

Study Area

The Black Sea has a surface area of 422,100 km^2 (excluding the Sea of Azov), and a mean and maximum depths of approximately 1,300 and 2,210 m, respectively. The Black Sea is connected to the Aegean and hence Mediterranean Sea through the Bosphorus and the Dardanelles, which themselves are connected by the Sea of Marmara.

The upper layer of the Black Sea has low salinity (averaging around 17–18 psu) and warmer average summer temperatures (up to 30°C), both of which inhibit the surface layer from mixing with the deeper layer, which has a salinity averaging 22–24 psu and temperatures of approximately 8.5°C. The majority of the Black Sea water column (about 90%), is deeper than 150–200 m and is anoxic and devoid of multicellular life (Oguz et al., 1998). The contrast between the river runoff (mainly from the Danube, Dniester and Dnieper rivers), and high-salinity waters (from the Mediterranean Sea, entering the Black Sea via the Bosphorus Strait) enhance the stratification, and prevent any mixing between surface and deeper layers. Although the lower 90% of the Black Sea basin is devoid of oxygen and contaminated with hydrogen sulfide, the upper layer is productive and provides suitable habitats for numerous epipelagic and neritic species (Zaitsev, 2008).

The Black Sea ecosystem has suffered from several anthropogenic disturbances, such as eutrophication, the introduction of alien species (*Mnemiopsis leidyi*) and the overexploitation of large pelagic predators in the mid- to late twentieth century (Prodanov et al., 1997; Zaitsev and Mamaev, 1997; Caddy, 2008). Eutrophication has dramatically altered the base of the marine food web; additionally, the overexploitation and decline of some fish populations, such as large pelagic fishes, contributed to providing the necessary conditions for successful alien species invasions (Daskalov, 2002).

In 1946, a large sea snail, the invasive rapa whelk (*Rapana venosa*), was first seen in the Black Sea. The rapa whelk was successful in its new environment and became widespread (except in very low salinity areas). It is a notorious predator which feeds on oysters, mussels and other bivalves, and thus exerts a major influence on local populations of malacofauna. In the 1980s, in response to an international demand for sea snails, a massive fishery for the rapa whelk emerged in Turkish waters. Along the Bulgarian coast, a rapa whelk fishery commenced in 1994 (Daskalov and Rätz, 2010), which helped reduce the rapa whelk's impact on its prey species. This may possibly be the only example of a human-induced decline in an introduced species in the Black Sea.

Despite the entire Black Sea ecosystem being affected by these and similar issues, they are all treated as "national" issues, as there is no ecosystem-wide management authority or agreement.

Fishing History

The Bulgarian Exclusive Economic Zone (EEZ) is around 35,000 km^2 (**Figure 1**, http://www.seaaroundus.org), which corresponds to just under 7% of the total Black Sea area (Popescu, 2011). The Black Sea corresponds to Major Fishing Area 37 of the General Fisheries Commission for the Mediterranean (GFCM), Sub-area 37.4; Division 37.4.2, and Bulgaria's fisheries occur within Geographical Sub-area 29.

Bulgaria's continental shelf (to 100 m depth) along the Bulgarian coast is about 40 km wide; the relatively shallow fishing grounds (down to depth of 100–120 m) range from Cape Kartalburun (near the Romanian border) to the Rezevo River (near the Turkish border). The exploitation of fisheries resources is limited to the upper shelf, since depths below 100–150 m are anoxic.

Bulgarian marine fish catches have exhibited trends similar to other Black Sea countries. In the mid-1960s, Atlantic mackerel (*Scomber scombrus*), Atlantic bonito (*Sarda sarda*) and bluefish (*Pomatomus saltatrix*) were the commercially most important species (Ivanov and Beverton, 1985). In the late 1960s and early 1970s, Atlantic mackerel, Atlantic bonito and bluefish catches dramatically decreased in the Bulgarian Black Sea fisheries. Among demersal species, turbot (*Scophthalmus maximus*) was one of the most important commercial species, and catches averaged around 330 $t \cdot year^{-1}$ in the 1960s, but dropped to 12 $t \cdot year^{-1}$ by the 1980s (Zaitsev and Mamaev, 1997). In the 1970s, the over-exploitation of larger pelagic predators, combined with the increased eutrophication of the north-western Black Sea led to a dramatic increase in the catches of small pelagics such as sprat (*Sprattus sprattus*), anchovy (*Engraulis encrasicolus*) and Mediterranean horse *mackerel* (*Trachurus mediterraneus*). The sprat population saw a massive increase in biomass from the mid-1970s and 1980s, and its maximum catch was recorded in 1989, after which the stock collapsed, but later rebounded (Radu et al., 2010). In the late 1980s, an alien invasive ctenophore, the warty comb jelly (*Mnemiopsis leidyi*) reached its maximum abundance in the Black Sea, and thus became a powerful food competitor of adult planktivorous fish, and a significant predator of their eggs and larvae. As a consequence of this and other changes in this Large Marine Ecosystem (LME, Pauly et al., 2008), the rapa whelk has become, since 1995, the most commercially important taxon, followed by sprat.

Modernization of the Bulgarian fishing fleet began just before the 1950s. Industrial or large-scale purse seine and trawl vessels developed in the 1950s. In the 1960s, however, Bulgaria began to buy high-seas fishing and support vessels from the Soviet Union, Poland and East Germany, and began to build infrastructure for fish processing. From 1965 to 1990, Bulgaria owned a large high-seas distant-water fleet (consisting of 30 high-capacity trawlers and 6 transport vessels) that was actively engaged in the Atlantic and in the south-eastern Pacific. This fleet was liquidated in the early 1990s after the collapse of the former USSR, and the Bulgarian fishing fleet refocused their efforts on the Black Sea coastal zone (Popescu, 2011). In the 1970s, approximately 80% of marine catches came from the industrial fisheries, and the remainder came from the artisanal sector, which used mainly passive gears (Kumantsov and Raykov, 2012). In 2008, the Bulgarian fleet consisted of 2,547 vessels with a total gross tonnage (GT) of 8,378 and total kilowatts (kW) of 63,860 (**Table 1**). The small-scale sector represented 96% of the fishing fleet in term of vessel numbers, i.e., 2,440 vessels under 12 m in length, and was responsible for landing around 57% of the Black Sea catch (Radu et al., 2010). Throughout this study, we use the term "industrial" to refer to the large-scale commercial sector, and "artisanal" to refer to the small-scale commercial sector.

Bulgarian fisheries policy is shaped by several international fisheries agreements (i.e., UNCLOS, UNCLOS, CITES) and the European Union Common Fisheries Policy (since its entry into the European Union in 2007). The country is also a member of General Fisheries Commission for the Mediterranean

FIGURE 1 | Exclusive Economic Zone (EEZ) and continental shelf (to 100 m depth) of Bulgaria in the Black Sea.

(GFCM) and the FAO. The National Agency for Fisheries and Aquaculture within the Ministry of Aquaculture and Food is the executive body responsible for national policy on fisheries and aquaculture and implements the Fisheries Legislation in Bulgaria. In this context, Total Allowable Catches (TACs) for sprat and turbot were set in the mid-late 2000s. Some other management implementations include a licensing system for fishers, effort control via limiting fishing gear, engine power and vessels; seasonal closures are imposed to protect some stocks during their reproductive periods; and closed areas and bans of bottom trawling and dredging are imposed. Since 2012, beam trawling is allowed only in selected areas. No permit or licenses are required to participate in the marine recreational fishery.

"Industrial" (Large-Scale) Fishery

In 2008, the industrial fleet consisted of 108 vessels >12 m in length. Sprat is to this day targeted mainly by large-scale pelagic trawlers seasonally from February to November. Whiting (*Merlangius merlangus*), turbot, anchovy, shad (*Alosa* spp.), Mediterranean horse mackerel and red mullet (*Mullus barbatus*) are incidentally caught as by-catch (Radu et al., 2010), but sold commercially. The bottom trawl fishery began to develop for turbot in the 1950s, but was banned in 1994 to protect declining turbot stocks and beds of Mediterranean mussel, *Mytilus galloprovincialis* (Konsulova et al., 2001).

Dredges and beam trawlers were used in the rapa whelk fishery, but were also banned in 2001 to protect vulnerable benthic biotic communities such as mussel beds. Note that dredge and beam trawl fisheries may be classified as small-scale fisheries in Bulgaria, as domestic classification is based on vessel size only. However, for the purposes of the *Sea Around Us* (www.seaaroundus.org), any fishing gears that are actively dragged across the sea-floor or through the water column using engine power are considered "industrial" (i.e., large-scale), following Martín (2012).

TABLE 1 | Composition of the Bulgarian fishing fleet in 2008 (Radu et al., 2010).

		Length (m)				
		<6 m	**6–12**	**12–18**	**18–24**	**24–40**
Registered vessels		842	1598	68	27	12
Active vessels		213	434	45	13	11
Active gear	Pelagic trawlers	0	3	8	2	11
	Other gear	22	115	17	4	0
Passive gear	Hook and line	14	23	2	0	0
	Drift/fixed netters	166	224	8	1	0
	Pots/traps	3	33	1	0	0
	Other passive gear	2	11	0	0	0
Variable gear	Active and passive gear	6	25	9	6	0

"Artisanal" (Small-scale Commercial) Fishery

The coastal fishery has traditionally been carried out by small vessels (<12 m) which use mainly passive fishing gear, such as trap nets (uncovered pound nets), and beach seines in the inshore area. Here, these vessels/gears are considered "artisanal." Pound nets are deployed in 9 to 12 m depth in coastal inshore waters (Radu et al., 2010) from March to November, and target species vary according to season: sprat is targeted during spring and the beginning of summer, and anchovy and Mediterranean horse mackerel are targeted in summer and autumn. Whiting, turbot, red mullet and other demersal species are incidentally caught as by-catch, but retained for commercial sale (Radu et al., 2010). The set gillnet fishery operates in the coastal and offshore waters of Bulgaria and targets primarily turbot, while dogfish (*Squalus acanthias*), thornback ray (*Raja clavata*), common stingray (*Dasyatis pastinaca*) and sturgeons (Acipenseridae) are often incidentally caught as by-catch (Radu et al., 2010). The number of vessels operating by LOA (length overall) in 2008 is given in **Table 1**.

METHODS

Reported Catch Data

The baseline data used for the work presented here are the catch statistics submitted annually by Bulgaria to FAO which are incorporated into the global database (FishStat; www.fao.org/fishery/statistics/software/fishstatj/en), complemented by national Bulgarian data published by Prodanov et al. (1997); Mikhailov and Prodanov (2003), and Panayotova et al. (2012). Tunas and other large, highly migratory pelagic fishes (e.g., swordfish), which were originally abundant in the Black Sea, are not considered here.

According to the data reported by FAO on behalf of Bulgaria in the Mediterranean and Black Seas (FAO Area 37, release date March 2015), total catches appeared very high for the years between 1964 and 1969 (driven by high values for "marine fishes nei," i.e., "marine fish not elsewhere identified"). On closer inspection of Bulgarian FAO data for areas other than 37, it was found that duplicate "marine fishes nei" (or Miscellaneous Marine Fishes, MMF) values had been reported for Bulgaria fishing in three other areas (the central-eastern Atlantic, south-eastern Atlantic and north-western Atlantic), i.e., the exact same values were present in all three areas. By comparing FAO data with Northwest Atlantic Fisheries Organization (NAFO) data, it was found that these MMF values were indeed incorrect. It was therefore assumed that the reported catch for FAO Area 37 (Mediterranean and Black Seas) also had these values mistakenly added on to the real reported MMF catch. We therefore subtracted the duplicated MMF tonnage reported in the other areas from the MMF in FAO Area 37 for the years 1964–1969. This resulted in an adjusted FAO baseline, which was used for the rest of the reconstruction as reported baseline data. We suggest Bulgaria formally request a retrospective data correction of FAO data.

Since all taxa were reported as "marine fishes nei" from 1950 to 1963, we disaggregated this category taxonomically by using reports of national data to assign most of the tonnage to specific species or families (Prodanov et al., 1997; Mikhailov and Prodanov, 2003; Panayotova et al., 2012). Any remaining tonnage was kept as "marine fishes nei." These national reports were also used to improve the catch data from 1964 to 1969, as much of these data still remained as MMF and many species/families had rounded, estimated values listed.

Unreported Catches

Unreported catches as defined here include unreported commercial, subsistence and recreational catches, as well as discarded catch.

Commercial Catches

Sprat has been the main catch for Bulgaria since 1970. However, published reports on Bulgarian fisheries have clearly documented that some commercial sprat catches have gone unreported (Mikhailov and Prodanov, 2003; Daskalov and Rätz, 2010). On average, Daskalov and Rätz (2010) estimated of actual catches for 1992 and 1993 were 55% higher than the reported sprat catches in 1990 and 1991. From 1994 to 1999 sprat catches were assumed to have been under-reported by the same ratio and averaged 1.79 times higher than reported data (Daskalov and Rätz, 2010), and were used to estimated unreported sprat component for 2000 and 2001. The ratio was not applied to the years 2002–2003, as the reported data exhibited a spike in these years and it was assumed that reporting coverage was more complete in this time period. Therefore, in order to remain conservative, we linearly interpolated the unreported tonnage from 2001 to 2004. There was also an expert assessment in 2007 which estimated catches to be 2,985 t as opposed to 2,559 t (EU, 2008), with FAO using the former value. Thus, we assume that catches were fully reported in 2007 and use the ratio (unreported = 0.17*reported) between the two 2007 estimates in Daskalov and Rätz (2010) to obtain a conservative estimate of unreported catches in 2008–2013. We also assumed there to be a much lower likelihood of under-reporting from 1950 to 1989 (during communist rule), and therefore added a conservative 10% of landings to account for under-reporting of sprat during that period.

In Bulgaria, marine bivalve catches include the striped Venus clam (*Chamelea gallina*), bean clam (*Donax* spp.) and mussel. According to information available at the FAO (http://www.fao.org/fi/oldsite/FCP/en/bgr/body.htm), the 2000 FAO reported data for rapa whelk equated to 90% of the total shellfish catch. We considered the remaining 10% to be comprised equally of *C. gallina*, *Donax* spp. and miscellaneous marine molluscs ("marine molluscs nei") for the 1994 to 2013 period.

Some sturgeons are anadromous or potamodromous, as in the case of the sterlet sturgeon (*Acipenser ruthenus*) (Mikhailov and Prodanov, 2003); thus, *A. ruthenus* was excluded from consideration in the present study. While the fringebarbel sturgeon (*Acipenser nudiventris*) is commercially extinct, the beluga sturgeon (*Huso huso*) and the Russian sturgeon (*Acipenser guldenstaedti*) are still commercially important in the Bulgarian fishery. Wild caviar export data were used to estimate unreported sturgeon catches from 1998 to 2006 (Kecse-Nagy, 2011; **Table 2**). We converted caviar weight to fresh fish weight for *H. huso*, *A. gueldenstaedti* and *Acipenser stellatus*, using gonado-somatic coefficients from Jivkov et al. (2003), and then estimated catches by using the sex ratio of the same three species (**Tables 2, 3**).

Bulgaria became a member of the European Union (EU) in 2007, and intra-EU trade no longer appears in the CITES (Convention on International Trade in Endangered Species of Wild Fauna and Flora) data for caviar exports. It is likely that caviar export to other EU countries have continued after 2007 without being recorded in CITES data, and the estimated unreported catch in 2006 was thus used as estimate for the years 2007 to 2013.

TABLE 2 | Wild origin caviar exports used to estimate sturgeon catches (wet weight) in Bulgaria (from the CITES Trade Database; Kecse-Nagy, 2011).

	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Exported caviar (kg)	2,392	2,025	2,788	992	2,337	1,563	920	1,421	667	–	–	–	–
Estimated female (t)	13	11	15	6	13	9	5	8	4	–	–	–	–
Estimated male (t)	40	34	46	17	39	26	15	24	11	–	–	–	–
Estimated total (t)	53	45	62	22	52	35	20	32	15	–	–	–	–
Unreported catch (t)	39	33	59	22	45	31	16	30	15	15	15	15	15

Rapa whelk has become a commercially valuable resource with high demand on the international market. In Bulgaria, this fishery commenced in 1994 and rapa whelk were originally caught by scuba divers. However, shortly thereafter, there was illegal rapa whelk fishing by bottom trawlers, beam trawlers and dredgers (Daskalov and Rätz, 2010). For the period from 2000 to 2010, the bulk of rapa whelk catches were illegally taken by dredges and beam trawls (V. Raykov, pers. obs.). We estimated an unreported catch component for rapa whelk based on export data for the period from 2002 to 2010 (**Table 4**). The same percentage rates for the select processing types of rapa whelk in 2009 (Daskalov and Rätz, 2010) were used and applied to the 2002–2010 period to disaggregate the unreported catch component. Since rapa whelk is exported without its shell, the exported amounts first had to be converted to equivalent weights with shell on, to account for total fishery removals. A rate of 85.8% of total weight was added to both the frozen meat and sweetbread rapa whelk exported amounts to account for this (Düzgüneş et al., 1988). Unreported rapa whelk catches were interpolated from zero in 1993 to the estimate of 12,313 t in 2002 that came from the export data. Finally, the ratio of reported to unreported rapa whelk catches in 2010 was applied to the 2011–2013 reported data.

An unreported catch of turbot (*Scophthalmus maximus*) taken by Bulgaria was estimated from sources stating that Bulgarian fishers also have under-reported their own turbot catches from the Bulgarian EEZ in recent years (total estimated at 300 t·year^{-1}; EU, 2009). The total turbot catch was accepted as 250 t·year^{-1} to avoid over-estimation, and this was used as an anchor point in 2007 (last year of data in the EU, 2009 report). To remain conservative, the unreported catch was then interpolated from zero in 1994 (year before turbot catches started again) to 183 t in 2007 (difference between 250 t and the reported amount). The ratio of reported to unreported data in 2007 was then applied to the reported data from 2008 to 2013. We also assumed some turbot catches to have been unreported throughout the 1950–1989 period, but to a much lesser extent. Thus, from 1950 to 1989, an additional 10% of the reported turbot catch amount was estimated to have been unreported, and added to the reported component.

Lastly, there were also data in the national reports used above (Prodanov et al., 1997) from an expert assessment of whiting (*Merlangius merlangus*) that we incorporated, and which indicated that catches were severely under-reported from 1975 to 1993.

TABLE 3 | Gonado-somatic coefficients (G) and sex ratio (female: male) for sturgeons in Bulgaria (adapted from Jivkov et al., 2003).

Species	G (%)	Sex ratio	Species contribution (%)
Huso huso	18	3:1	83
Acipenser gueldenstaedti	16	1:1	10
Acipenser stellatus	16	2:1	7

Discards

To estimate discards, published reported discard rates by select fisheries from the Black Sea and eastern Mediterranean were sought, which included both industrial (mid-water trawl, bottom trawl, purse seine, dredge) and artisanal fisheries (gill and trammel nets, hand line, long line, fish pound net, beach seine net). These discard rates were then applied to the reported data for each of the target species for each fishery with the help of expert advice (**Table 5**). Given that discard rates were only applied to reported catches (and thus represent minimum estimates of discards), the discards of the rapa whelk fishery are likely considerably underestimated as there was a substantial unreported landings component to that fishery.

Whiting contribute greatly to the trawl catches in the Black Sea, but are not a targeted fishery and are mostly discarded by Bulgarian fishers (Raykov et al., 2008). In neighboring

TABLE 5 | Discard rates applied to select fisheries in Bulgaria.

Ecosystem	Fishing gear	Discards (%)
Marmara Sea[a]	Bottom trawl	16.2
Black Sea[b]	Sea snail dredge	11.5
Global[b]	Bottom long line	8.2
Global[b]	Beam trawl	7.5
Black Sea[b]	Mid-water trawler	5.1
Global[b]	Beach seine	4.4
Global[b]	Hand line	1.8
Black Sea[c]	Purse seine	1.0
Global[b]	Gill net and trammel net	0.5
Global[b]	Pound nets, weirs	0.5

[a] *Zengin and Akyol (2009).*
[b] *Kelleher (2005).*
[c] *Şahin et al. (2008).*

TABLE 4 | Exported rapa whelk tonnages (NAFA, Bulgaria for the purposes of National report of Focal point of Bulgaria to AG FOMLR, BCS).

Type of Rapa whelk	2002	2003	2004	2005	2006	2007	2008	2009 (%)	2010
Frozen	284	343	302	269	351	436	324	146 (13)	167
Frozen sweetbread	656	792	698	620	811	1,005	747	326 (30)	386
Frozen meat	1,136	1,373	1,209	1,075	1,405	1,743	1,295	572 (52)	668
Frozen meat with shell	109	132	116	103	135	168	125	59 (5)	64
Exported	2,185	2,641	2,325	2,067	2,702	3,351	2,491	1,104 (–)	1,285

In 2009, the processed category percentage is given in brackets (adapted from Daskalov and Rätz, 2010, Table 4.7.3.1).

Romania, the whiting portion of reported demersal catches was 42% from 2000 to 2006 (Maximov and Staicu, 2008). To account for discarded whiting in Bulgaria, an additional 20% was conservatively assumed to account for this component and was applied to the reported catches of demersal taxa by industrial bottom trawls from 1950 to 1994 (as bottom trawling was banned after 1994).

Recreational and Subsistence Catches

Recreational fishing is understood here to mean fishing primarily for leisure or enjoyment, while subsistence fishing is understood to mean fishing for the primary purpose of providing protein for self- or family-consumption (recreational and subsistence fisheries are here assumed not to generate discards) While the two sectors are difficult to separate, it is generally understood that subsistence fishing over time evolved into recreational fishing, as incomes increased and food security was no longer a primary concern.

In Bulgaria, recreational fishing is most popular from April to June, and from September to November. It occurs in inshore waters and targets gobies (Gobiidae), grey mullets (Mugilidae), horse mackerel, bluefish, Atlantic bonito, turbot, Mediterranean horse mackerel and garfish (*Belone belone*). However, no data on the number of recreational fishers and/or their catch rates or amounts have been collected in Bulgaria.

There has been both recreational and subsistence fishing in Bulgaria for the 1950 to 2010 period. Since no data on this topic exists, estimated catch rates from the Black Sea coast of Turkey were used as a starting point (Ulman et al., 2013) to estimate recreational and subsistence catches, i.e., 0.258 t·fisher^{-1}·year^{-1} in 1950 and 0.129 t·fisher^{-1}·year^{-1} in 2010. To derive the number of recreational/subsistence fishers for Bulgaria, we assumed that in 1950, 2% of the coastal population fished either recreationally and/or for subsistence purposes, and this rate was linearly decreased to 0.95% of the coastal population by 2013 due to the declining availability of larger fish. To derive the coastal population, we started with total population data from Populstat (1950–1959; http://www.populstat.info) and The World Bank (1960–2013; www.data.worldbank.org) and then assumed that only people living within 20 km from the coast were involved in these fisheries. The coastal population data, however, was only available for 100 km from the coastline (CIESIN, 2012); therefore, we conservatively assumed 25% of the population within 100 km of the coast were actually living within 20 km of the coast. The coastal population data was also only available for the years 1990, 2000, and 2010. Therefore, we used the proportion of total population living 100 km from the coastline in 1990 and applied this from 1950 to 1989 and the proportion for 2010 was applied to 2011–2013. We then also interpolated the proportion between the 1990 and 2000 anchor point, as well as the 2000 and 2010 anchor point and applied this to the total population. We then reduced the catch rates used for Bulgaria by 50% from that used for Turkey in 1950, i.e., 0.129 t·fisher^{-1}·year^{-1}, and 20% in 2010, i.e., 0.103 t fisher^{-1}·year^{-1}, since recreational fishing appeared to be less intensive than in Turkey (V. Raykov, pers. obs.); the interpolation was carried forward to 2013. We also made an adjustment to the catch in the early 1990s, as all fisheries were affected by a massive invasion of ctenophore in the Black Sea, which was deemed a “fisheries crisis” and resulted in a temporarily collapse of the pelagic fisheries (Daskalov, 2002). In light of this crisis, from 1989 to 1991, we decreased the recreational/subsistence catch rates by a further 75%. The newly adjusted 1991 value and the 1993 catch amount were then interpolated as there was a quick recovery period for small pelagics. In order to assign the estimated recreational/subsistence catches to the two sectors, we assumed that in 1950, 70% of these catches were taken for subsistence purposes, which was linearly decreased to 30% by 2010 (with decline carried forward to 2013), and the remaining catches were assigned to the recreational fishery (i.e., increasing from 30 to 70%). Sturgeon, Atlantic bonito, Atlantic mackerel, bluefish, turbot, Mediterranean horse mackerel, grey mullet and gobies were the main recreational/subsistence taxa for the 1950–2013 period (**Table 6**). We assumed that the overwhelming majority recreational/subsistence fishers operate from shore.

RESULTS

The reconstructed total catch for the marine fisheries of Bulgaria for 1950–2013 was estimated to be 1.7 times the (adjusted) data reported by FAO for the Black Sea fisheries of Bulgaria (**Figure 2A**). Total catches were only slightly higher than those reported by the FAO (after adjustment for likely over-reporting) on behalf of Bulgaria up until 1993 (just before the rapa whelk fishery commenced). Total catches increased from an annual average of around 5,800 t·year^{-1} in the 1950s (only slightly

TABLE 6 | Catch composition (%) for recreational and subsistence catches in Bulgaria from 1950 to 2013 (based on V. Raykov unpublished data).

Taxon	1950–1959	1960–1969	1970–1979	1980–1989	1990–1999	2000–2013
Atlantic bonito	35	30	5	1	1	2
Atlantic mackerel	25	22	5	2	–	–
Bluefish	15	20	10	2	1	2
Horse mackerel	3	3	50	60	50	35
Grey mullet	5	5	15	20	23	30
Goby	2	2	13	15	25	30
Turbot	10	15	1	–	–	1
Sturgeon	5	3	1	–	–	–

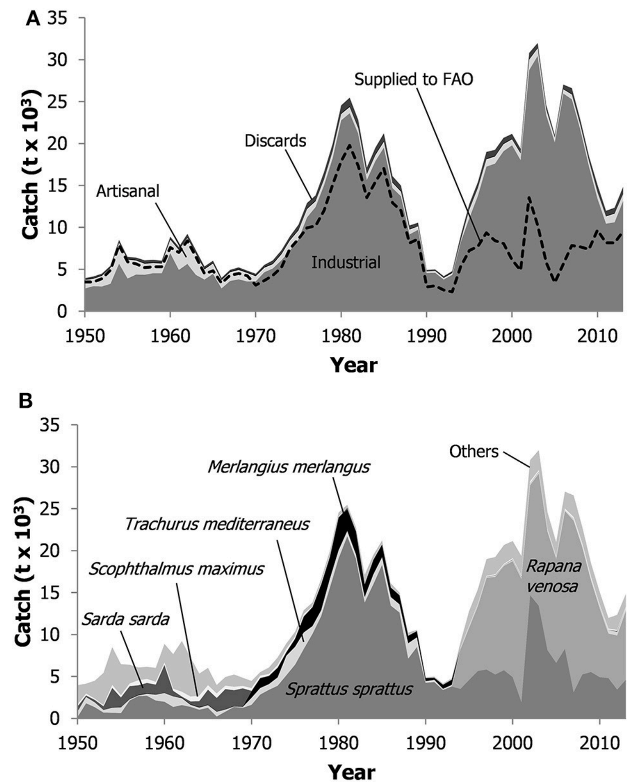

FIGURE 2 | Reconstructed total catches for Bulgaria in the Black Sea, 1959–2013. (A) Landings by fisheries sector + discards; officially reported data as reported by FAO (adjusted for duplicate reporting between 1964 and 1969) on behalf of Bulgaria are overlaid as line graph. Subsistence and recreational catches are included, but too small to be visible; **(B)** by major taxa. The category "others" consists of 38 additional, minor taxa. The significant reduction in fishing around 1990 resulted from the privatization of the fishing fleet from a state-owned industry.

higher than the 5,100 t·year^{-1} reported by the FAO on behalf of Bulgaria) to a peak of 25,500 t in 1981 (of which 19,800 t were reported; **Figure 2A**). Catches declined to a low in the early 1990s with an estimated 4,700 t·year^{-1} and then increased to a second peak of 32,000 t in 2003, before declining to an average of 13,600 t·year^{-1} at the end of the time period (2010–2013). Total reconstructed catch was on average only 1.2 times the adjusted reported data from 1950 to 1989, and increased to 1.9 times in the 1990s (**Figure 2A**), and were then, on average, 3.1 times for the rest of the time period (**Figure 2A**; Appendix Table 1 in Supplementary Material). The reconstructed total catch consisted of reported industrial landings (54%), unreported industrial landings (34%), industrial discards (3.3%), reported artisanal landings (6.1%), unreported artisanal landings (0.6%), artisanal discards (0.1%), subsistence catches (0.9%), and recreational catches (0.8%).

Total industrial catches increased from 4,100 t·year^{-1} in the 1950s, to a peak of 24,600 t in 1981. Catches then declined to a low of 3,900 t in 1992. Catches increased in 1994, due to the opening of the rapa whelk fishery, to a second peak of 31,000 t in 2003, before declining to an average of 12,600 t·year^{-1} at the end of the time period (2010–2013, **Figure 2A**). Industrial unreported catches were 41% of the reconstructed total industrial catch (37.5% unreported landings and 3.6% discards). Unreported industrial landings increased throughout the time period, from 3% of the industrial catch in the 1950s to an average of 20% and 17% in the 1970s and 1980s, respectively. Unreported industrial landings increased rapidly in the mid-1990s due to the rapa whelk fishery and averaged 58% in the 2000s.

The discards from the industrial and artisanal fisheries amounted to 3.3 and 0.1%, respectively, of the reconstructed total catches (**Figure 2A**). Discards increased from 210 t·year^{-1} in the 1950s to 780 t·year^{-1} from the late 1970s to late 1980s. Discards then decreased to 130 t·year^{-1} in the early 1990s but increased again to an average of 570 t·year^{-1} for the rest of the time period. The main discarded species were sprat (55%), rapa whelk (26%), whiting (8%), turbot (4%) and Mediterranean horse mackerel (1%).

Reconstructed total catches were mostly composed of sprat (47%), rapa whelk (28%), Mediterranean horse mackerel (4%), whiting (4%), Atlantic bonito (3%) and turbot (2%; **Figure 2B**, Appendix Table 2 in Supplementary Material).

DISCUSSION

The prospects for the marine fisheries in the Bulgarian EEZ are limited by the specific characteristics and production potential of the Black Sea ecosystem, especially by its limited shelf area. Another constraint is the limited biodiversity, which is under constant threat. There are only 134 fish species recorded in the Bulgarian section of the Black Sea (Stefanov, 2007). During 1960–1970, 26 of these fish species were commercially targeted, which decreased to 5 major target species by the 1980s (Zaitsev and Mamaev, 1997). Our results show three separate periods revealing distinctive catch compositions for the Bulgarian coastal waters: (1) from 1950 to 1969, the major species caught were sprat and Atlantic bonito; (2) from 1970 to the mid-1990s, catches were dominated by sprat; and (3) and from the mid-1990s onwards, catches were dominated by rapa whelk, still with a large contribution of sprat (**Figure 2B**).

The contribution of Bulgarian fisheries catches to total Black Sea catches is low, only slightly over 2% of Turkey's reconstructed total catch from 1950 to 2010 (Ulman et al., 2013). On the other hand, the reconstructed total catch for 1950 to 2013 was 67% higher than the data submitted by Bulgaria to the FAO. Most of the unreported catches were deemed to have occurred after 1990, since reporting and control measures were much stricter in the planned economy of the earlier period, as was the case for neighboring Ukraine (Ulman et al., 2015). Total commercial catches in the Black Sea significantly decreased after the collapse of the Black Sea pelagic fisheries at the end of the 1980s due to overfishing, a trophic cascade and the ctenophore invasion (Daskalov, 2002; Daskalov et al., 2007). The catch dynamics of the most important species in the Bulgarian Black Sea shelf zone illustrate a prominent decreasing trend beginning in the 1990s.

On a sectoral basis, the reconstructed total catch of Bulgaria was similar to that of the Turkish Black Sea (Ulman et al., 2013), both having a small artisanal catch component (7–15%) and a much higher industrial component (75–90%), although, as stated above, the catches of Turkey slightly under of Bulgaria. Bulgaria's reconstructed total catches differed from that of Romania, in terms of its much lower artisanal catch contribution (7% for Bulgaria compared with 66% for Romania) due to the highly popular traditional Romanian fishing method "crawling" (a stationary inshore net deployed in shallow waters) which was the main fishing technique used in Romania until the 1980s (Ulman et al., 2015). The reconstruction for Ukraine demonstrated that the national catch statistics included only commercial large-scale landings and failed to include small-scale, recreational or artisanal catches (Ulman et al., 2015), and at present are just over 6 times that of Bulgaria's marine fisheries.

The three distinct periods of catch, characterized by three distinct ecological shifts, can be distinguished in the catch composition of Bulgarian fisheries: during the first and second periods, the catch composition was similar to that of other Black Sea countries in terms of dominance by pelagic fishes, i.e., larger pelagics in the first period and small pelagics in the second. The third period differed from the trends in other Black Sea countries owing to a high rate of rapa whelk catches in Bulgaria. During this third period, targeted species were small pelagic fish (i.e., sprat, Mediterranean horse mackerel, anchovy) and demersal fishes (turbot, gobies, dogfish and most recently red mullet), while the rapa whelk gained the prominent role in the commercial fisheries. Although the introduction of the rapa whelk contributed to the fisheries economy after 1993, high disturbance to the benthic ecosystem from destructive fishing practices (dredging and beam trawling) resulted in negative ecological effects on benthic communities, especially on the Mediterranean mussel beds (Konsulova et al., 2001; Daskalov and Rätz, 2010), as also noticed in neighboring Ukrainian waters where macrobenthos biomass was reduced 20-fold due to intense trawling (Ulman et al., 2015). Taking into consideration the amount of illegal unreported rapa whelk taken from Bulgarian, Ukrainian (Ulman et al., 2015) and Turkish waters (Ulman et al., 2013), habitats and biodiversity are likely much more under threat from illegal mobile bottom-fishing gear than previously assumed.

Russia, Ukraine, Bulgaria, Romania, Turkey and Georgia all share the stocks of migratory Black Sea species. Cold-water small pelagics complete their entire life cycle in the Black Sea, seasonally migrate to reach wintering areas in the south and return to feeding and spawning areas in the following spring in the north (Ivanov and Beverton, 1985). In contrast, larger warm-water pelagics, such as bluefish, Atlantic mackerel and Atlantic bonito are highly migratory, i.e., move from the Sea of Marmara or to the Eastern Aegean Sea through the Bosphorus, then swim westwards and northward along the Bulgarian and Romanian coasts to reach their summer feeding grounds in the western and northwestern Black Sea (Demir, 1957; Türgan, 1959).

The northwest and western region of the Black Sea, with its large shallow continental shelf areas and high nutrient inputs by rivers provide highly productive waters, which are suitable for spawning and feeding. Sprat, a cold-water species, prefers the coldest habitable portions of the Black Sea, as the shoals move toward coastal waters in the northwest in winter and offshore in autumn (Ivanov and Beverton, 1985). Mediterranean horse mackerel are a warm-water migratory species which pass from south to north to spawn along the Bulgarian coast in spring, and from north to south for feeding in autumn. These two species also provide seasonal catches in the Bulgarian EEZ.

Turbot is the main commercial demersal fish species and is mainly found in the western and northwestern shelf of the Black Sea along the coasts of Bulgaria, Romania and Ukraine. Its migration along the shelf links shallow waters (in spring, for spawning) and deeper waters (in winter, for feeding). The previously discussed illegal turbot catch (by Turkish fishers) from Bulgarian and Romanian waters (Ulman et al., 2013; Banaru et al., 2015), points to a need of a common policy between member countries (Bulgaria and Romania), and cooperation with the remaining four non-EU bordering countries to recover turbot stocks to a previous larger-size and population levels.

In the Black Sea, the status of turbot and anchovy stocks were reported as "overexploited" and "in overexploitation," respectively, the Mediterranean horse mackerel stock was reported as "overexploited" and the dogfish population was considered "depleted" at the Black Sea scale. In contrast, Black Sea sprat stocks were deemed as sustainably exploited (GFCM, 2014).

This study illustrates some major deficiencies in the nationally (and hence internationally) reported fisheries data, such as the exclusion of some fisheries sectors, notably the absence of any catches stemming from subsistence and recreational fisheries. We feel that our estimates of total marine fisheries catch for Bulgaria provide a more accurate and comprehensive baseline, which should be further improved through targeted studies of the previously omitted sectors.

The European Union's Marine Strategy Framework Directive, 2008/56/EC (MSFD), the first legislative instrument dedicated to protecting biodiversity for all of Europe's regional seas by 2020, seeks to achieve a Good Environmental Status (GES) in European Seas by protecting the resource base. Although the MSFD seeks to foster the ecosystem approach, environmental protection and sustainable use, if all resource users are not made to fish sustainably, it is highly unlikely that the directive will work. In the Mediterranean and Black Sea basins, the regions in most peril from overexploitation are the Black Sea and the Eastern Mediterranean (Tsikliras et al., 2015). The main driver for the high rate of exploitation is likely the overcapacity of the Turkish large-scale commercial fishery. As long as rebuilding stocks to some optimal former level is not prioritized by all shared users of the Black Sea (Ulman, 2014), it will remain at its current degraded state yielding mainly low value species such as sprat and anchovy, and the future of the fisheries will remain questionable.

This reconstruction of marine fisheries catches for Bulgaria provides an improved baseline for its marine fisheries, to help understand the impact fisheries have had, and to help the implementation of management rules of the MSFD. Because of the many assumptions that were made, some parts of this reconstruction will be very uncertain, however. Thus, readers are welcome to send suggestions for corrections, updates and/or other improvements via www.seaaroundus.org, from which the detailed data underlying this reconstruction can also be downloaded.

AUTHOR CONTRIBUTIONS

The original methodology was decided upon by DZ. VR and GD provided some of the background data. ÇK, AU, KZ, and DZ helped calculate the methodology. ÇK, AU, KZ, VR, GD, DP, and DZ contributed to both the writing and editing of the paper.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: http://journal.frontiersin.org/article/10.3389/fmars.2017.00053/full#supplementary-material

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Analysis of Long-Term Changes in a Mediterranean Marine Ecosystem Based on Fishery Landings

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In the Mediterranean Sea, structured and standardized monitoring programs of marine resources were set only in the last decades, so the analysis of changes in marine communities over longer time scale has to rely on other sources. In this work, we used seven decades (1945–2014) of disaggregated landings statistics for the Northern Adriatic Sea (Mediterranean) to infer changes in the ecosystem. Analysis of landings composition was enriched with the application of a suite of ecological indicators (e.g., trophodynamic indicators, such as the primary production required to sustain the catches—PPR; size-based indicators, such as the large species indicator—LSI; other indicators, such as the elasmobranchs-bony fish ratio—E/B ratio). Indicators were further compared with main ecosystem drivers, i.e., fishing capacity, nutrient loads and climate change. Species most vulnerable to fishing (i.e., elasmobranchs and large-sized species) dramatically declined at the beginning of the industrialization of fishery that occurred right afterwards World War II, as can be inferred by the negative drop of LSI and E/B ratio in the mid-1950s. However, until the mid-1980s landings and PPR increased due to improvements in fishing activities (e.g., the introduction of more efficient fishing gears) increasing fishing capacity, high productivity of the ecosystem. Overall, the effects of fishing were buffered by an increase in productivity in the period of high nutrient discharge (up to mid-1980s), while significant changes in fish community structure were already occurring. From the mid-1980s, a reduction in nutrient load caused a decline in productivity but the food-web structure was already modified and unable to support, or recover from, such unbalanced situation, resulting in the collapse of landings. This collapse is coherent with alternative stable states hypothesis, typical of complex real systems, that implies drastic interventions that go beyond fisheries management and include regulation of nutrient release for recovery. The work highlights that, despite poor capabilities to track species dynamics, landings and applied indicators might help to shed light on the long-term dynamics of marine communities, thus contributing to place current situation in an historical framework with potential for supporting management.

Keywords: landings, marine historical ecology, ecological indicators, long-term changes, ecosystem drivers, Adriatic Sea

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INTRODUCTION

Long-term analyses of the interactions between human society and the oceans are necessary for understanding the processes that brought the marine ecosystems as we see today, avoiding the so-called "shifting the baseline syndrome" and understanding the magnitude and causes of change (Pauly, 1995; Jackson et al., 2001). In this framework, marine historical ecology (MHE) can bring a significant contribution to present-day management of marine ecosystems, both for conservation and for sustainable exploitation of resources (Engelhard et al., 2015). However, often the analyses of historical changes in marine communities cannot be based on results of structured and standardized monitoring programs, since in most of the cases those were set in the very last decades. The need to bridge the gap between request of knowledge on past status of ecosystems and the available monitoring data, triggered the uses of different approaches to extract information from data coming from other sources, including paleontological, archeological, and historical sources, as well as the use of landings (e.g., Rosenberg et al., 2005; Sàenz-Arroyo et al., 2005; Lotze et al., 2006; Fortibuoni et al., 2010, 2016; Van Beveren et al., 2016).

In this context, detailed and disaggregated fishery statistics represent an important source of information that can be used as proxies to evaluate long-term changes in marine fisheries and communities. Changes in the composition of landings, evaluated through opportune weighting metrics (indicators), showed to reflect changes in the structure of underlying fish communities due to anthropogenic impacts and environmental changes (e.g., Caddy, 1993; Pauly et al., 1998; de Leiva Moreno et al., 2000; Pinnegar et al., 2002; Libralato et al., 2004; Pauly and Watson, 2005; Baeta et al., 2009; Munyandorero and Guenter, 2010; Kleisner et al., 2013). Moreover, catch statistics are recognized to be linked to fishing and environmental pressures and respond selectively to management action (Coll et al., 2016).

Nevertheless, the intrinsic limitations of fishery-dependent data—such as landings—include the lack of standardization, the dependence from fishing fleet activity features as well as market preferences of products that usually change across time and space. All this imposes caution in deriving marine population densities directly from catch statistics (e.g., Essington et al., 2006; Pauly et al., 2013).

The capability to connect modification in landings composition to changes in the community at sea is more robust when local disaggregated landings result from multi-target and multi-gear fisheries (i.e., several distinct métiers), and when changes in fishing activities (e.g., introduction of new technologies, shift from one fishing gear to another, shift in fishing grounds, fishing capacity as number and tonnage of boats) are traceable. In this context an important aspect to be considered is the trend in indices over time, rather than the absolute values they assume, being reference points or limit values for many indicators not yet been established (Shin et al., 2010).

The Northern Adriatic Sea (Mediterranean Sea) represents a valuable case study for MHE, due to the long history of exploitation (Botter et al., 2006; Fortibuoni, 2010), human-induced changes (Lotze et al., 2011), as well as documented long-term modifications of the physical and chemical oceanographic characteristics of the basin due to anthropogenic impact (Mozetič et al., 2009; Solidoro et al., 2009) and temperature change (Russo et al., 2002).

In this study, a long-term time-series (1945–2014) of landings disaggregated by species (Mazzoldi et al., 2014) for the Northern Adriatic Sea was analyzed to detect changes in total yields and variations in landings composition by functional groups over time. A suite of ecological indicators was applied to landings data to integrate responses to multiple stressors (Fu et al., 2015; Coll et al., 2016). They include trophodynamic indicators (e.g., mean trophic level, primary production required), climatic indicators (mean temperature of the catch), and other indicators, such as elasmobranchs-bony fish ratio. These indicators were compared with independent data describing main ecosystem drivers, in order to corroborate findings.

Our analysis falls within the general need of taking into account ecological processes when considering long-term changes in fishery resources where fishery-independent data are lacking, by testing several ecological indicators, and their responsiveness to fishery and environmental drivers. The approach is suitable to be applied for the purposes of the Ecosystem Approach to Fishery Management (EAFM) and contributes to establishing historical baselines to be used to compare current and future ecosystem status, for instance in the context of the Marine Strategy Framework Directive (MSFD) implementation.

MATERIALS AND METHODS

Area of Study

The Northern Adriatic Sea is the shallowest (average depth of 33.5 m) and northern-most area of the Adriatic and Mediterranean Seas (**Figure 1**). This area is characterized by strong riverine outflows from the Po River (the largest Italian river) that is a primary source of nutrients and organic matter to the basin (Giani et al., 2012). Water circulation is dominated by two counter-clockwise gyres, which confine a large part of the nutrient-enriched riverine inputs along western coastal regions (Zavatarelli et al., 1998). In fact, the western coastal waters were long considered as ones of the most productive of the Mediterranean Sea (Hopkins et al., 1999), and occasionally local hypoxia/anoxia events have been reported especially close to the Po River mouth (Giani et al., 2012). The reduction in phosphorus loads in Italian rivers in the 1980s triggered reversal in the eutrophication trend and was indicated as the start of a (cultural) oligotrophication process for the basin (Mozetič et al., 2009; Solidoro et al., 2009).

The seabed is characterized by muddy and sandy bottoms, with the presence of few rocky outcrops. Due to the presence of a wide flat trawlable platform coupled with the high productivity, the Northern Adriatic Sea is the Italian basin with the highest fishery pressure, and one of the most exploited areas in the Mediterranean Sea (AdriaMed, 2004).

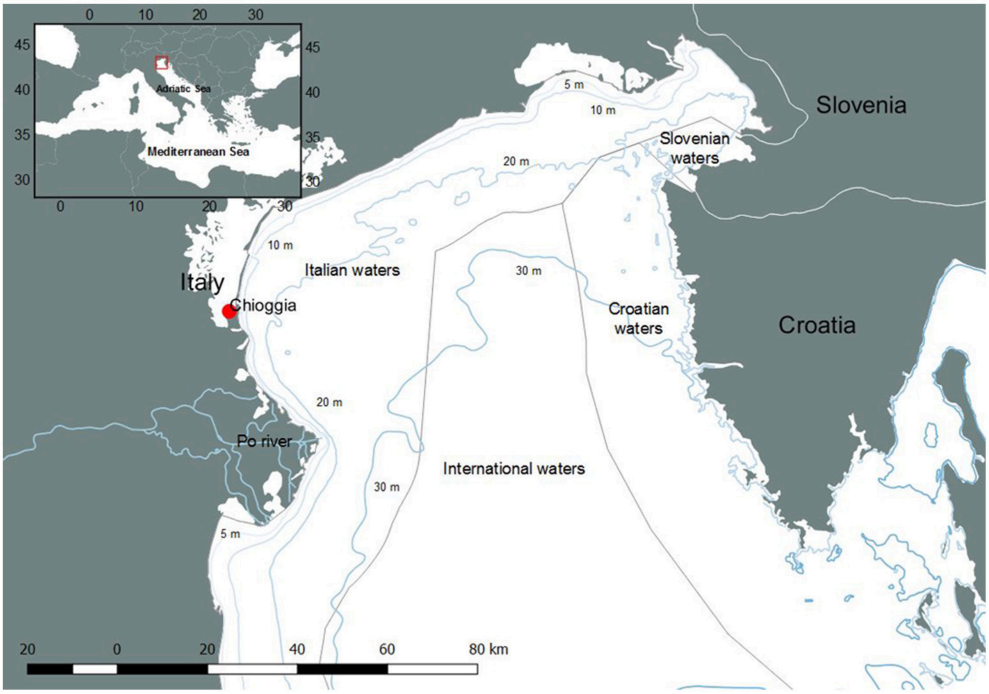

FIGURE 1 | The area of study (Northern Adriatic Sea). Commercial fisheries landings derive from the area shown in the figure, Slovenian and Croatian waters excluded.

History of Fisheries in the Northern Adriatic Sea

The biological resources of the study area have been intensively exploited since centuries, and the port of Chioggia (**Figure 1**) hosts the most important fishing fleet of the Adriatic Sea and one of the most important of the entire Mediterranean basin (Botter et al., 2006; Fortibuoni, 2010; Mion et al., 2015).

Before and immediately after World War II (WWII) the Chioggia fishing fleet adopted a wide variety of artisanal gears, both passive and active and the industrialization of fisheries in the Adriatic Sea gradually became consolidated starting from the 1950s, having begun in the period between the two world wars with the first experiments with engines (Fortibuoni, 2010). The period following WWII was characterized by marked changes in fishing equipment and technologies. There was a great increase in both demand for fish products and technical innovations, which enabled fleets to expand considerably. Consequently, there was a continuous and substantial increase in the fishing capacity (Cataudella and Spagnolo, 2011).

The use of progressively larger ships and engines allowed fishing areas to be expanded as well as larger and heavier gears to be used. As an example, the bottom otter-trawl was previously towed by pair sailing boats (Botter et al., 2006), and after WWII it was increasingly adopted by single mechanized vessels. Most traditional fishing gears were abandoned (e.g., beach seines and longlines, commonly used throughout the nineteenth century) and new and more efficient ones were introduced. However, the geographical characteristics of the Northern Adriatic Sea (shallow and semi-closed basin) constrained the expansion of fisheries, thus fishery grounds exploited by Chioggia's fleets can be considered almost stable throughout the period analyzed (Mazzoldi et al., 2014).

The first of the major innovations in fishing equipment introduced was the "*saccaleva*" surrounding net aided with a light source for attracting fish. It became widespread in the 1940s in Chioggia and gradually replaced all other methods for fishing small pelagic fish, such as the traditional "*menaide*" drift net (Fortibuoni, 2010). Successively, the "*saccaleva*" was substituted in the late 1960s by the more efficient "*volante*" (mid-water pelagic trawl, towed by paired vessels) that since the 1970s is the main gear used to catch pelagic species (Cingolani et al., 1996). In the mid-1950s the "*rapido*" trawl (a sort of beam trawl rigged with 10 cm long iron teeth; Pranovi et al., 2001) was introduced targeting flatfish and shellfish (such as the Mediterranean scallop *Pecten jacobaeus*), but also demersal resources, as spottail mantis shrimp (*Squilla mantis*) and common cuttlefish (*Sepia officinalis*). In the early 1970s, the first hydraulic dredge came into use, substituting the traditional hand-maneuvered gears to harvest different species of clams (Romanelli et al., 2009). In relation to this, the clam fishery quickly became one of the most valuable.

Furthermore, in the mid-1980s, the introduction of LORAN (Long Range Navigation) and subsequently the video plotter and GPS (Global Positioning System) greatly improved navigation precision, allowing the exploitation of areas that were previously inaccessible because of their proximity to unsuitable trawling sites, as the presence of rocky outcrops.

As regard fisheries management, a comprehensive scheme in Italy was initiated with the Law 41/1982, establishing that all professional fishing vessels had to possess a license reporting the characteristics of the vessel (e.g., GT), limitations of fishing areas, gear use and spatial licensing (Piroddi et al., 2015). The Italian fisheries management system is actually based on fishing effort/capacity regulation systems, and technical measures. No quotas or TACs (total allowable catch) have been established, except for Atlantic bluefin tuna (*Thunnus thynnus*) and Striped venus clam (*Chamelea gallina*). From 1983, the national fishing fleet was subject to reduction constraints in relation to two reference parameters, fleet tonnage and engine power. A further incentive toward fleet capacity/effort reduction was provided by European Structural Funds that financed the voluntary removal of vessels. Moreover, in recent years there has been a voluntary departure from the sector due to the general old age of the fishing fleet and the fisheries crisis (Cataudella and Spagnolo, 2011). However, as regards the Chioggia's fishing fleet, fishing capacity (i.e., total GT) has increased until recent years (Barausse et al., 2011).

Data

Landings Dataset

Official landings data (1945–2014) from the Chioggia's wholesale fish-market were retrieved from the Clodia database (Clodia database, 2015). Landings of a wide variety of benthic and pelagic species represent the aggregated commercialized quantities caught by the highly diversified fishing gears employed by fishermen of Chioggia. Data do not include any estimate of the discard, and landings disaggregated by gear are not available. Landings refer only to fish and seafood caught by local fishermen from the Chioggia's fleet that operates in the Adriatic Sea. The database was validated by Mazzoldi et al. (2014) to show that landings composition provides reliable indication of fish abundance.

Information on the habitat (pelagic/demersal) and maximum length ($L_{\max}$) for each species were taken from FishBase (Froese and Pauly, 2016). Moreover, the thermal preference (median temperature preference, T) was assigned according to Cheung et al. (2013). The trophic level of species (TL), specific for the Northern Adriatic Sea, was obtained from Fortibuoni et al. (2013), from other literature and estimates (e.g., Stergiou and Karpouzi, 2002) or retrieved from FishBase in the case of fish, and SeaLifeBase (Palomares and Pauly, 2016) in the case of invertebrates.

Ecosystem Drivers: Fishing Capacity, Nutrient Loads, and Climate Change

Data on Chioggia's fishing fleet capacity in terms of gross registered tonnage (GRT) were gathered from ISTAT (Italian National Institute of Statistics) for the period 1951–1989 and in terms of gross tonnage (GT) from the Community Fleet Register for the period 1990–2014. Total fishing capacity was expressed as GT for the entire time-series and used as a proxy for fishing pressure in the analyses because no long-term records of fishing effort were available. It was also not possible to include in fishing pressure any estimate of the technological creep due to the lack of data (e.g., CPUE from scientific surveys; Engelhard, 2016).

The monthly discharge of the Po river (m^3/s), measured at Pontelagoscuro (Ferrara, Italy) for the period 1945–2014 was provided by the Regional Environmental Protection Agency of Emilia Romagna and used to calculate monthly mean annual discharge. Nutrient yearly discharge, in terms of annual input of nitrogen (NO_3) and phosphorus (PO_4) load (t/y) from the Po river, was obtained from Ludwig et al. (2009) for the period 1960–2000, and from EU FP7 PERSEUS project for the period 2001–2014.

The winter (December-March) station based index of the North Atlantic Oscillation index (Hurrell and National Center for Atmospheric Research Staff, 2016) was used to represent the large-scale climatic variability in the area in the period 1945–2014. The NAO is based on the difference of normalized sea level pressure between Lisbon (Portugal) and Stykkisholmur/Reykjavik (Iceland). Positive values of the NAO index are typically associated with stronger-than-average westerlies over the middle latitudes and wetter/milder weather over western Europe.

Finally, monthly data on sea surface temperature (SST) were downloaded from the International Comprehensive Ocean–Atmosphere Data Set (ICOADS). SST data at 13°E–45°N, 15°E–45°N, 13°E–43°N, and 15°E–43°N for the period 1957–2014 were used to compute the annual mean values.

Ecological Indicators

Data were also used to compute ecological indicators, meant to provide a holistic description of the system. Disaggregated landings per species (landed quantities in kg per year) were integrated into metrics by applying a suite of ecological indicators (described in **Table 1**) based on TL, thermal preference, habitat and species' size.

Metrics used included: the mean Trophic Level of landings, an indicator of food webs structure ($\bar{m}$TL; Pauly et al., 1998); the Mean Temperature of the Catch (MTC; Cheung et al., 2013), which is the average inferred temperature preference of the species weighted by their annual catch used for evaluating the effect of sea warming on fish communities; the ratio of small pelagic fish to demersal and benthic landings (P/D ratio; de Leiva Moreno et al., 2000); the Large Species Indicator (LSI), i.e., the biomass proportion in landings of large-sized fish species (Shephard et al., 2012); the ratio between elasmobranch and bony fish in the landings (E/B ratio; Piet and Pranovi, 2005); the Primary Production Required to sustain fishery catches (PPR; Pauly and Christensen, 1995) that is the amount of energy exported from the system by landings and can be seen as the ecological footprint of fishing activities (Swartz et al., 2010); the Q-90 statistic (Ainsworth and Pitcher, 2006) that is a variant on Kempton's Q index to evaluate biodiversity (Kempton and Taylor, 1976). Landings per Unit of Fishing Capacity (LPUC) were also computed considering the yearly total gross tonnage of the fleet.

TABLE 1 | Ecological indicators calculated for the time series of landings.

Indicator (acronym)	Rationale	Formulation	References
Mean Trophic Level of landings (mTL)	Indicator of the impact of fishing on ecosystems, which selectively removes larger (and higher TL) species. It is expected to decrease with increasing fishing pressure.	$mTL = \frac{\sum_{i=1}^{n} TL_i{}^{*}Y_i}{\sum_{i=1}^{n} Y_i}$ where TL_i is the trophic level of species i, n is the total number of species, and Y_i is the landings of species i	Pauly et al. (1998)
Mean Temperature of the Catch (MTC)	Indicator of ocean warming on fish communities that leads to increased catches of warmer-water species and decreased catches of colder-water species. It is expected to increase with increasing ocean warming.	$MTC = \frac{\sum_{i=1}^{n} T_i{}^{*}Y_i}{\sum_{i=1}^{n} Y_i}$ where T_i is the median temperature preference of species i, n is the total number of species, and Y_i is the landings of species i	Cheung et al. (2013)
Primary Production Required to sustain fishery (PPR)	The PPR is a measure of the level of exploitation of the studied area, accounting for the fraction of Primary Production sequestrated by fisheries. The method is based on the trophic level of the caught species, the energy transfer efficiency between trophic levels, and on the primary productivity of the basin. It is expected to increase with increasing fishing pressure.	$PPR = \sum_{i=1}^{n} \frac{Y_i}{CR} {}^{*} \left(\frac{1}{TE}\right)^{(TL_i - 1)}$ where Y_i is the landings of species i, n is the total number of species, CR is the conversion rate of wet weight to carbon (fixed at 1:9), TE is the transfer efficiency (fixed at 10%), and TL_i is the trophic level of species i	Pauly and Christensen (1995)
Ratio between pelagic and demersal species biomass in landings (P/D ratio)	Highlights the influence of nutrient enrichment on fish communities, since nutrient availability has a differential effect on pelagic fish (positive) and on demersal stocks (negative). It is expected to increase with increasing nutrients availability.	$P/D\ ratio = \frac{\text{Landings of small pelagic species}}{\text{Landings of demersal fish plus benthic species}}$	de Leiva Moreno et al. (2000)
Large Species Indicator (LSI)	Quantifies relative changes in landings of larger fish species that are selectively removed by fishing. It is expected to decrease with increasing fishing pressure.	$LSI = \frac{\sum_{i=1}^{n} Y_{i\,(L_{\max} \geq 30)}}{\sum_{i=1}^{n} Y_i}$ where $L_{\max}$ is the maximum length of the species i, n is the total number of species, and Y_i is the landings of species i. Species are classified as large or small according to their $L_{\max}$ adopting a threshold value that was set at 30 cm in agreement to the method proposed by Greenstreet et al. (2011)	Shephard et al. (2012)
Ratio between elasmobranch and bony fish landings (E/B ratio)	Summarizes changes in the fish community structure between groups of species that are characterized by contrasting life-histories traits and by differential vulnerability to fishing activities. It is expected to decrease with increasing fishing pressure.	$E/B\ ratio = \frac{\text{Landings of elasmobranch}}{\text{Landings of bony fish}}$	Piet and Pranovi (2005)
Q-90 statistic	It is a variant on Kempton's Q index developed to measure the effects of mortality from fishing on species diversity. The statistic represents the slope of the cumulative functional groups abundance curve between the 10- and 90-percentiles. It is expected to decrease with increasing fishing pressure.	$Q - 90 = \frac{0.8 \times n}{log(Y2/Y1)}$ where n is the total number of functional groups, $Y1$ and $Y2$ are landings of the 10^{th} and 90^{th} percentiles in the cumulative abundance distribution	Ainsworth and Pitcher (2006)

Analysis of Data

Multivariate Analysis

Landings data were aggregated into 12 functional groups, according to their taxonomical and ecological features, to reduce missing values and restrict the number of variables in order to better elucidate main changes. Invertebrates were subdivided into three groups, i.e., bivalves, cephalopods, and crustaceans (no reliable data for gastropods were available in the database and thus this group was omitted). Pelagic bony fish species were grouped into three size classes according to fish species $L_{\max}$ (small: $L_{\max} < 30$ cm; medium: 30 cm $\leq L_{\max} < 90$ cm; large: $L_{\max} \geq 90$ cm). Analogously, three groups were used for aggregating demersal bony fish species by size. Flatfishes, sharks and "skates and rays" represented three further groups.

Functional groups' proportion in landings (%) was computed yearly in order to analyse landings composition and remove the effect of landings abundances. A fourth root transformation was applied to data to downweight the influence of predominant groups (Kaiser et al., 2000) and the similarity between every pair of years was computed using the Bray-Curtis similarity coefficient. Chronological clustering using the un-weighted pair-group average (Legendre and Legendre, 1998) was applied to identify periods with similar landings composition. Functional groups' proportion in landings was compared among periods by means of the non-parametric Kruskal-Wallis H-test ($\alpha = 0.05$). Ecological indicators were compared between consecutive periods identified through cluster analysis by means of the non-parametric Mann-Whitney U-test ($\alpha = 0.05$). Analysis was done with PAST v. 3.14 (PAleontological STatistics; Hammer et al., 2001).

Ecological indicators and drivers relationship was analyzed for the period 1960–2014 (for which all drivers were available) through the statistical procedure BIO-ENV from PRIMER v. 6.1.5 (global BEST-test; Clarke et al., 2008). The method consists in the computation of the correlation coefficients between similarity matrices of ecological indicators and drivers, and identifies the combination of drivers that maximizes the correlation. Indicators and drivers were normalized prior to the construction of the Euclidean distance matrices, since they represented different units of measure. The skewness and the individual correlations between drivers were explored by constructing a draftsman plot and examining the resulting Spearman rank correlations to eventually reduce redundancy and dimensionality of the data. We included all drivers in the analysis after testing the absence of highly correlated drivers ($\rho \geq 0.95$).

Time-Series Analysis

Trends in total landings (Y), ecological indicators and drivers time-series were analyzed using the Mann–Kendall test and the non-parametric Sen's method was used to quantify the magnitude (slope) of the trend, using the Microsoft Excel template MAKESENS (Mann-Kendall test for trend and Sen's slope estimates) developed by Salmi et al. (2002).

Drivers time-series were further explored using the sequential t-test analysis of regime shift (STARS v. 3.4) first developed by Rodionov (2004) in order to detect potential abrupt changes in the mean. The algorithm was applied to the filtered time series calculated by removing red noise through a "pre-whitening" procedure based on the IP4 method (Rodionov, 2006) to take into account the effect of serial correlation on shift detection. The cut-off length was set at 10 years, the significance level at 0.05 and Huber's weight parameter at 1.

RESULTS

Multivariate Analysis

Chronological clustering allowed distinguishing seven periods with different landings composition at a similarity threshold of 0.94: 1945, 1946–1954, 1955–1961, 1962–1985, 1986–1993, 1994–2008, and 2009–2014 (**Figure 2**). Year 1945, which represented an autonomous cluster at this similarity threshold, was associated to the first period (then becoming 1945–1954).

The difference among periods of functional groups' proportion in landings was statistically significant for all functional groups. Landings were dominated by small pelagics in all periods, with a percentage contribution ranging between 37% (*SD*: 8%; 1945–1954) and 68% (*SD*: 3%; 2009–2014). Cephalopods was the second most relevant group in the landings in all periods, with a contribution ranging between 10% (*SD*: 2%; 1955–1961) and 20% (*SD*: 5%; 1986–1993). In the first two periods, the third group in terms of biomass was medium pelagics that represented more than 10% of the landings [13% (*SD*: 4%) and 10% (*SD*: 6%), respectively], but then medium pelagics declined in the following periods down to 1.1% (*SD*: 0.4%) in recent years (2009–2014). Medium demersals ranged between 12% (*SD*: 2%; 1945–1954) and 6% (*SD*: 1%; 1955–1961). The other groups contributed with <10% in all periods. It is worth noting that skates and rays showed a sharp decline, from 3% (*SD*: 1%) in 1945–1954 to 0.04% (*SD*: 0.01%) in 2009–2014 (**Figure 3**). Another interesting dynamic was showed by bivalves that from 2% (*SD*: 1%) of the landings biomass in the first period increased to 8% (*SD*: 6%) in the period 1986–1993, and then sharply declined down to 1.9% (*SD*: 0.4%) in the most recent period (**Figure 3**).

Mann-Whitney U-test results are reported in **Table 2**. Y, MTC, LPUC, PPR, and P/D ratio significantly increased between the first two periods, while mTL, LSI and E/B ratio significantly decreased (**Figures 4**, **5**). Between 1955–1961 and 1962–1985 only MTC significantly increased, while mTL, LSI, and P/D ratio significantly decreased (**Figure 5**). In the subsequent period, mTL and LSI significantly increased, while Y, LPUC, PPR, Q-90, and P/D ratio significantly decreased (**Figures 4**, **5**). Between 1986–1993 and 1994–2008 a significant increase of MTC, Q-90, and P/D ratio was observed, while E/B ratio further decreased (**Figure 5**). Finally, by comparing the last two periods (1994–2008 and 2009–2014) a significant decrease of MTC, PPR, LSI, Q-90, and E/B ratio occurred, while P/D ratio significantly increased (**Figure 5**).

The global BEST-test showed a moderate ($\rho = 0.26$–0.34) significant ($p < 0.01$) link between ecological indicators and drivers. The similarity matrices obtained with phosphorous discharge and fishing capacity correlated highest ($\rho = 0.34$) with the similarity matrix of ecological indicators.

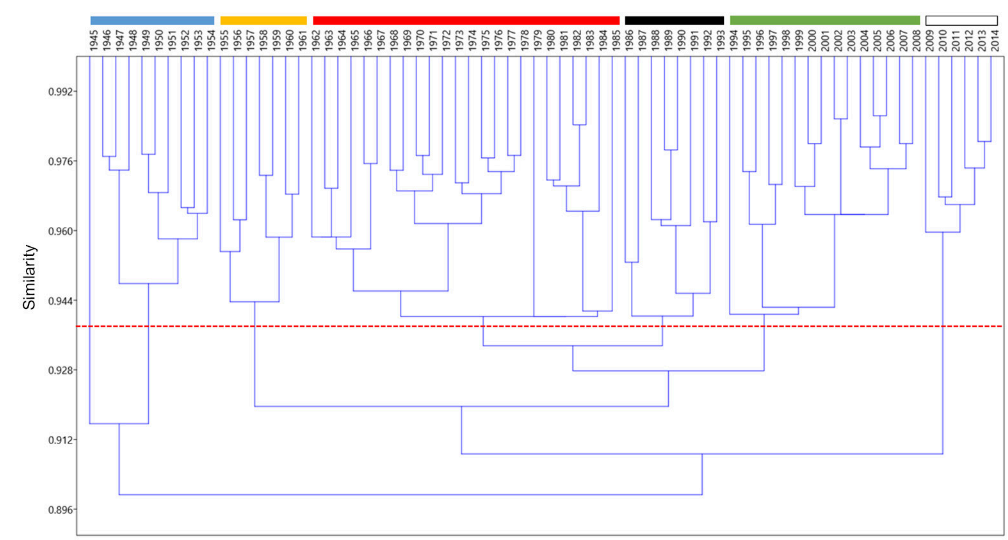

FIGURE 2 | Chronological clustering (Bray-Curtis similarity, unweighted pair-group average) of the composition of landings for the years 1945–2014.

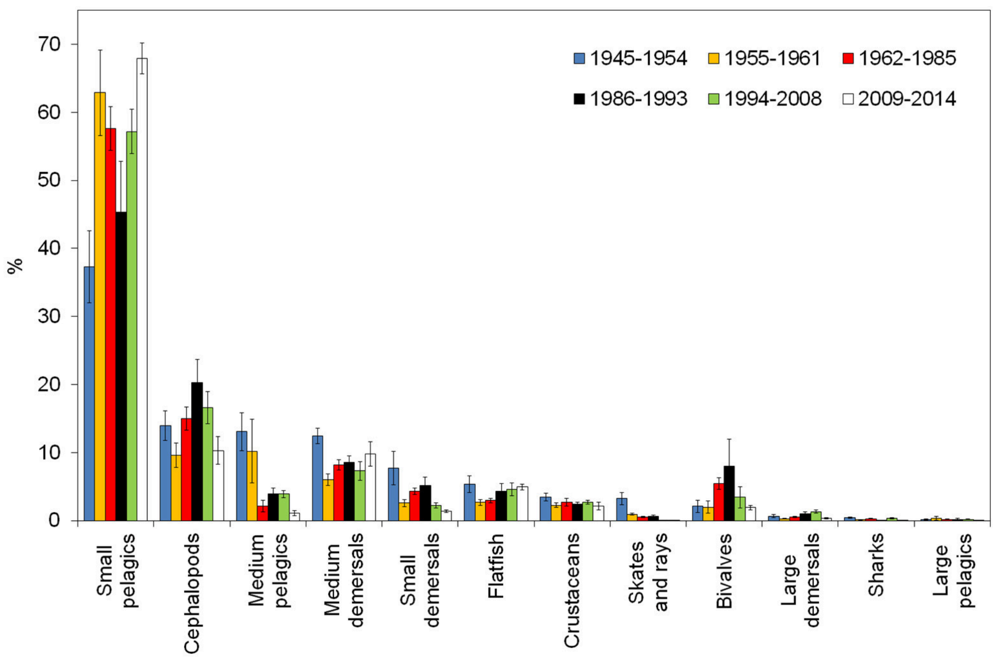

FIGURE 3 | Percentage composition of the fish community in the periods identified through chronological clustering. The confidence interval (95%) is reported in the vertical bar.

Time-Series Analysis

Landings (Y) significantly increased between 1945 and 2014 ($Z = 3.36$, $p < 0.001$, slope $= 58.9$ t year^{-1}, **Figure 4A**). Conversely, landings rescaled over fishing capacity (LPUC) significantly declined in the whole period of study ($Z = -3.95$, $p < 0.001$, slope $= -8.13$ t GT^{-1} year^{-1}, **Figure 4B**). The mTL significantly declined along the whole time series ($Z = -3.38$, $p < 0.001$, slope $= -0.002$ year^{-1}, **Figure 5A**). MTC significantly increased from 1945 to 2014 ($Z = 7.27$, $p < 0.001$, slope $= 0.048$°C year^{-1}, **Figure 5B**). PPR showed no significant trend between 1945 and 2014 (**Figure 5C**). LSI and E/B ratio significantly declined from 1945 to 2014 ($Z = -3.21$, $p < 0.01$, slope $= -0.002$ year^{-1}; $Z = -8.67$, $p < 0.001$, slope $= -0.0003$ year^{-1}, **Figures 5D,E**). The same temporal trend resulted for Q-90 ($Z = -4.92$, $p < 0.001$, slope $= -0.021$ year^{-1}, **Figure 5F**). The P/D ratio significantly increased from 1945 to 2014 ($Z = 2.7$, $p < 0.01$, slope $= -0.02$ year^{-1}, **Figure 5G**).

TABLE 2 | Significant differences (Mann-Whitney U-test, $p < 0.05$) of total landings (*Y*), landings per unit of capacity (LPUC), and ecological indicators between successive periods.

	1945–1954	1955–1961	1962–1985	1986–1993	1994–2008	2009–2014
Y (t)	3520 (3293–4174)	▲		▼		
LPUC (t)	0.99 (0.95–1.06)	▲		▼		
mTL	3.65 (3.12–3.18)	▼	▼	▲		
MTC	13.21 (12.42–13.55)	▲	▲		▲	▼
PPR ($10^{12}gCy^{-1}$)	0.08 (0.07–0.11)	▲		▼		▼
LSI	0.37 (0.35–0.41)	▼	▼	▲		▼
E/T ratio	0.04 (0.03–0.06)	▼			▼	▼
Q-90	4.66 (4.48–4.96)			▼	▲	▼
P/D ratio	0.94 (0.80–1.19)	▲	▼	▼	▲	▲

It is reported the median value and the interquartile range (in brackets) for the first period and significant positive (green) and negative (red) changes for successive periods.

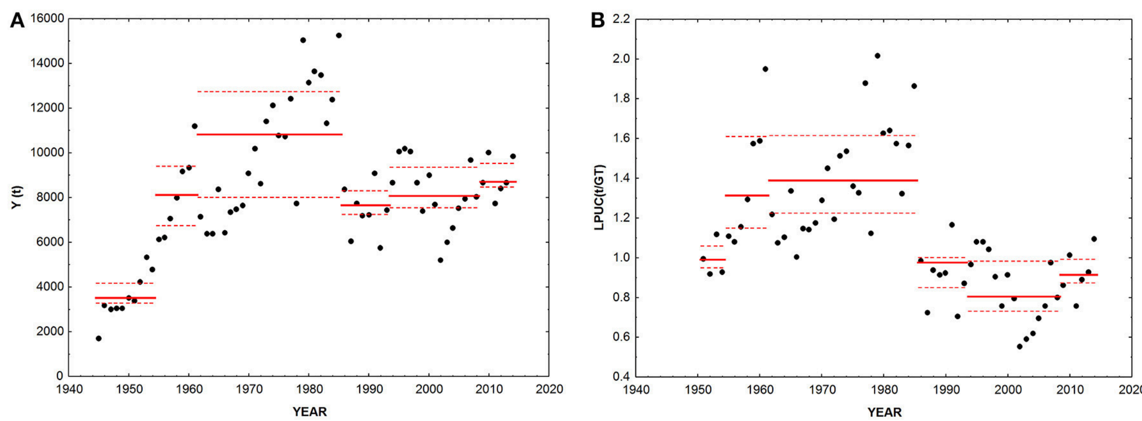

FIGURE 4 | (A) Total landings (Y) and **(B)** landings per unit of fishing capacity (LPUC). Black dots, data; continuous red line, median value in each period identified through the cluster analysis; dotted red lines, interquartile range in each period.

As regards drivers, Po river mean annual discharge did not show a significant trend. However, the time-series presented a significant negative drop in mean in 2003 and a positive one in 2008 (**Figure 6A**). Nitrogen load significantly increased between 1945 and 2014 ($Z = 4.17$, $p < 0.001$, slope $= 1.37$ t year^{-1}). The time-series presented a significant positive drop in mean in 1972 (**Figure 6B**). Conversely, phosphate load did not show any significant trend, but an increase in the mean value in 1972 and a significant decrease in 1988 (**Figure 6C**). Neither the NAO showed any significant trend, but two negative shifts in 1962 and 2009 and a positive shift between the two in 1972 (**Figure 6D**). SST significantly increased in the period of study ($Z = 3.56$, $p < 0.001$, slope $= -0.01$°C year^{-1}) and showed two positive shifts in mean in 1998 and 2011 (**Figure 6E**). Finally, also fishing capacity significantly increased ($Z = 9.46$, $p < 0.001$, slope $= 89.88$ GT year^{-1}) without any significant shift in the mean (**Figure 6F**).

DISCUSSION

Six periods with significantly different community structure were identified through cluster analysis of the landings composition by functional group. The most abundant group was small pelagics (mainly European anchovy *Engraulis encrasicolus* and European pilchard *Sardina pilchardus*) in all periods, followed by cephalopods in almost all periods. Major changes in community composition between periods include skate and rays and medium pelagics decline, and bivalves dome-shaped trajectory.

The increase of bivalves' proportion in the landings from 2% in 1955–1961, to 5 and 8% in the following periods, is probably linked to the introduction in the mid-1950s of the "*rapido*" trawl, and successively in the 1970s of the hydraulic dredge, that substantially improved fishing efficiency. However, the proportion of this functional group in the landings decreased to 3% in 1994–2008, and further decreased to 2% in 2009–2014. This sharp decrease is related to the collapse of the Mediterranean scallop (*Pecten jacobaeus*) in the late 1990s (data not shown) due to overfishing. In fact, between the 1960s and the 1990s, the species showed large fluctuations determined both by the intensity of fishing effort and by mass mortalities due to hypoxic conditions that occurred episodically over wide areas of the Northern Adriatic Sea (Hall-Spencer et al., 1999). A previous study (Maurizio and Castagnolo, 1986) showed that

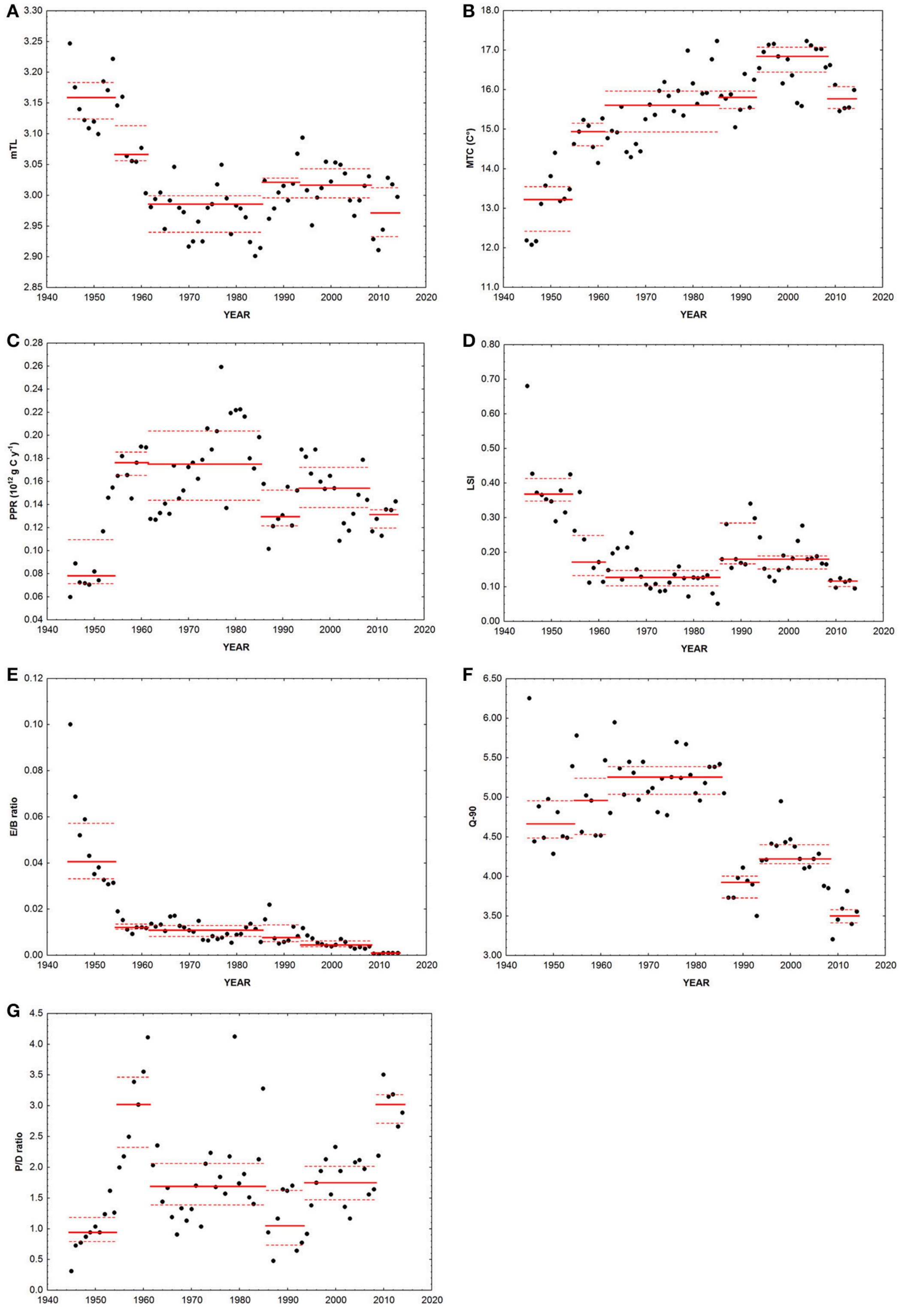

FIGURE 5 | Ecological indicators calculated on the basis of landings disaggregated data. Black dots, data; continuous red line, median value in each period identified through the cluster analysis; dotted red lines, interquartile range in each period. **(A)** mTL, mean trophic level; **(B)** MTC, mean temperature of the catch; **(C)** PPR, primary production required; **(D)** LSI, large species indicator; **(E)** E/B ratio, ratio between elasmobranch and bony fish in the landings; **(F)** Q-90, a variant on Kempton's Q index; **(G)** P/D ratio, ratio of small pelagic fish to demersal fish plus benthic landings.

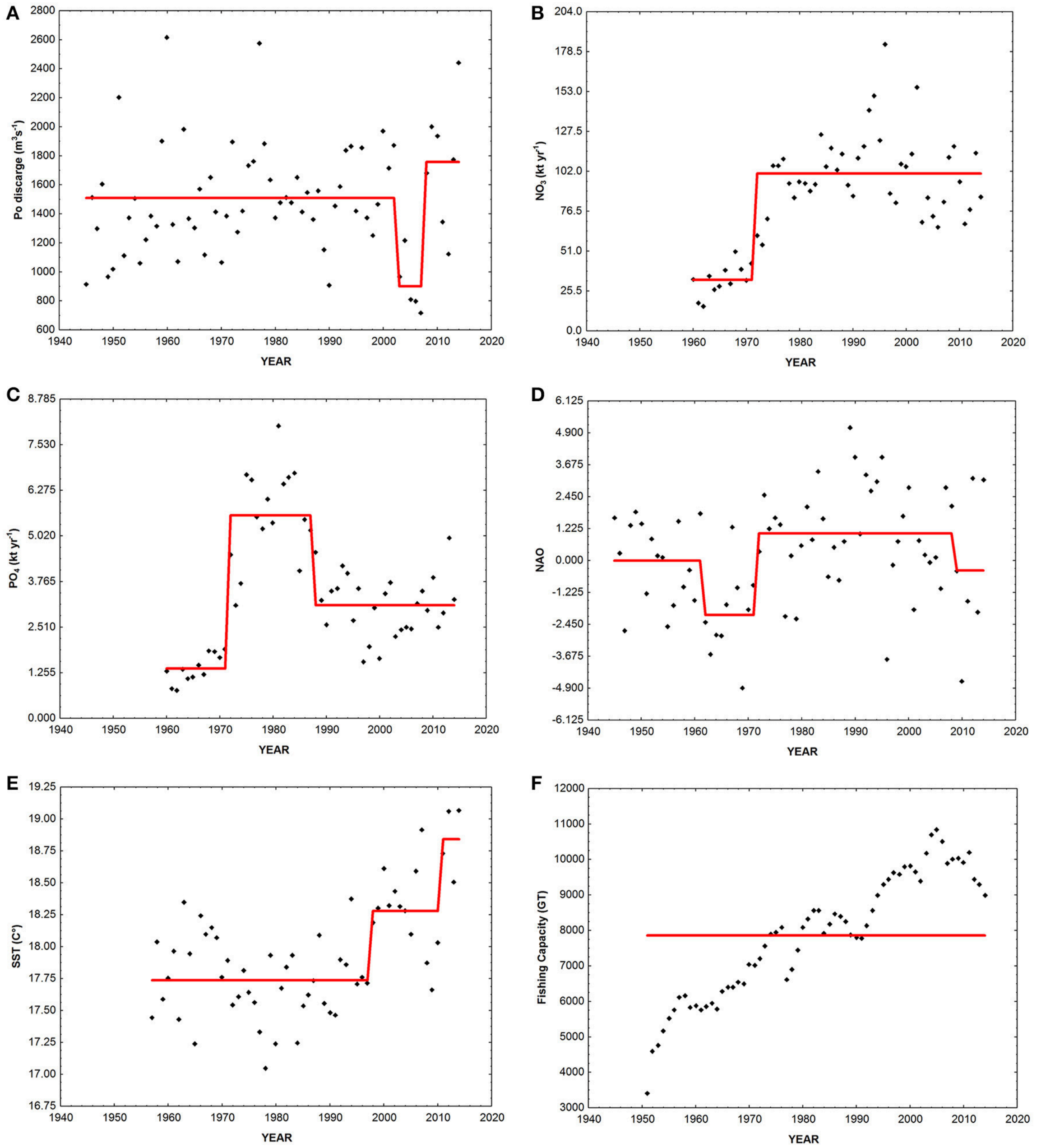

FIGURE 6 | Time-series of drivers of ecosystem change. Black diamonds, data; red line, regime shift. **(A)** Po discharge, mean annual Po river freshwater discharge; **(B)** NO_3, annual nitrogen flux from the Po river; **(C)** PO_4, annual phosporus flux from the Po river; **(D)** NAO, North Atlantic Oscillation index; **(E)** SST, sea surface temperature; **(F)** GT, total gross tonnage of vessels of the Chioggia's fishing fleet.

after a 6-month period of fishing, commercially sized *P. jacobaeus* catches collapsed by 83%, indicating the high vulnerability of the species to unsustainable exploitation, and the need for the institution of selected areas closed to trawling (Hall-Spencer et al., 1999).

Moreover, a suite of ecological indicators applied to time-series of landings provided the basis for gaining useful insights on possible causes of long-term changes. The use of multiple metrics allowed to obtain a picture of how the ecosystem has changed over the past 70 years, since different metrics emphasize distinct aspects of the underlying communities, and consequently allow disentangling the role of different drivers.

Early Changes: The Decline in Size of Fished Communities

LSI, E/B ratio, and mTL showed a significant decrease between 1945 and 2014. Among the range of ecological indicators analyzed in this paper, these are directly (LSI) and indirectly

(E/B ratio and mTL) related to size. Since fishing is usually size-selective, both within and among species (Jennings, 2005), these indicators are considered to be sensitive to fishing disturbance and are expected to decrease under unsustainable exploitation.

It is worth noting that LSI does not take into account the actual size-distribution of exploited populations (that requires the availability of information of the size of caught individuals), but it is based on the $L_{\max}$ of species (see **Table 1**). Thus, the LSI changes are attributable to changes in composition of populations rather than species' size composition. Therefore, the LSI differs substantially from the Large Fish Indicator (LFI, Greenstreet et al., 2011), but it may be useful for management purposes since it requires less detailed data than LFI for highlighting effects of fishing, and can be applied also to long-term landings data series where the size structure of catches is most often not known.

The negative trend for these indicators highlights a shift toward smaller species in the community, or anyway a decrease of proportion of larger fish. Larger fish (which usually have high trophic levels) are more vulnerable to fishing and have less capacity to sustain great rates of mortality (Dulvy and Reynolds, 2002; Jennings, 2005; Myers and Worm, 2005). This phenomenon could be further exacerbated by the possible increase of small species due to the "predation release" as their predators are depleted (Bruno and O'Connor, 2005; Jennings, 2005; Myers et al., 2007).

Therefore, fishing seems to have had significant detrimental effects on the fish community composition since the first years of the time-series. Indeed in mid-1950s, the first rearrangement of the fish community structure occurred, as emerged from the cluster analysis, with a shift from large-sized high trophic level species to small planktivorous ones. Consequently, a significant negative decrease of mTL, LSI, and E/B ratio was observed.

The decline of elasmobranchs and large-sized species started even before the 1950s in the area (i.e., in the nineteenth century; Fortibuoni et al., 2010; Raicevich and Fortibuoni, 2013), but was exacerbated afterwards probably as a consequence of the industrialization of fishery and the introduction of new highly impacting fishing gears (Ferretti et al., 2013; Barausse et al., 2014). Especially linked to the decrease of skates and rays (Barausse et al., 2014; Engelhard et al., 2015), the E/B ratio decline indicates the important role of elasmobranchs as sensitive key species for detecting early signals of fisheries disturbances (Baum et al., 2003).

However, the early collapse of large-sized species is not only a consequence of the decline of elasmobranchs. In the mid-1950s medium pelagic species reached a maximum in landings (1449 kg in 1956), and dramatically declined afterwards. Medium pelagics (mainly the Atlantic mackerel *Scomber scombrus*) represent an important group of species for the local fish market, whose decline is hardly a consequence of changes in market demand (Meneghesso et al., 2013). Thus, it can be assumed quite conservatively that the decline in catches for medium pelagics reflects a dramatic decline of populations at sea.

Overall, the decline in mTL, E/B ratio and LSI clearly highlight that there has been a long-term fishing-down food web phenomenon (*sensu* Pauly et al., 1998).

Signals of Structural Changes

The Q-90 index significantly declined between 1945 and 2014, with a significant negative median-shift in the mid-1980s, indicating a reduction in the biodiversity of landings with increasing fishing impact. The change in biodiversity of landings is concurrent to the significant decrease of total landings and LPUC, suggesting that main modification of marine communities affected local fisheries production.

In the mid-1980s, regime shifts are reported for different ecosystem components in many areas, the Mediterranean Sea, the North Sea, the Baltic Sea, and the Black Sea, possibly suggesting regional effects of a larger scale northern hemispheric pattern (Conversi et al., 2010). Barausse et al. (2011) reported that a similar shift occurred also in the Northern Adriatic fish community, including also medium-high trophic level species belonging to both the demersal and pelagic habitats. Our analysis, however, while confirming the existence of the shift, do not support the hypothesis that climatic drivers played a major effect on it, and rather point to the impact of local pressures, i.e., overexploitation and nutrient loads.

Such structural changes may have altered food-web structure and impaired its functioning and resilience. Coll et al. (2008) compared North-Central Adriatic Sea food-web structure between the 1970s and 1990s, and reported a high food-web degradation regarding overexploitation of higher trophic levels and a simplification of food-web structure (lower omnivory and higher generality). Thus, it is not surprising that LPUC showed a downwards significant shift in 1986, reaching its minimum value in 2002. Only in 2014, the index recovered to values comparable to the very beginning of the time-series, when fishing technologies were markedly less developed and efficient.

Changes in the Trophic State

The significant positive trend over time in the P/D index found in the present study may depend both from eutrophication and overexploitation of resources (Libralato et al., 2004). Indeed, eutrophication and overfishing may have similar and synergistic effects on fish communities, i.e., a decline in diversity, an initial increase in productivity of benthic/demersal and pelagic food webs, then the progressive dominance of the production system by short-lived, especially pelagic species (Caddy, 1993). However, the P/D ratio in the present case seems to point out the importance of eutrophication driven events.

Pelagic fishes are generally influenced by nutrient enrichment when it stimulates the plankton production (Caddy, 1993), while demersal fishes are influenced by the dynamics of benthic community, which generally responds negatively to the conditions of excessive enrichment as shown by de Leiva Moreno et al. (2000). These authors found a mean value of P/D equal to 3.76 in the Adriatic for the historical series 1978–1988. In the present study, the P/D index had a wide dynamic trajectory, ranging between 0.31 and 4.12 with a mean value of 1.81 ($\pm$ 0.84), thus confirming the Adriatic as a mesotrophic ecosystem (de Leiva Moreno et al., 2000). The index reached some peaks that can be partly related to severe anoxic/hypoxic events. For instance, anoxias in bottom waters linked to eutrophication occurred in the periods 1955–1956 and 1972–1982 (Sangiorgi and Donders, 2004), when the P/D index reached a value of ~2. Finally, the P/D index showed an increasing trend in recent years (significant upward median-shift in 2009), probably linked to a partial recovery of small pelagic species, mainly European anchovy (Carpi et al., 2015).

PPR showed a significant positive median-shift in the mid-1950s. In the mid-1980s, PPR collapsed, mainly driven by the strong reduction of small pelagic landings. As regards anchovy, its population started declining since the late-1970s, and the reasons of this abrupt reduction have been previously ascribed to climate forcing (Santojanni et al., 2006), modified inflow of Mediterranean waters in the Adriatic Sea and associated salinity changes (Grbec et al., 2002), over-fishing, increased predation of eggs and larvae by the jellyfish *Pelagia noctiluca* and the presence of mucilage events (Regner, 1996). PPR further significantly decreased in the last period 2009–2014.

It is worth noting that during the 1970s an increase of eutrophication occurred in the basin, lasting until the mid-1980s (Giani et al., 2012). Although nitrogen loads increased up to the mid-1970s and then maintained approximately the same values up to now (**Figure 6B**), phosphate peaked in the mid-1980s (**Figure 6C**), and its following marked decline may have resulted in limiting production. In 1985, to reduce the negative effects of cultural eutrophication (e.g., anoxia events), the nutrient load delivered to the Adriatic Sea was reduced, mainly by changing the chemical composition of soap powders (banning phosphorous from the mixture) and by improving the treatment of urban sewage and farm litter products (Decree-law No. 667 of November 25th 1985—Urgent measures to limit the eutrophication of waters).

A significant decrease of phytoplankton abundance was also observed after the 1980s, along with changes in its species composition with a shift toward smaller organisms. Such changes modified also zooplankton community (Kamburska and Fonda-Umani, 2009). This trend was a consequence of a reduction of phosphorous load, being the Northern Adriatic waters phosphorous-limited (Solidoro et al., 2009), and a decline of atmospheric precipitation and the runoff in the basin (Giani et al., 2012).

Signals of Climatic Changes

MTC significantly increased between 1945 and 2014 at a decadal rate of 0.5°C, with three significant positive median-shifts in the mid-1950s, in the early-1960s, and in the mid-1990s. A significant negative median-shift was instead observed in the last period (2009–2014), even if the median value (15.8°C) was still much higher than at the one observed at the beginning of the time-series (1945–1954: 13.2°C). Thus, overall an increasing dominance in catches of warm affinity species occurred in the landings of Chioggia, coherently with the pattern observed in other Mediterranean areas (Cheung et al., 2013; Tsikliras and Stergiou, 2014; Fortibuoni et al., 2015; Tsikliras et al., 2015). Also SST significantly increased between 1957 and 2014, with a positive shift in mean in 1998. However, SST resulted not to be one of the main ecological drivers in driving community changes in the Northern Adriatic Sea, and results from this study do not allow establishing a relationship between MTC, SST in the area and NAO.

Integrating in a Coherent Framework the Community Changes

Long-term changes in the Northern Adriatic fish community resulted to be mainly related to the impacts of fisheries and nutrient dynamics, while climate had a secondary role up to now. A coherent dynamic is obtained by scaling the PPR to N:P ratio (NO_3/PO_4) to account for the changes in the limiting factor (Solidoro et al., 2009), and comparing it with the fishing capacity through time (**Figure 7**).

The PPR to N:P ratio increased up to the mid-1980s, showing that the exploitation development was supported by nutrient enrichment. In the mid-1980s there was an abrupt collapse after which, even for large changes in fishing capacity, PPR to N:P ratio attained much lower values (**Figure 7**). Notably, the mid-1980s shift is coherent with a shift between two alternative stable states, as described in Scheffer and Carpenter (2003): from the first state (line A–B in **Figure 7**), to a second state (line C–D–E in **Figure 7**). Therefore, in the mid-1980s a shift between two alternative stable states of the system likely occurred in the Northern Adriatic Sea, which is reflected also in a change in the community structure (see chronological clustering; **Figure 2**). The shift to a new community composition and the lower trophic potential (see previous sections) thus resulted in a much lower productive capacity (here represented by PPR to N:P ratio), even for the high fishing effort exerted in the last decades of the time series (**Figure 6F**). Importantly, to induce a switch back to the

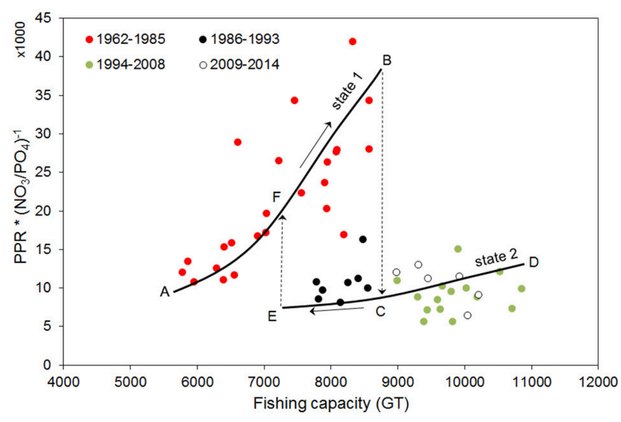

FIGURE 7 | Dynamics of fisheries production under changes of fishing capacity and nutrient limitation from 1960 to 2014. PPR is scaled to N:P ratio to take into account changes in the nutrient limiting factor. Solid lines represent subjective indication of average main trajectories identifiable as two alternative states of the system (state 1: line A–B; state 2: C–D–E). The mid-1980s shift is coherent with a catastrophic shift between two alternative stable states (dashed arrow from B to C) and the presence of hysteretic behavior. For going back from the actual state (state 2, lower solid line) to a state prior to the catastrophic event of mid-1980s (state 1, upper solid line) it is necessary to considerably reduce fishing capacity (left dashed line E–F, placed subjectively).

original state, it is not sufficient to restore the conditions present before the collapse (Scheffer and Carpenter, 2003): **Figure 7** shows the hysteresis (B–C–E–F) typical to alternative stable points of complex systems. From the actual situation (state 2), to reach the same PPR to N:P ratio observed before its collapse (state 1), a relevant reduction of fishing capacity is necessary (see the hypothetical line E–F).

Although from our data it is not possible to estimate the reduction in fishing capacity necessary to switch back from state 2 to state 1, **Figure 7** highlights that a reduction in fishing capacity to values lower than the ones that characterized the 1980s would be necessary, together with an intervention on nutrient loads. This result points to the fact that the current critical situation of fisheries is not solely the result of mismanagement of the fisheries sector, but is due also to other environmental policies, in particular those relative to water quality. Thus, actual management needs to account for the fact that the ecosystem is now in a different state (state 2), and the reversal of the shift of the mid-1980s implies changes in fishing capacity and nutrient balance that go far beyond those of the period of the shift.

Overcoming Limitations in the Use of Landings for Ecological Analyses

This work gives support to the possibility of using landings statistics for inferring changes in marine ecosystems through the analysis of landings composition and the application of a set of ecological indicators. Despite the intrinsic limitations of fishery-dependent data (Essington et al., 2006; Hilborn, 2007), the analysis reported here highlights that opportune indicators can produce interesting and useful assessments from landings, especially if combined with local knowledge on fisheries changes. In particular, the capability to understand relationship between landings composition to community at sea is more robust when local disaggregated landings result from multi-target and multi-gear fisheries (i.e., several distinct métiers), and when changes in fishing activities (e.g., introduction of new technologies, shift from one fishing gear to another, number and tonnage of boats) are traceable.

Being aware of the poor capabilities of landings absolute quantities to assess single species abundances (Pauly et al., 2013), we used landings composition (percentage proportion of functional groups in total landings) to detect community changes. Moreover, the use of data lumped into functional groups allowed overcoming problems of changes in aggregation detail in landings statistics.

The potential is great given that landings data are the most widespread information that can be used to analyse marine ecosystem changes in the past, and probably the cheapest information that can be collected by surveying archives and statistical bulletins and that can be used also in data poor conditions.

CONCLUSIONS

The analysis of landings from the fish market of Chioggia allowed inferring information on long-term changes in the Northern Adriatic ecosystem. Most vulnerable species (i.e., elasmobranchs and large-sized species) considerably declined at the beginning of the industrialization of fishery and continued to decline in the following decades, probably because the exploitation rates were not sustainable. Indeed, fishing capacity increased enormously during the 1960s and 1970s, i.e., larger boats, higher tonnage and engine horsepower, improved fishing gears, use of high-technology equipment (Fortibuoni, 2010). Until the mid-1980s total landings continuously increased, possibly as a consequence of the modernization of fishing fleets and of the growing cultural eutrophication. However, while landings were still increasing, the LPUC was already declining.

Later, the nutrient load (in terms of phosphorus) delivered to the Adriatic Sea decreased, thus leading to a combination of high exploitation and reduced productivity, which may well-explain the collapse in landings in the following years. Indeed, from our analysis resulted that phosphorous load (a proxy of primary production) and fishing capacity (a proxy of fishing effort) were the main drivers of change among the considered explanatory variables. Conversely, climate relate variables had a smaller impact.

It is likely that long-term effects of fishing drove significant changes in fish community structure in the Northern Adriatic Sea that were partially masked or balanced by an increase in productivity in the period of high nutrient discharge. Once productivity declined, the food-web structure was already modified and probably the resilience of the system was unpaired. The ecosystem was in a "fishing status" (*sensu* Jennings and Kaiser, 1998), thus reducing its recoverability from environmental driven imbalance. As regards the role played by fishing, it is expected that over time the enhanced skipper skills, adoption of auxiliary equipment and more efficient gear and materials, replacement of old vessels by new ones and upgraded engines (Damalas et al., 2014; Engelhard, 2016), resulted in an increased catching efficiency. However, since no reliable information was available for the area we did not consider the effect of the technological creep, keeping our results rather conservative with respect to fishing impacts.

This study shows that the Northern Adriatic ecosystem and ecological drivers has dramatically changed in the last decades, and thus greater knowledge of past states is crucial to set appropriate baselines for current management. Indeed, the actual crisis faced by the Northern Adriatic Sea fishery sector may be ascribed both to long-term over-exploitation and changes in nutrient load. This evidence should be considered in fishery management, for instance by rescaling the fishing capacity according to the present status of environmental parameters (e.g., trophic conditions related to nutrient discharges). Since fisheries management in Italy (as in the whole Mediterranean) is predominantly capacity/effort-based, accounting for changes in these parameters is decisive. However, because of technological creep, measuring nominal capacity and effort in conventional terms (e.g., GT, KW, days at sea) may produce estimates far from the effective fishing mortality exerted by the fleet (Damalas et al., 2014). All this may partly explain why in Italian waters the positive impact on resources expected from fishing capacity/effort reduction was lower than expected (Cataudella and Spagnolo, 2011). Thus, research on fishing power change and fine-scale analysis of fishing effort through time are highly recommended in order to understand real changes in the capacity of fishing fleets, and their potential to exploit fish stocks (Engelhard, 2016). Moreover, the results might provide evidence on the need for considering broadly the ecosystems impacts of human interventions and management actions, since actual critical state of the fisheries have been exacerbated by regulations on water quality.

AUTHOR CONTRIBUTIONS

SL, SR, and TF conceived the study. SL, CS, and TF defined the hypotheses and methodologies. TF, SL, and CS analyzed and discussed the results with input from SR, FP, and OG. All authors were involved in reviewing and editing the manuscript, and approved it for publication.

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Corrigendum: Analysis of Long-Term Changes in a Mediterranean Marine Ecosystem Based on Fishery Landings

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Keywords: landings, marine historical ecology, ecological indicators, long-term changes, ecosystem drivers, Adriatic Sea

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In the original article, there was a mistake in **Table 2** as published. The median value of the mTL was not 3.65 but instead 3.16. The corrected **Table 2** appears below. The authors apologize for this error and state that this does not change the scientific conclusions of the article in any way.

Conflict of Interest Statement: 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.

TABLE 2 | Significant differences (Mann-Whitney *U*-test, $p < 0.05$) of total landings (*Y*), landings per unit of capacity (LPUC), and ecological indicators between successive periods.

	1945–1954	1955–1961	1962–1985	1986–1993	1994–2008	2009–2014
Y (t)	3520 (3293–4174)	▲		▼		
LPUC (t)	0.99 (0.95–1.06)	▲		▼		
mTL	3.16 (3.12–3.18)	▼	▼	▲		
MTC	13.21 (12.42–13.55)	▲	▲		▲	▼
PPR (10^{12} g C y^{-1})	0.08 (0.07–0.11)	▲		▼		▼
LSI	0.37 (0.35–0.41)	▼	▼	▲		▼
E/T ratio	0.04 (0.03–0.06)	▼			▼	▼
Q-90	4.66 (4.48–4.96)			▼	▲	▼
P/D ratio	0.94 (0.80–1.19)	▲	▼	▼	▲	▲

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Reconstruction of Domestic Marine Fisheries Catches for Oman (1950-2015)

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Domestic marine fisheries in Oman are increasingly viewed as the eventual economic alternative to the soon to be depleted oil reserves. This has galvanized the Omani government to invest in the management of its marine living resources. This study aims to provide a better estimation of Oman's domestic marine fisheries catches that can be used to improve fisheries management in the country. Using the catch reconstruction approach, total domestic marine fisheries catches by Oman are estimated for the time period 1950-2015, including reported and previously unreported large-scale and small-scale commercial catches, subsistence, and recreational catches, as well as major discards. Catches from the Omani exclave, Musandam, are estimated separately, given this governorate's geographical separation from the rest of Oman. Reconstructed total catches increased from around 64,000 t·year^{-1} in the 1950s to over 200,000 t·year^{-1} in the 2000s, which are overall 1.2 times the landings reported by the FAO on behalf of Oman. Fish stocks need to be sustainably managed to allow long-term economic viability. This cannot be done without the improvement of fisheries statistical systems around the world, including in Oman.

Keywords: artisanal fishing, Gulf of Oman, industrial fishing, IUU, non-reporting, subsistence fishing, unreported catch

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INTRODUCTION

Growing fisheries have intensively exploited fish stocks since the 1950s, leading to global overfishing and to worldwide resource depletions (Pauly et al., 2002, 2005; Watson et al., 2013). This has severely impacted the economies and societies of maritime countries around the world, particularly in the coastal countries of the developing world (Pauly et al., 2005; Béné, 2006; Swartz et al., 2010). In many of these countries, small-scale fisheries are particularly suffering from competition with industrial fisheries (Allison, 2001). Given the importance of these fisheries in providing food security and livelihoods to numerous coastal communities (Pauly and Zeller, 2014; Golden et al., 2016), proper management is required.

The Food and Agriculture Organization of the United Nations (FAO) has been reporting "official" fisheries catches by country since 1950. In many countries, this is the only available information on marine living resources (Froese et al., 2012; Pauly and Zeller, 2016). Given that most methods to assess the status of fish stocks require substantial and costly data (e.g., fisheries independent surveys etc.), fisheries catch data remain, in many cases, the only basis for fisheries management (Worm et al., 2009; Costello et al., 2012; Pauly et al., 2013). Despite the importance of these data (Pauly et al., 2013), fisheries catch data reported by countries to the FAO are often heavily focused on commercial sectors only. FAO data requests specifically exclude discards, while data for most small-scale sectors (i.e., artisanal, subsistence and recreational) are often missing or substantially under-represented (Pauly and Zeller, 2016). The fact that global FAO data do not even differentiate between large- and small-scale catches (Pauly and Charles, 2015) makes proper evaluations of sectoral importance and affiliated management actions even harder to derive (Pauly and Zeller, 2016).

By (re-)evaluating official and unofficial marine fisheries components, the catch reconstruction approach (Zeller et al., 2007, 2015) can provide a more comprehensive, and likely realistic picture of what is being withdrawn from world oceans. These components involve catches from the large-scale (industrial) and small-scale (artisanal, subsistence, and recreational) sectors, plus major discards (Pauly and Zeller, 2016). These catch estimates may be approximate, and with higher uncertainty than reported data, but they are better than assigning a value of zero catch to unmonitored fishing sectors (Pauly and Zeller, 2016).

This study aims to provide a better estimation of the Sultanate of Oman's domestic marine fisheries catches that can be used to improve fisheries management in the country. Oman is an Arab country situated in the south east of the Arabian Peninsula, with a land area of around 300,000 km^2, a continental shelf area of 54,000 km^2 and an Exclusive Economic Zone (EEZ) of 536,000 km^2 (www.seaaroundus.org; **Figure 1**). Because of its separation from the rest of the Arabian Peninsula by the *Rub al Khali*, i.e., the largest sand desert in the world, Oman's main connections with the rest of the world were via the ocean (Metz, 1993; Vincent, 2008). Musandam, one of Oman's governorates, is an exclave surrounded by the United Arab Emirates (**Figure 1B**). This governorate itself contains an exclave in the UAE, called Madha (75 km^2), which amazingly contains an even smaller exclave of the UAE, called Nahwah.

Before the discovery of oil in 1962, the economy of Oman was based mainly on agriculture and fisheries, which represented 70% of the GPD (Metz, 1993). Until the mid-1980s, the economy of the country experienced a rapid expansion, with the oil industry accounting for 59% of GDP in 1985 (Metz, 1993). A drop in oil prices slowed down this expansion between 1986 and 1989, but prices increased again in the 1990s (Metz, 1993). During the pre-oil period, and due to relatively abundant fisheries resources (Strømme, 1986), the fishing sector was the second largest contributor to the economy, after farming (Riphenburg, 1998). However, with the expansion of the oil industry, fishers started leaving their boats for a more remunerative activity (Metz, 1993). Thus, in the early 1970s, the Omani government started developing and organizing the fishing sector by establishing the Fisheries Department followed by the creation of the Ministry of Agriculture and Fisheries, or MAF (Alhabsi et al., 2011); in 1978, it started subsidizing the fisheries, via a "Fishermen's Encouragement Fund" to increase employment in the fishing industry (Metz, 1993; FAO, 2001). During the 1990s, the Omani government decided to invest even more in potentially sustainable sectors, and thus funded several fisheries development and research projects, e.g., the Oman Fisheries Development and Management Project (Metz, 1993). In 2007, the Ministry of Fisheries Wealth was formed (Alhabsi et al., 2011). Until the 1980s, the Omani fishing industry was only small-scale in nature. In the 1980s, an industrial fishery was launched, following the signing of fishing agreements between Oman and other countries. In 1989, Oman ratified the UN Convention on the Law of the Sea (Morgan, 2006).

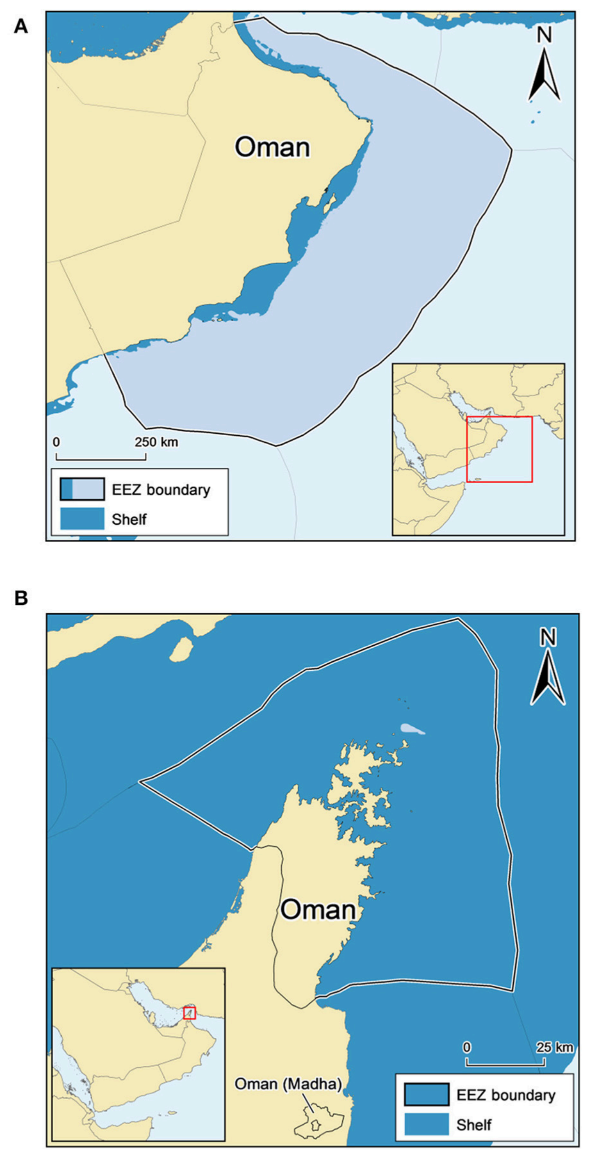

FIGURE 1 | (A) Oman (excluding Musandam), its shelf (to 200 m depth) and Exclusive Economic Zone (EEZ). **(B)** The Musandam Peninsula (Oman), its shelf (to 200 m depth) and Exclusive Economic Zone (EEZ).

METHODS

"Catches" are defined as the sum of "landings" (i.e., retained and landed catch) plus "discarded" catch. Available data for total landings are assembled by taxon and year, for the period 1950-2015. Although, the national Omani fishery data and the reported FAO data for Oman have an overall similar trend, the taxonomic disaggregation in the national reports is more detailed. Therefore, national data are used as the baseline for the years 1985-2015 and data from the FAO's Fishstat database are used for the years 1950-1984, as data from Oman were unavailable. To this baseline dataset, we added estimates of previously unreported commercial large- and small-scale, recreational, and subsistence landings, as well as major discards, as obtained from independent and government studies, as well as the gray literature; throughout, we followed the general catch reconstruction approach outlined in Zeller et al. (2007, 2015). Catches were reconstructed for the whole country, then for the Musandam Governorate separately. Estimates of the catches of the sectors mentioned were then obtained for the rest of the country by subtraction. A taxonomic disaggregation is then performed for both spatial datasets, i.e., Musandam and the rest of Oman.

Reported Large- and Small-Scale Commercial Catches

From 1980 to 2010, two commercial fisheries sectors co-existed in Oman: artisanal/coastal (or "traditional") and industrial (FAO, 2001; Alhabsi et al., 2011; Fisheries Statistic Department of Oman, 2016). In 2011, the artisanal/coastal fishing was split into two components for statistical reporting, i.e., "artisanal fishing" and "coastal fishing" (Fisheries Statistic Department of Oman, 2016). However, in the present reconstruction, we considered reported artisanal (i.e., small-scale) catches as the sum of coastal and artisanal reported catches. Thus, reported commercial catches are assigned to either the large-scale commercial sector (i.e., industrial) or the small-scale commercial sector (i.e., artisanal/coastal).

The fishing industry in Oman is predominantly artisanal/coastal, and few regulations control the activities of this sector (Morgan, 2006; Anon, 2015). **Table 1** shows different types of vessels making up the artisanal/coastal fleet. Fiberglass boats are the most common, i.e., 93% of artisanal vessels in 2010 (Alhabsi et al., 2011; Fisheries Statistic Department of Oman, 2016). *Dhows* are mainly used in the governorate of *Alsharqiah*, i.e., in the eastern part of Oman, and *Shashas* in the governorate of *Albatinah*, in the northeast (Alhabsi et al., 2011). A mixture of predominantly passive fishing gears are used, including hand lines, traps, and gill nets, etc., depending on the target species and season (FAO, 2001). The industrial fishery, initially foreign, became partly owned by Omani companies (Morgan, 2006; Fisheries Statistic Department of Oman, 2016). Industrial vessels are limited by a quota, are constrained to operate within certain areas of the EEZ (e.g., demersal trawlers had to operate at least 10 nm off the coast and at a minimum depth of 50 m), and are under satellite surveillance (i.e., vessel monitoring system) (Morgan, 2006). Industrial vessels in Oman used to be of 2 types: demersal trawlers and pelagic longliners. However, trawlers were banned in 2011, and as of this writing, only longliners are permitted, targeting large pelagic fishes at least 20 nm off the coast (Fisheries Statistic Department of Oman, 2012).

TABLE 1 | Characteristics of Omani artisanal/coastal fishing vessels.

Boats	Construction material	Length (m)
Skiffs	Fibreglass or aluminum	5–9
Dhows	Wood	10–15
Houris	Wood	3–10
Shashas	Palm fronds	3–4

National data sources, from 1985 to 2015, reported commercial catches by sectors (Fisheries Statistic Department of Oman, 2016). Reported landings are considered 100% artisanal from 1950 to 1979, as the industrial fishery only began in 1980 (Morgan, 2006). In order to fill the gap for the 1980-1985 time period, proportions were interpolated, assuming zero industrial catches in 1979. Large-scale landings were reported by the Omani authorities separately for trawlers and longliners for the period 1985-2015 (Fisheries Statistic Department of Oman, 2016). We assign the industrial catches to either trawlers or longliners for the period 1980-1984 by extrapolating their ratios to 1980.

Both the FAO and the national catch statistics suggest that there was a sudden and very steep increase toward a peak in reported catches in 1975, followed by a decrease in the late 1970s and early 1980s. While a distinct increase in landings in the mid-late 1970s may have been real, the magnitudes in these numbers around 1975 seem artificial. Given that during the 1970s, the Omani government invested in increasing fishing effort and developing the fishing industry (Alhabsi et al., 2011), we made a simplifying assumption that part of this peak in 1975 resulted from incidentally over-estimated official catches. This over-reporting would likely have been corrected with the establishment of the research program of the new Marine Science and Fisheries Center (MSFC) in the early 1980s (Alhabsi et al., 2011). Thus, to de-emphasize the likely artificiality of the high 1975 peak, we halved the value of this peak for 1975 and interpolated the reported data for the intervening years, i.e., interpolations between 1968 and 1975, and 1975 and 1981.

Unreported Large- and Small-Scale Commercial Catches

Oman supports the FAO's efforts to combat Illegal, Unreported, and Unregulated (IUU) fishing, e.g., by monitoring access to the ports and employs the Omani Air Force, Navy, and Coast Guard to monitor for illegal activities (Dr. Hamed Said Al-Oufi, interview in www.theworldfolio.com, 2012). Issues that are being addressed are prohibited gears, fishing and exporting unauthorized species, and using unlicensed fishing boats (FAO, 2009).

Nonetheless, given the isolated rural character of most non artisanal fishing communities in Oman, it is difficult for the authorities to monitor and control fishing activities around the country (Morgan, 2006). Furthermore, 66% of small-scale fishers are unlicensed (Belwal et al., 2015). Based on this, we assumed that unreported small-scale commercial catches decreased from the equivalent of 30% of reported artisanal catches in 1950 to 10%

in 2015. These percentages were applied to the reported small-scale catches, except for catches of spiny lobster, as these were estimated separately. According to Morgan (2006) unreported catches of spiny lobster were estimated to be three times the official reported landings. Hence, artisanal catches of spiny lobster were obtained by multiplying the reported catches of spiny lobster between 1950 and 2015 by a factor of 3.

The industrial fishery is smaller (in terms of number of vessels and fishers) and more regulated and monitored than the small-scale commercial fishery, i.e., through quotas, gear control, and fishing area restrictions. Officers are deployed on almost every vessel to monitor its activities (Morgan, 2006). To broadly approximate potential unreported catches by the industrial fleet in Oman, we applied a percentage of 10%—which is equivalent to the 2015 artisanal unreported catch rate - to the reported catches of trawlers and longliners for the period 1980-2015.

Subsistence Fishery

A subsistence fishery involves people who fish mainly for their personal and family consumption rather than primarily for commercial purposes. Until the 1970s, most of the Omani population was dependent on agriculture or fishing. The discovery of oil during the 1960s introduced an alternative source of livelihood. Thus, during the 1970s, numerous subsistence fishers left the fishing industry for other work opportunities (Dr. Hamed Said Al-Oufi, interview in www.theworldfolio.com, 2012).

Our estimates of subsistence fishery catches are based on the rural coastal population of Oman, defined as people living within a 5 km range from the coast in rural areas (**Table 5**) and without easy access to urban markets. This information was available from the Socioeconomic Data and Applications Center for the years 1990, 2000, and 2010 (CIESIN, 2012). For the periods 1990-2000 and 2000-2010, data were interpolated.

Information on the percentage of the rural population compared to the total Omani population, for the 1960-2014 period was available through the World Bank (data.worldbank.org). In 1960 and 1990, the rural Omani population comprised around 84 and 34% of the total population, respectively. Using this information and the percentage of the coastal rural population of 1990, i.e., 2.8% (**Table 4**), we could estimate the percentage of the coastal rural population for 1960, which was almost 7%. This percentage was then applied to the total Omani population of 1960, and interpolated to 1990.

Information on the total population between 1950 and 2015 was obtained online from the Department of Economic and Social Affairs of the United Nations (2015) (https://esa.un.org/unpd/wpp/). For 1950, we assumed that the percentage of the coastal rural population from the total population was equivalent to 7%, i.e., equal to the percentage of coastal rural population obtained for 1960, as no major societal changes occurred during the 1950s.

The percentage of the coastal rural population in 2010 from the total population is 2.44% (**Table 5**). We assumed that this percentage decreased slightly to 2% in 2015, and interpolated between 2010 and 2015.

According to FAO (2014), the apparent *per capita* consumption of fish in Oman was estimated to be between 20 and 30 $kg \cdot year^{-1}$ during the 2008-2010 time period, which is much higher than in neighboring countries. Based on this, we assumed an annual *per capita* subsistence catch rate of 45 $kg \cdot year^{-1}$ in the 1950s, which decreased to 30 $kg \cdot year^{-1}$ in 1975, then to 10 $kg \cdot year^{-1}$ in 2015. Interpolations were applied between the different anchor points. These rates were then applied to the total coastal rural population. These assumptions were based on the fact that most other food sources and livelihood opportunities became available when the oil industry was launched.

Discards

According to Kelleher (2005), the discard rate in Oman is about 1% of total landings. Discards of small-scale fisheries were obtained by applying this rate to the reconstructed total small-scale catches (reported and unreported). According to Morgan (2006), discards are not allowed in the industrial fishery, but occur occasionally. The discarded fish consist mainly of damaged, non-targeted, and/or undersized fish. We assumed that trawlers discarded the equivalent of 5% of their landings. Discards from the industrial sector were estimated only for trawlers. Longliners, which are more selective, are assumed to not have any discards.

Recreational Fishery

No data could be found on recreational catches in Oman. However, both local and tourism-based recreational fisheries exist. To regulate and monitor their activities, the government provides two types of licenses for people who wish to fish for leisure (www.oman.om): annual, and daily "non-professional" fishing licenses for recreational fishing using hooks and lines.

Although the number of annual licenses is publically available, there is no information on the duration of the recreational fishing trips. To roughly estimate the number of domestic recreational fishers, we applied a recreational fishing participation rate of around 0.12%, estimated for Western Asia by Cisneros-Montemayor and Sumaila (2010), to the annual total Omani population. We then assumed that recreational fishing in Oman was non-existent in 1960 (i.e., zero in 1960) and increased to 5 $kg \cdot fisher^{-1} \cdot year^{-1}$ by 2010. We interpolated the catch rate between 1960 and 2010 and extrapolated it to 2015. Recreational catches were obtained by multiplying the estimated number of recreational domestic fishers by the annual recreational fishing catch rate for the 1960-2015 period.

While tourism-based recreational fishing also exists, we did not estimate their recreational catches. Thus, overall, our recreational catch is likely an underestimate.

Catch Reconstruction for Musandam

The fishery in the Musandam Peninsula is solely small-scale. Reported landings in this region for the 1985-2015 time period were made publically available by the Fisheries Statistic Department of Oman (2010, 2012, 2016), suggesting that Musandam's contribution to the reported marine fisheries yield of Oman increased from 1.9% in 1985 to almost 8% of reported artisanal Omani catch in 2015. Landings for the years prior to 1985 were obtained by assuming that catches in that region were equivalent to 0.5% of the total Omani reported artisanal catches in 1950 and increased gradually to 1.9% in 1985. To estimate unreported artisanal landings and discards, we applied the same methods as used for the rest of Oman.

Recreational and subsistence catches in Musandam were derived by applying the annual ratio between Musandam's and the total of Oman's commercial catches (e.g., in 1988 commercial catches by Musandam were 1.2% of Omani total catches) to the total subsistence and recreational catches. For instance, recreational and subsistence catches of Musandam were estimated to be 1.3% of respectively total recreational and subsistence catches of the whole of the country in 1988.

Taxonomic Disaggregation

The taxonomic breakdown of reported artisanal as well as industrial landings was available for the 2000-2015 time period in the "Fisheries Statistics Book" of the Fisheries Statistic Department of Oman (2010, 2012, 2016). For each of the small- and large-scale sectors, the proportions of each species or taxon group for the year 2000 were calculated and applied to the total artisanal catches for the 1950-1999 time period, and the total industrial catches for the 1980-1999 time period. The taxonomic disaggregation was made separately for trawlers and longliners.

For the artisanal discards and the subsistence catches, we applied the estimated proportion of fish families caught by the artisanal fishery during the 1950-2015 time period. The same method was applied to the unreported artisanal catches, except that catches of spiny lobster were estimated separately. Finally, for the recreational fishery, we identified the most targeted families of fish by recreational fishers, in Oman according to Fishfishme Inc., i.e., one of the largest online platforms, allowing tourists to locate and book charter trips around the world (www.fishfishme.com). The percentage of each family targeted by this fishery was then estimated according to its assumed importance and popularity in the region (**Table 2**).

The taxonomic disaggregation of the artisanal sector for Musandam was made based on the "Fisheries Statistic Book" of the Fisheries Statistic Department of Oman (2010, 2012, 2016) and the work of Cornelius et al. (1973). The taxonomic disaggregation of discards, as well as unreported artisanal, recreational, and subsistence catches were completed similarly to the rest of the country.

Subtractions were then applied between each taxonomic group of each sector in Musandam as well as the whole country in order to obtain the annual catches by taxonomic group by sector for the rest of the country separately.

Estimation of Uncertainty

This catch reconstruction is based on assumptions and different information sources, some of which were mutually inconsistent. To evaluate the uncertainty of our reconstruction, we used the approach described in Zeller et al. (2015). This approach is based on criteria (**Table 3**) used by the Intergovernmental Panel on Climate Change to estimate uncertainty of information sources (Mastrandrea et al., 2010). Herein, the data and information sources used for reconstructing each sector are ranked with a quality score ranging from 1 to 4 (see **Table 3**) in each of three time periods (1950-1969, 1970-1989, and 1990-2015). Then, uncertainty ranges are computed, based on the catch weighed percent uncertainty in **Table 3**, which were scaled based on Monte-Carlo simulations in Ainsworth and Pitcher (2005) and Tesfamichael and Pitcher (2007). The Uncertainty scores assigned for each sector are represented in **Table 4**.

TABLE 2 | Taxonomic composition assumed to be caught in the recreational fishery.

Family	%
Carangidae	20
Istiophoridae	30
Scombridae	50

TABLE 3 | "Score" for evaluating the quality the catch reconstruction, with their confidence intervals (adapted from Mastrandrea et al., 2010).

Score		Confidence interval ±%	Corresponding IPCC criteria
4	Very high	10	High agreement and robust evidence
3	High	20	High agreement and medium evidence or medium agreement and robust evidence
2	Low	30	High agreement and limited evidence or medium agreement and medium evidence or low agreement and robust evidence.
1	Very low	50	Less than high agreement and less than robust evidence

TABLE 4 | "Score" assigned for each sector and period of time.

Sector \ Years	1950-1979	1980-1984	1985-2015
Reported small-scale	3	2	4
Reported large-scale	3	2	4
Recreational	1	1	1
Subsistence	1	1	1
Discards	1	1	1
Unreported commercial	1	1	1

RESULTS

Overall, total reconstructed domestic marine fisheries catches in the whole of Oman (i.e., Musandam plus the rest of the country, **Figure 4**; Appendix 5) increased from around 64,000 t·year^{-1} in the early 1950s (∼48,000 t·year^{-1} reported in the 1950s according to FAO data) to around 92,000 t·year^{-1} in the 1960s (71,000 t·year^{-1} reported according to FAO data). During the 1970s to the 1990s, catches reached respectively around 127,000, 144,000, and 156,000 t·year^{-1}. During the past 15 years, total marine fisheries catches more than doubled, increasing from around 142,000 t in 2000 to almost 290,000 t in 2015. Overall, the reconstructed total catch is 1.2 times the landings reported by the FAO on behalf of Oman for the period 1950-2015.

Reconstructed total catches for the main part of Oman (excluding Musandam) are dominated by the artisanal sector, i.e., 90% of total catches are artisanal (**Figure 2A**; Appendix 1). Around 20% of the total artisanal catches are unreported.

The industrial fishery rapidly gained importance in the 1990s, reaching a peak of 28% of total catches in 1997. Due to the ban on trawlers, by 2015, this fishery became almost non-existent (i.e., 0.08% of total catches, with only one active longliner). Subsistence and recreational catches are estimated to be 1% and <0.01% of total catches, respectively. Discards contributed around 1.2% of the total catch.

The main fish families caught by fishers in the main part of Oman, **Figure 2B**; Appendix 2, are the Clupeidae (~32%), which consist mostly of Indian oil sardine (*Sardinella longiceps*), followed by mackerels (Scombridae, ~19%), emperors (Lethrinidae, ~6%), jacks (Carangidae, 4.6%), and groupers (Serranidae, ~3.6%).

Catches of separate area Musandam represented 3% of the reconstructed total catch for Oman. Reconstructed marine fisheries catches in Musandam consist of 98% small-scale catches, of which about 12% are unreported (**Figure 3A**; Appendix 3). Subsistence and recreational catches represent a negligible fraction of marine catches, i.e., ~0.7% and <0.01%, respectively. Discards represent around 1% of the catch in Musandam. As illustrated by **Figure 3B**; Appendix 4, Scombridae are the most important taxonomic group (~38%), followed by anchovies (Engraulidae,~15%), and Carangidae (~14%). Lethrinidae, Clupeidae, and Serranidae make up around 4% each of total marine fisheries catches in Musansdam.

DISCUSSION

The marine fisheries catch reconstruction for Oman for the period 1950-2015 combines the reported large- and small-scale

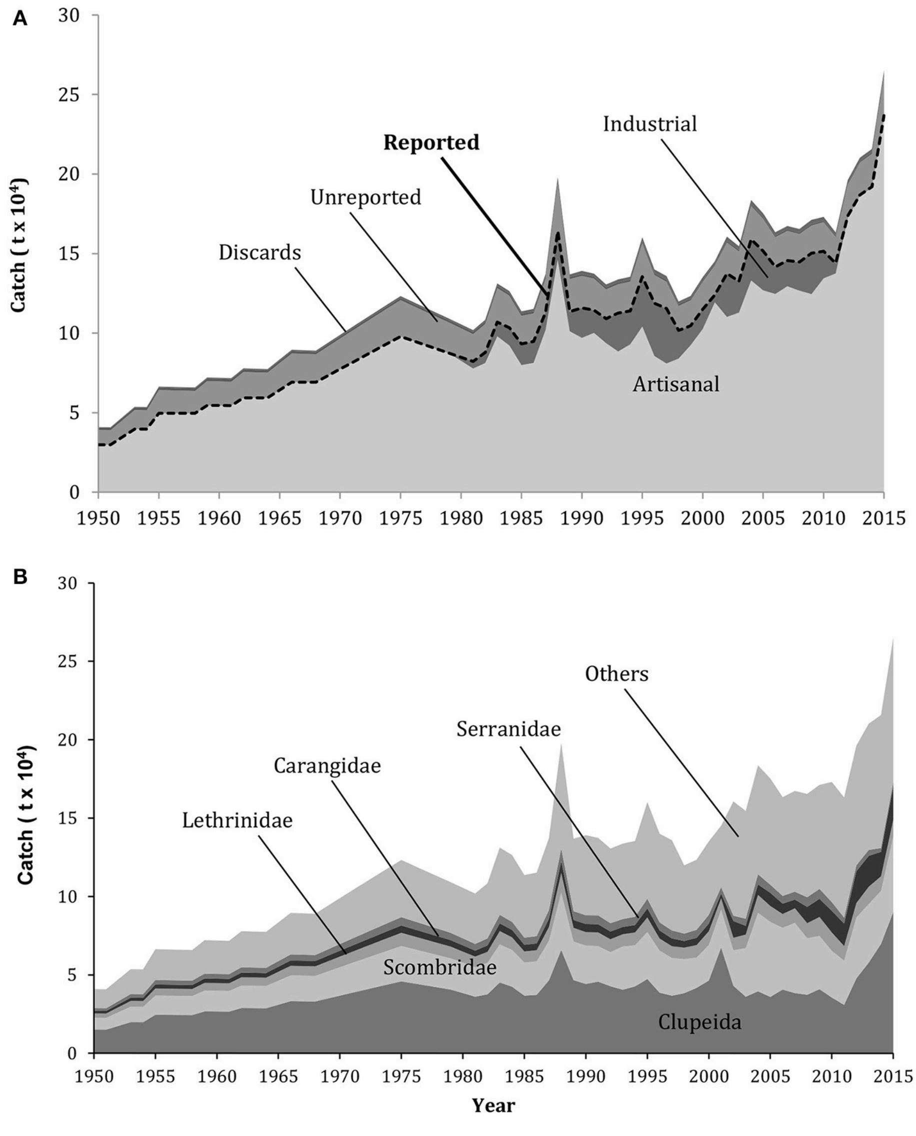

FIGURE 2 | Reconstructed catches for Oman (excluding Musandam), 1950-2015, by (A) sector, with discards shown separately, and adjusted reported landings overlaid as a dashed line graph. Subsistence and recreational catches are included, but are too small to be visible; and **(B)** by main taxonomic group. "Others" includes 19 additional taxonomic groups.

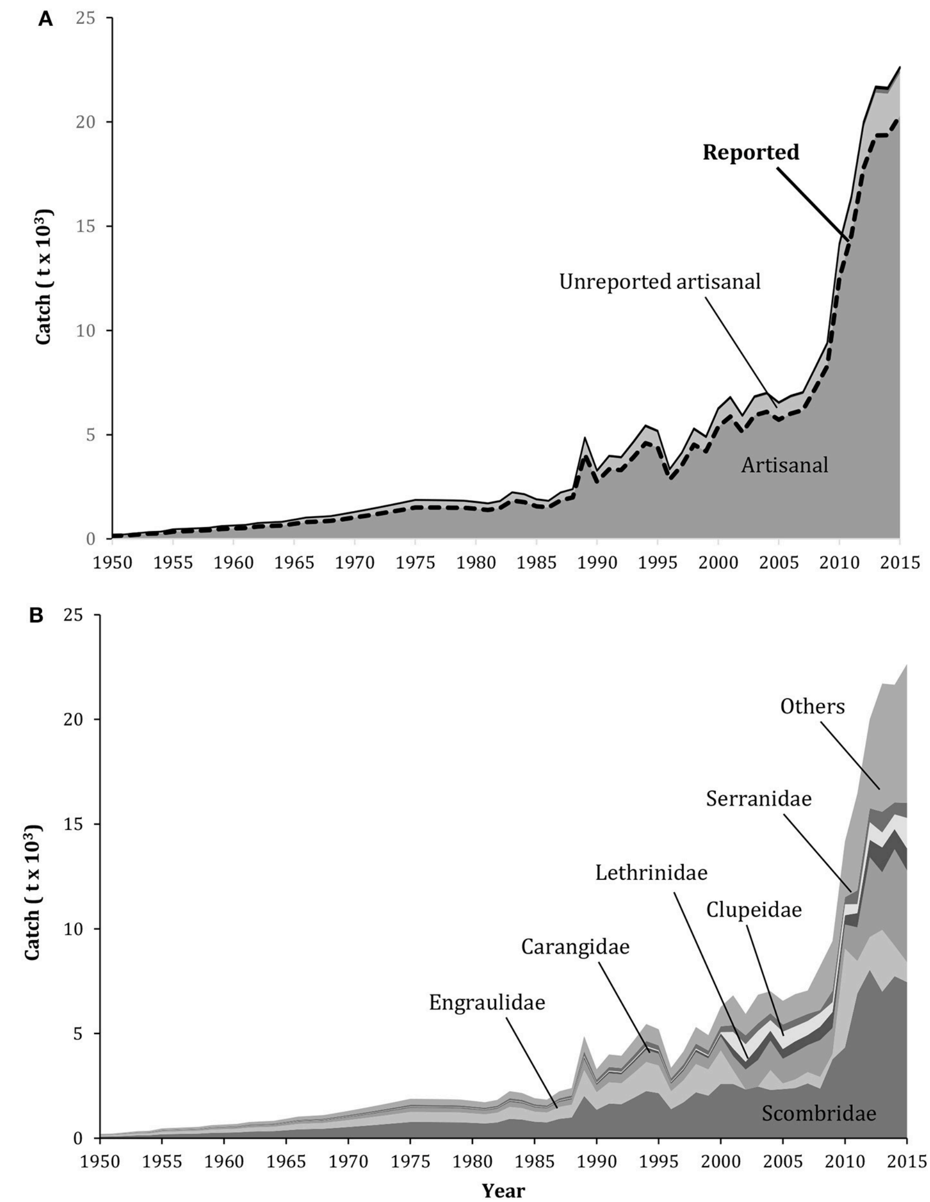

FIGURE 3 | Reconstructed catches for the Musandam Peninsula (Oman), 1950-2015, by (A) sectors shown separately and reported landings overlaid as a dashed line graph. Discards, subsistence and recreational catches are included, but are too small to be visible; and **(B)** by main taxonomic group. "Others" includes 17 additional taxonomic groups.

commercial landings with our best estimates of unreported large- and small-scale commercial, recreational, and subsistence catches, as well as estimates of large- and small-scale discards. Some of these estimates are very uncertain (**Table 5**, **Figure 4**), but they likely represent, overall, a more accurate picture of the total catch than if these components were omitted (which is the unavoidable result of not reporting on existing, but unmonitored components).

Small-scale fisheries are very important in Oman, i.e., nearly 98% of total catches in 2015 are artisanal in nature. The industrial fishery, composed of trawlers and longliners, has been decreasing in importance over the past decade. For several reasons, including conflicts between artisanal and industrial fishers, the Omani authorities have banned trawling since 2011 (Fisheries Statistic Department of Oman, 2012; Alhabsi, 2013).

TABLE 5 | Anchor points for the rural Omani coastal population within 5 km from coast (CIESIN, 2012).

Year	Population
1990	51,255
2000	56,002
2010	68,325

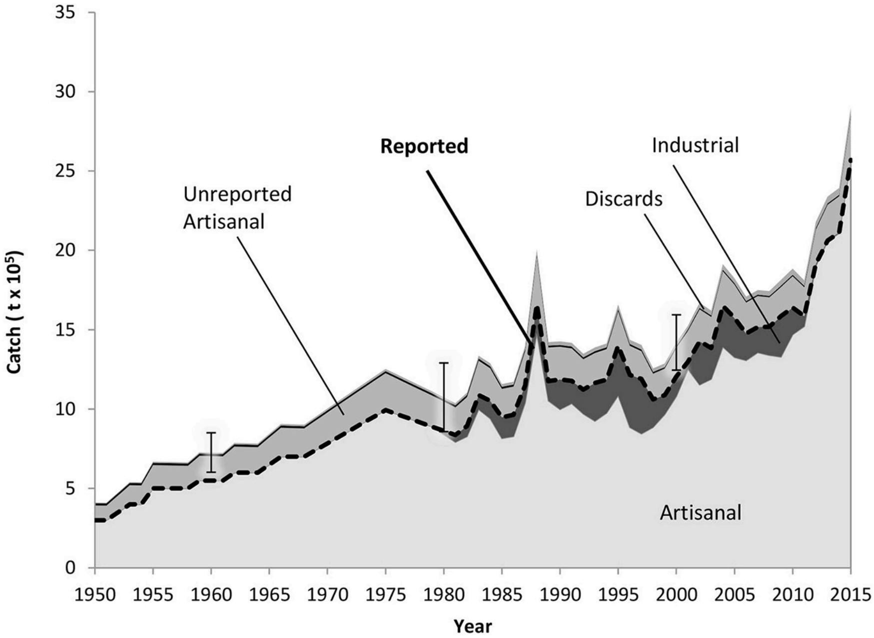

FIGURE 4 | Reconstructed catches for all Oman (including Musandam), 1950-2015, by sector, with discards shown separately, and adjusted reported landings overlaid as a dashed line graph. Subsistence and recreational catches are included, but are too small to be visible. Uncertainty bars are displayed for the periods 1950-1969, 1970-1989, 1990-2015.

Even before this measure, the Omani government invested greatly in controlling the activities of the industrial fishing sector through quotas, gears, temporal and fishing areas restrictions, the prohibition of discarding and the deployment of on-board governmental observers (Morgan, 2006). Since the 1970s, the fishing industry has been heavily subsidized and several initiatives were taken to improve fishery management, product quality and fisheries research (Morgan, 2006; Alhabsi et al., 2011). This includes the production of annual fisheries statistical reports that are much more detailed than those of neighboring countries (Fisheries Statistic Department of Oman, 2010, 2012, 2016).

Nevertheless, the catch reconstruction for Oman shows that almost 20% of total marine fisheries catches, including discards are unreported. This result is based mostly on conservative assumptions, and thus may be higher. While it may be argued that 20% is low, especially compared with neighboring countries (Al-Abdulrazzak and Pauly, 2013), there is still a need for local studies to estimate the real incidence of the different unreported fishing activities in Omani waters.

Recreational fishing has been growing exponentially in Oman, in parallel with the rapid development of the tourism sector in general[1], i.e., number of arrivals increased by almost 50% between 2011 and 2014. A simple online search using key words such as "fishing in Oman" leads to numerous websites and online platforms that give very detailed fishing guides to foreign recreational fishers in Oman[2], e.g., providing information on the best seasons, species, area, and gears for "a good fishing experience." For instance, annual and daily licenses for sport fishing provided by the Omani authorities increased by a factor of 3 in the 2010-2015 time period, increasing from just over 1% of total fishing licenses in 2010 (including professional licenses) to 3% in 2015 (Fisheries Statistic Department of Oman, 2011, 2016). Recreational fishing is currently so common that conflicts between professional and recreational fishers are starting to emerge[3]. Subsistence fishing, although not as important as in the pre-oil period, still plays a role in the Omani society. Fishing has always been culturally and traditionally part of the lives of the Omani people. According to Maynard (1988), "*the Omani coastal populations are traditional sea-faring people with the basic skills for a working life at sea.*" Although, this might not be currently as prevalent as previously, Belwal et al. (2015) pointed out that families of fishers practice fishing without a license and that subsistence fishing does exist.

Unreported artisanal catches are likely to be considerably higher than the findings of this study. Several commercial artisanal fisheries are not being monitored or even considered to be fisheries. The tribal, independent nature of coastal communities of fishers across Oman is what characterizes the traditional small-scale Omani fishery. Yet, this very same nature, combined with the large number of artisanal fishers, is what makes the management and the monitoring of the artisanal

[1] www.indexmundi.com/facts/oman/international-tourism (accessed on 25-06-2016).

[2] www.gt-fishing-oman.com, www.fishfishme.com/blog/best-fishing-season-oman (accessed on 25-06-2016).

[3] http://www.y-oman.com/2015/01/traditional-fishing-makes-waves (accessed on 25-06-2016).

commercial fishery challenging for the Omani government (Al-Marshudi and Kotagama, 2006; Morgan, 2006; Qatan, 2010). Instead of adapting to the nature of its traditional fishery, the Omani government appears to have decided, perhaps based on its experience with the industrial fishery, to use a centralized top-down fisheries management approach, while allowing open access to poorly regulated artisanal fisheries (Morgan, 2006; Alhabsi, 2013). This is likely to lead to overcapacity problems in the future.

As for the commercialization of catches, even when fishers are licensed, they do not necessarily sell their catches through the regulated channeled markets, and their catches are thus not monitored by the fisheries catch data collection system (Morgan, 2006), e.g., selling fish directly to consumers on the road, without passing through the fish markets[4]. One non-monitored small-scale commercial fishery is particularly interesting: the invertebrate fishery by Omani fisherwomen. These women have been part of the small-scale fishing industry in Oman for a long time, and mainly collect gastropods and bivalves from beaches as a source of income (Rashdi and McLean, 2014). Such under-valued and often ignored fisheries contributions by women are widespread around the world (Harper et al., 2013).

Despite the efforts of the Omani government in limiting and even prohibiting discarding, this practice is likely to occur occasionally (Kwiatkowska et al., 2000; Morgan, 2006), as fishing operations need to be tightly monitored to suppress discarding entirely. Note that the FAO explicitly requires countries not to include discards as part of their annual fisheries catch reports (Pauly and Zeller, 2016).

Oman is the first Arab state to ratify the 2009 FAO Port State Measures Agreement. Yet, illegal fishing has been occurring in the Omani EEZ. For instance, there used to be an export of spiny lobster and fish to other countries that is not reflected by the data recording system (Morgan, 2006). Several foreign countries used to fish in Omani waters and their catches have not been reported or monitored, e.g., Thailand used to fish on the coast of Oman during the 1970s (Pauly, 1996). In this catch reconstruction, this illegal fishing was not accounted for because of the scarcity of information. However, this warrants further historical research.

A tentative stock assessment was performed for the Narrow-barred Spanish mackerel, known in Oman as Kingfish, (*Scomberomorus commerson*, McIlwain et al., 2005), but scarcity of data precludes other major exploited species from being assessed (Fouda et al., 2009). What little is known is consistent with the observation that "fishing down" occurs in Omani waters (Abd-El-Rahman, 2014), e.g., in Dhofar and Albatinah. As well, by comparing the reported artisanal marine fisheries catches of each province, we noticed that marine catches in the north (Musandam) and in the south (Sharqiyah, Dhofar, and Wusta) are increasing, while catches in the center (Muscat and Batinah) are decreasing (**Figure 5**). This may be a consequence of stronger declines in the central area, where major urban centers occur.

Compared with the cost of traditional stock assessments, catch-based indicators would represent a cheaper and less data-demanding method to assess the status of fisheries in Oman (Pauly et al., 2013). Such indicators, however, require accurate catch data, i.e., including the landings from all fisheries sectors, and their discards, if any.

This study illustrates the need for continuously improving the data monitoring system for Oman, with emphasis on all fishing sectors and components. This cannot be done without the improvement of its fisheries related infrastructure such that it can address the need of rural coastal communities of artisanal and subsistence fishers, and also requires methods to be developed

[4]www.y-oman.com/2015/01/traditional-fishing-makes-waves (accessed on 24/06/2016).

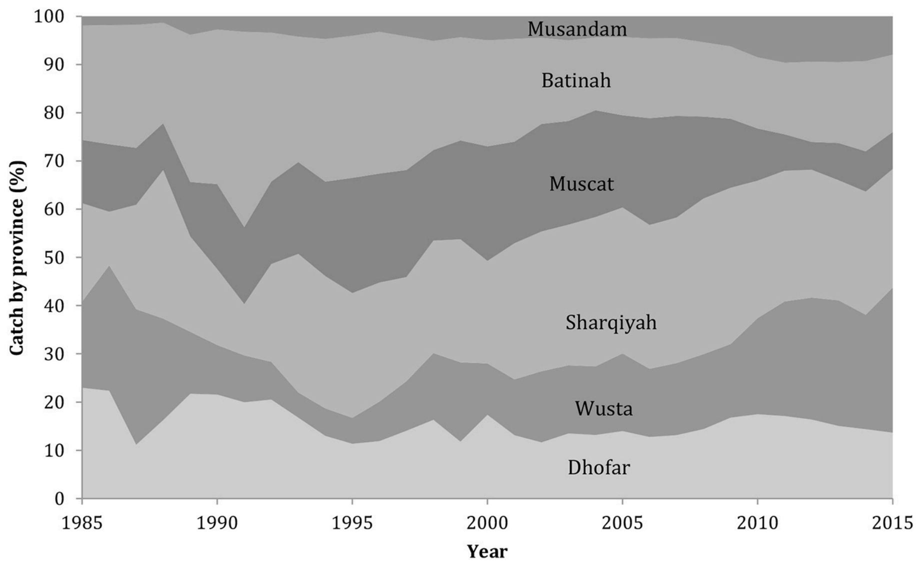

FIGURE 5 | The percentage of marine fisheries catch by Omani province, between 1985 and 2015; presented in this graph according to their geographic position, from Dhofar in the South to Musandam in the North.

and applied for estimating recreational catches. Oman aims to rely on its marine living resources when its oil is depleted. It will be able to do this only if it ensures that its fish stocks do not meet the same fate as its oil, and sound management starts with best possible data.

AUTHOR CONTRIBUTIONS

MK: Completed the data assembly and analysis, and drafted the article; KZ: Assisted in general catch reconstruction queries, and edited the manuscript; DZ: Advised on methodological approaches, guided analytical decisions, and contributed to the manuscript; DP: Guided the conceptualization of the study, reviewed and edited the manuscript, and presented the findings to the government of Oman.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: http://journal.frontiersin.org/article/10.3389/fmars.2016.00152

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Conched Out: Total Reconstructed Fisheries Catches for the Turks and Caicos Islands Uncover Unsustainable Resource Usage

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The Turks and Caicos Islands' total marine fisheries catches were estimated for 1950–2012 using a catch reconstruction approach, estimating all removals, including reported catch destined for export, and unreported domestic artisanal and subsistence catches. Total reconstructed catch for the period is approximately 2.8 times that reported by the Turks and Caicos to the FAO, and 86% higher than the export-adjusted national reported baseline. The pattern of total catches (strong decline to 1970, followed by gradual increase) differs distinctly from that shown by data reported to FAO. Reported landings show a steady increase from less than 1000 t·year^{-1} in the 1950s to around 6000 t·year^{-1} in the 2000s. In contrast, the total reconstructed catches suggest declines in total catches from around 20,000 t in 1950 to a low of about 5000 t in 1970, before gradual increases to about 12,500 t·year^{-1} in the late 2000s. Major discrepancies between reported and reconstructed data are under-reported artisanal catches in the early decades (accounting for 86% of total catches), and the absence of subsistence catches (14% of total catches) in reported data. Queen conch (*Strombus gigas*) and Caribbean spiny lobster (*Panulirus argus*) dominate reconstructed catches. No discards were estimated as fishing has been highly selective, carried out by hand collection (conch), trap or hook (lobster), or hook and line (finfish). New data published here from local seafood consumption surveys demonstrates that the total local consumption of conch equates to almost the entire total allowable catch, before exported amounts are even factored. Policy-makers in the Turks and Caicos need to act if the sustainability of the fisheries stock and fishing industry is to be ensured.

Keywords: artisanal fishery, catch reconstruction, Caribbean fisheries, gastropod fisheries, queen conch, subsistence fishery, sustainable consumption, unreported catch

INTRODUCTION

Fisheries catch under-reporting is evident in multiple regions and nations (e.g., Pauly et al., 2014; Ulman et al., 2015; Zeller et al., 2015; Pauly and Zeller, 2016). It can often be attributed to the acceptance and use of zeros where data are missing, even when there is documented evidence a fishery exists. When this occurs, it can lead to erroneous expectations about present and future resource levels and therefore may lead to poor management and policy decisions. Without comprehensive accounting of total catches from all sectors, it is difficult to measure the formal and informal economic values of resources, and to identify the risks that the under-reported catch may represent.

Catch reconstructions previously conducted in several small island states have shown under-reporting of fishery landings, particularly in small-scale fisheries (Ramdeen et al., 2012; Van der Meer et al., 2014). The Turks and Caicos Islands (TCI), an archipelago nation (**Figure 1**) where fishing has historically been the main industry, shares the profile of these nations and its catches may be similarly under-reported. Its fisheries are already identified as being fished at potentially unsustainable levels (Lockhart et al., 2007), so any such finding would have profound implications for fisheries management within the country. Here, the aim is to reconstruct the total marine fisheries catches for the TCI from 1950 to 2012 by supplementing existing fisheries data with new data sources. A reliable baseline of commercial fish catches would be a welcome aid to local marine resource managers if it allowed them to ensure that those resources were truly sustainable.

The TCI fisheries are defined here as having a small-scale commercial (i.e., artisanal) sector, a subsistence sector (i.e., for the primary purpose to feed one's self or one's family), and a small recreational sector (i.e., fishing primarily for enjoyment and pleasure). The three main commercial fishery target species on the islands are queen conch (*Strombus gigas*), Caribbean spiny lobster (*Panulirus argus*), and finfish (Taylor and Medley, 2003; Lockhart et al., 2007). All three groups are also caught for subsistence consumption and local commercial sale. Lobster is the preferred catch, since their value exceeds the value of conch fourfold, but most fishers switch to conch when the lobster fishery is closed or when conch catches are high. Finfish are opportunistically speared by lobster fishers (Medley and Ninnes, 1999). In recent decades, tourism has surpassed fishing as the leading industry, and visitors demanding locally caught seafood have put additional pressure on the TCI's marine resources (Klaus, 2001).

The Department of Environment and Marine Affairs (DEMA) is the TCI institution responsible for coastal zone management and it has taken the lead role in enforcing legislation pertaining to the marine environment. It collects daily conch (since 1887) and lobster (since 1947) landings data at each of the islands' processing plants, and estimates consumption for all species using national seafood surveys. Their data is crucial in conducting this reconstruction, and will be supplemented with new data where necessary.

Lobster

The lobster fishery is the most economically important fishery, becoming profitable in the late 1950s when snorkeling gear was introduced and the first processing plant was established (CRFM, 2011). Further value was added with the advent of freezing technology in 1966 (Halls et al., 1999). Profitability brought steep catch increases with the fishery growing until 1979, after which declines began due to overfishing. The average lobster taken by early trap fisheries was around 3 kg in weight, but this decreased to only 0.7 kg by the 1970s (Rudd, 2003). Lobsters are landed whole, and weighed as such, although only tails are exported.

Catch per unit effort (CPUE) reportedly declined, from approximately 65 $kg{\cdot}boat^{-1}{\cdot}day^{-1}$ in the early 1990s to around 20 $kg{\cdot}boat^{-1}{\cdot}day^{-1}$ by 2000 (Tewfik and Béné, 2004). Some suggest that the CPUE has actually remained stable at around 58 $kg{\cdot}boat^{-1}{\cdot}day^{-1}$ (Clerveaux et al., 2003), however this likely does not account for increases in engine power and depth fished; thus masking a decline by not accounting for technological creep.

There is no quota on the amount of lobster caught, but a seasonal closure does exist. The majority of lobster is landed when the fishery opens from August 15-March 31, with over 1/3 landed immediately following the fishery opening during the "Big Grab" (Halls et al., 1999; Tewfik and Béné, 2004). The reported DEMA data only include lobster sent for processing, destined for export. Thus, reported data lack information on domestic and tourist consumption.

Conch

In the late 1800s, the TCI's largest conch export markets were Haiti and the Dominican Republic (Doran, 1958). Catches increased substantially from 1937–1945 as local labor switched from salt production to fishing (Béné and Tewfik, 2000). The export industry rapidly developed again in the mid-1970s, when the USA began importing frozen conch to supply newly settled Caribbean immigrants accustomed to this traditional food (Brownwell and Stevely, 1981). Processing peaked in the late 1970s as processors reached capacity at 20,000 $conch{\cdot}day^{-1}$ (Brownwell and Stevely, 1981).

Conch meat is removed from the shells at sea and then frozen for export. Processing or "cleaning" involves trimming the head, foot and digestive system. There is currently a catch quota of 700–750 t of unprocessed meat of wild origin (not farmed), or between 270 and 290 t of "cleaned" processed meat, which equates to about 1900 t of live (wet) animal weight (Thiele, 2001; Lockhart et al., 2007; TCI Government, 2013).

The fishery is managed by a quota system intended to keep the stock at sustainable levels, with the quota divided in two; one portion set aside for exports and the other for domestic consumption. Catch quotas are calculated by a derivative of the previous year's exports and estimated domestic consumption (Clerveaux and Lockhart, 2008), and are occasionally adjusted based on the results of underwater visual surveys. Thus, quotas are not based on fully informed scientific stock assessments.

The export quota for the 2010-2011 season was 4125 $t{\cdot}year^{-1}$ of wild unprocessed meat but the catch was <2800 t. The quota was lowered for the 2012–2013 season to 2540 t, 62.5% of which was reserved for export and the remainder for local consumption.

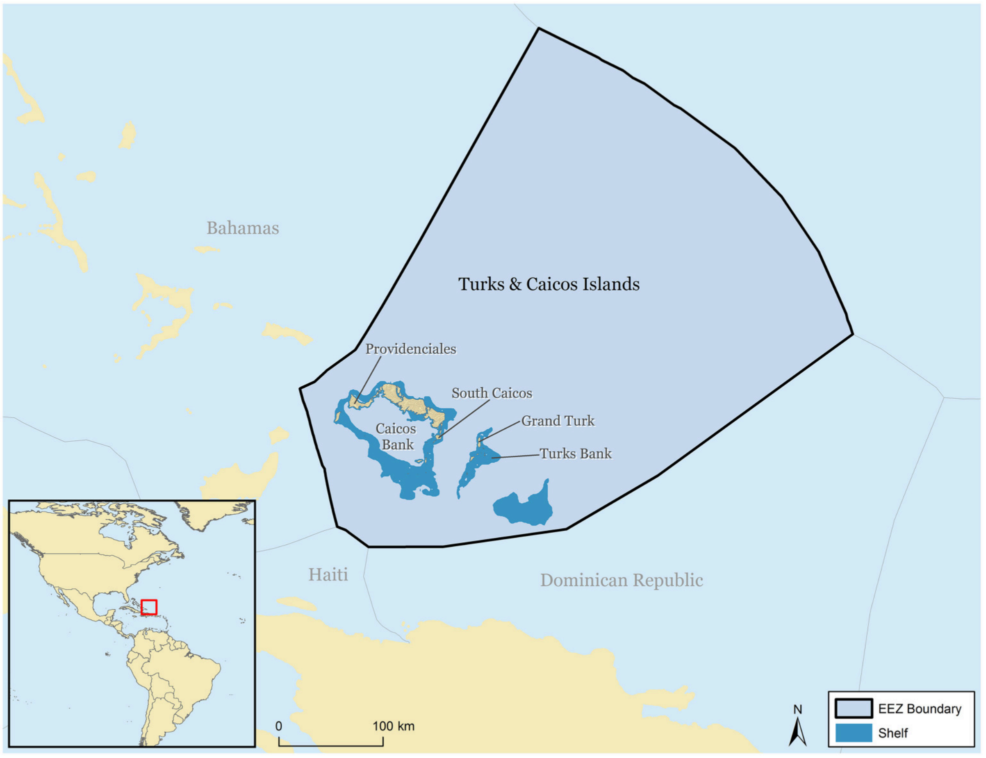

FIGURE 1 | The Exclusive Economic Zone (EEZ) and continental shelf (to 200 m depth) of the Turks and Caicos Islands.

Landings contributions to the export quota only include the meat landed and weighed at the five processing plants. While these data are accurately recorded by DEMA, contributions to domestic quota are not as precisely recorded. Conch eaten domestically is landed at public docks or informal sites where no official recording takes place. The filling of this quota is estimated using a decadal household and tourist consumption survey (Clerveaux and Lockhart, 2008). The TCI Government is obligated to report their conch catches if they wish to continue to trade with signatory nations to the Convention of International Trade of Endangered Species of Wild Flora and Fauna (CITES).

Finfish

The majority of finfish are caught for domestic consumption (subsistence purposes and local commercial sales), and few are exported. It appears that bonefish (*Albula vulpe*) and Nassau grouper (*Epinephelus striatus*) were the preferred local species in the early period (circa 1950). Maitland (2006) calculated that at least once per week, over 97% of households in the TCI ate fish, 79% ate conch, and 46% consumed lobster. Fish populations appear to be in relatively good shape compared to neighboring islands as traditionally preferred species are still available. Species traditionally preferred are bonefish and Nassau grouper, but snapper (Lutjanidae), grunts (Haemulidae), hogfish (*Lachnolaimus maximus*), parrotfish (Scaridae), and triggerfish (Balistidae) are also landed (Klaus, 2001). A handline fishery exists for bigeye tuna (*Thunnus obesus*), blackfin tuna (*Thunnus atlanticus*), barracuda (*Sphyraena barracuda*) and other inshore pelagics (Halls et al., 1999).

The only finfish ever reported by DEMA are blue marlin (*Makaira nigricans*) (2 t in 2006), yellowfin tuna (*Thunnus albacares*) (1 t in 2007), "miscellaneous marlins and sailfishes" (*Istiophoridae*, 1 t in 2007), and "miscellaneous marine fish," which were reported until the late 1990s, after which they disappeared from the reported data. As DEMA does not record most finfish landings, local and tourist seafood consumption surveys have recently been used to gather data on their exploitation. All sales for domestic consumption are missing from reported catch data.

Here, total marine fisheries extractions from the TCI Exclusive Economic Zone (EEZ) were reconstructed to species level, by year, and for each sector. Attempts are made to account for all fishery removals by incorporating catches from previously unreported fishery sectors. Landings of turtles, sponges, and cetaceans were not considered.

METHODS

A catch "reconstruction" approach (Pauly, 1998; Zeller et al., 2007, 2015) was used to estimate total fisheries catches from 1950 to 2012. The first step was to understand the data reported by the TCI to the FAO. That data, reported in the institution's Fishstat database (Garibaldi, 2012), were used as the reported landings baseline in this study. The second step was to compare the reported data to other data sources for inconsistencies, and to make corrections to the baseline data where these sources were more trusted. Thirdly, missing fishery sectors were identified and added to the baseline. The best available data was then sought out and used to estimate the missing catches for the missing fishery sectors. These estimates were carried out using a series of established anchor points, with catches linearly interpolated between anchor points to reflect national trends as per Pauly and Zeller (2016). The principle behind this approach is that when no data are formally recorded, but the fishery is known to exist, it is imperative to use best available estimates rather than inserting a "Not Applicable, or NA" which later is turned into a zero in the database.

Reported Data Baseline

Based on the catch-reporting infrastructure of the TCI, the reported data only include commercial catches destined for export and a very small volume of historically farmed conch (Rudd, 2003; Tewfik and Béné, 2004; Lockhart et al., 2007). Farmed conch previously accounted for circa 1% of exports, but commercial conch farming has now ceased. Even though conch and lobster landings data for the TCI span a long time-series, it has been suggested that most reporting has been inaccurate (Lockhart et al., 2007). Any catches not sent to one of the five export-oriented processing plants are deemed missing from the national catch statistics reported to FAO. Imports are not accounted for as they generally address tourist demand and are thought to not affect local consumption patterns in a substantial manner.

Working closely with local experts, accurate landings data for both conch and lobster (after accounting for the shell conversion factor for conch) were found in a TCI Government report (TCI Government, 2004) and in Clerveaux and Lockhart (2008). At the time the latter was published, W. Clerveaux was head of the TCI Department of the Environment and K. Lockhart was a TCI fisheries scientist. These national conch data were higher than the data reported by FAO from 1950–1968 on behalf of the TCI, and they were used here to correct the reported baseline data as presented by FAO on behalf of the TCI, as the sources were deemed reliable. From 1969–1974, data reported by FAO appear to over-report conch catches, which were adjusted downwards based on data in a TCI Government (2004) plan and Clerveaux and Lockhart (2008). From 1975 onwards, the data reported to FAO were considered to be accurate and were accepted.

The reported lobster data from 1950–1971 were adjusted to account for minor over- and under-reporting discrepancies so as to match the trusted national data from the TCI Government (2004) plan and Clerveaux and Lockhart (2008), while data reported by FAO were accepted for 1972–2012. All of the reported catches were considered to have been caught by the artisanal sector (small-scale commercial sector) for export, leaving artisanal catches for local sale, and subsistence and recreational sectors to be estimated separately.

Local Population and Tourist Numbers

TCI human population data were available for 1950–1958 from the Population Statistics Historical Demography web site (www.populstat.info/) and for 1959–2012 from the World Bank (**Figure 2**). Data on the number of stop-over tourists (travelers who stay for more than a day) were available for 1962, 1967, and 1968 in Bryden (1973), for 1995–2005 from the TCI Department of Planning and Statistics, and for 2006–2012 from the TCI Tourist Board (**Figure 2**). A linear interpolation was used to estimate tourist arrivals in years with missing data.

Domestic Consumption

Since only exports for the TCI were reported during the 1950–2012 time-series, domestic and tourist seafood consumption were estimated using estimates from past seafood consumption surveys as anchor points. The *per capita* seafood consumption amounts were then multiplied by conversion factors to derive live fish weight, which were then multiplied by annual human population records to determine annual domestic consumption catches. These catches were then categorized to species level.

Seafood consumption anchor points were derived from Olsen (1985), Rudd (2003), Lockhart et al. (2006) and Hind (unpublished data, 2013); The most recent national seafood consumption survey interviewed over 580 residents and was undertaken in late 2013 (Edward Hind, unpublished data). It was the most extensive and representative survey completed to date because it included representation across all ages (18+), ethnic groups, genders, and islands. The portion sizes used for all domestic consumption are taken from Lockhart et al. (2006). The survey results presenting *per capita* consumption from this study are presented in **Table 1**.

Conch Conversion and Allocation

Conch data from the TCI is converted to live weight by the FAO using a 7.5 conversion factor (FAO, 2012). To convert serving sizes to live animal weight to estimate local consumption from the seafood consumption surveys, an initial conversion factor of 2 was applied to account for trimmed and unused meat (Thiele, 2001), which was multiplied by the FAO factor of 7.5 to account for the shell, equating to a total conversion factor of 15.

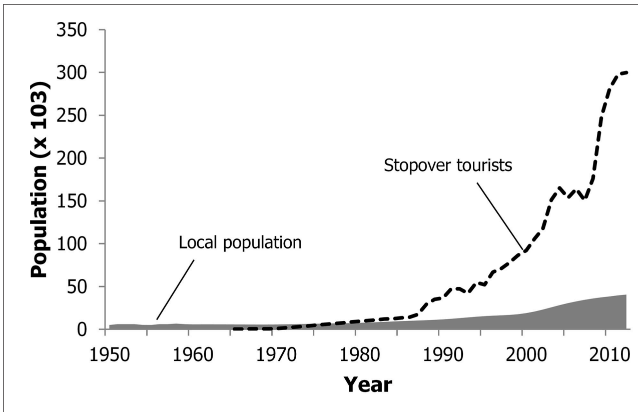

FIGURE 2 | Local and stop-over tourist population of the TCI, 1950–2012. Sources: (Bryden, 1973), 1962 anchor point; Caribbean Tourism Organization, 1980–2006 data; Turks and Caicos Islands Tour Board Statistics, 2007–2012 data. Note: stopover tourists average between 6 and 7 days each, and tourist-days were used to calculate consumption.

TABLE 1 | Per capita national seafood consumption rate in the Turks and Caicos Islands, 2013 (kg·year^{-1}).

Food item	Adult	Child
Conch	7.5	5.0
Lobster	6.7	4.4
Reef fish	12.6	8.4
Gamefish	1.6	1.1
Shark/ray	0.5	0.3
Bonefish	1.8	1.1
Total	33.4	22.3

Source: Edward Hind (unpublished data).

In 1950, conch catches were assumed to have been taken 75% for subsistence purposes and 25% for artisanal (i.e., commercial) purposes. These rates were linearly interpolated to 50% subsistence and 50% artisanal by 2013, as a 2004 survey indicated that 36% of locals receive conch as gifts from fishers, and 15% personally capture conch [*c.* 50% subsistence] (Lockhart et al., 2006). Thus, it was assumed the remainder of conch meat is bought commercially.

Lobster Conversion and Allocation

Lobsters are weighed whole before the tails are removed for export, and thus no conversion factor was required, unless just the tail was reported for export, in which case a factor of 2.6 was used (Halls et al., 1999). To convert the meal sizes from the seafood consumption survey to live fish weight for lobster, the FAO conversion factor of 2.6 was applied.

In 1950, lobster catches were assumed to have been 75% subsistence and 25% artisanal, which was linearly interpolated to 10% subsistence and 90% artisanal by 2012. This was based on rising lobster prices that encouraged most fishers to profit from their catches instead of keeping them for personal consumption.

Finfish Allocation

There are four types of fish consumed in the TCI: reef fish, gamefish, sharks and bonefish (Edward Hind, unpublished data). The allocations used for reef fish and gamefish are presented in **Table 2**. Sharks were categorized as Subclass Elasmobranchii since no local studies detailing shark taxa have been done. To convert individual portion weights to live fish weight, for game fish, tuna, and sharks, a conversion factor of 1.92 was applied to account for the filet of meat and likely higher uneaten portions, but a lower conversion factor of 1.35 was used for reef fish and bonefish. **Table 3** shows per capita domestic consumption amounts for conch, lobster and finfish.

The taxonomic breakdown applied to both 1950 and 2012 are displayed in **Table 4**. This table excludes gamefish in 1950, which we assumed began as a very small target fishery (at 1% of total finfish catch) after engines were first introduced in 1965. The gamefish contribution was linearly increased to the 2012 levels of 10% of the finfish catch, and all estimates were linearly interpolated for the intervening years. Nassau grouper has been the preferred target species for many decades due to their substantial size and ease of catching (Rudd 2003). Bonefish were once the preferred local fish species (Olsen, 1985), but consumption rates have decreased in recent decades with older fishers retiring and younger generations regarding it as "poor man's" food. For domestic finfish consumption in 1965, 50% was assumed to have been caught as subsistence and 50% as artisanal, which was linearly interpolated to 20% subsistence and 80% artisanal by 2012.

TABLE 2 | Taxonomic allocation used for reef-fish and gamefish for both domestic and tourist consumption in the Turks and Caicos Islands.

Reef fish	Proportion	Gamefish	Proportion
Lutjanidae	0.35	Scombridae	0.45
Haemulon spp.	0.30	*Coryphaena hippurus*	0.40
Epinephelinae	0.10	Xiphiidae	0.10
Labridae	0.10	*Acanthocybium solandri*	0.05
Misc. fish	0.08		
Haemulidae	0.05		
Ostraciidae	0.02		

TABLE 3 | Per capita seafood consumption used for domestic consumption, years applied and sources used.

Type of seafood	Kg·person^{-1}·year^{-1}	Years applied	Source
Lobster	25.0	1950–1980	
Lobster	10.0	1985–1990	Rudd, 2003
Lobster	6.7	1995–2012	Hind, 2013*
Conch	35.4	1950–1985	Olsen, 1985
Conch	10.0	1990–1999	Rudd, 2003
Conch	7.5	2012	Hind, 2013*
Finfish	35.0	1950–1985	Olsen, 1985
Finfish	16.5	2005–2012	Hind, 2013*

Linear interpolations used to estimate missing years.
**Hind (unpublished data).*

TABLE 4 | Fish allocation (fractions) for 1950 and 2012 for both subsistence and artisanal catches, interpolated for years between.

Year	Reef-fish	Bonefish	Sharks	Gamefish
1950	0.60	0.350	0.050	0.0
2012	0.77	0.105	0.025	0.1

Tourist Consumption

To calculate stopover tourist consumption, the following steps were taken:

1) The annual number of tourists from 1967–2012 was established (**Figure 2**; Bryden, 1973);
2) This was multiplied by the average number of meals (15.2) consumed on the island for an average 6–7 day stay (Lockhart et al., 2006);
3) This was multiplied by tourist seafood consumption rates from the 2013 consumption survey for conch (0.0071 kg·meal^{-1}), lobster (0.0102 kg·meal^{-1}), reef

($0.0163\,\text{kg}\cdot\text{meal}^{-1}$) and game fish ($0.0026\,\text{kg}\cdot\text{meal}^{-1}$, $0.0006\ \text{kg}\cdot\text{breakfast}^{-1}$), and then adjusted to mean live weight;
4) This was applied to individual taxonomic groups as was done for domestic consumption (**Table 2**);
5) Available information on imported fish was subtracted. Excluding conch and lobster (because conch are not imported and lobster imports are negligible), we assumed that 50% of tourist finfish consumption is domestically sourced, the remainder being imported;
6) The remainder was taken as the unreported tourist demand fulfilled by domestic artisanal fisheries.

A similar calculation was completed to account for cruise ship tourists who began arriving in the TCI in 2006. To estimate the percentage of cruise ship tourists consuming a local meal while on an onshore daytrip, a customer service representative estimated that approximately 30% of the guests consume one meal while ashore for the day (Nikki Beare, Princess Cruises, pers. comm.). Thus, it was assumed 30% of cruise ship passengers consumed one meal while ashore.

New data from the most recent 2013 survey suggested a tourist seafood consumption rate of $0.56\ \text{kg}\cdot\text{person}^{-1}\cdot\text{day}^{-1}$ which was used as an anchor point to calculate recent tourist seafood consumption.

Recreational Catches

Recreational catches are defined here as catches taken for the primary purpose of sport or pleasure. A sport fishery was assumed to have begun with the onset of tourism in 1965. Surveys suggested that 0.02% of all tourists in 2002, and 0.04% in 2004, came to the TCI primarily to fish (TCI Tourist Board, 2003, 2005). From 1965–1980, 0.01% of tourists were assumed to come primarily to fish, from 1990–2002, 0.02%, and from 2004–2013, 0.04%. The percentage of tourists assumed to be recreational fishers was linearly interpolated between the three time-series anchor points. All tourists with a focus on fishing were assumed to catch 10 $\text{kg}\cdot\text{visit}^{-1}$ (visits average 6 days). The following species were allocated at 10% of catches each: bonefish, blue marlin, sailfish (*Istiophorus albicans*), wahoo (*Acanthocybium solandri*), bigeye tuna, blackfin tuna, swordfish (*Xiphias gladius*), shark (Elasmobranchii), barracuda (Sphyraenidae), and dolphinfish (*Coryphaena hippurus*).

Foreign (Illegal) Fishing

There have been reports of illegal fishing (i.e., poaching) from neighboring Haiti and the Dominican Republic for conch, lobster and finfish (MacAlister Eliot Partners Ltd, 2003; Rudd, 2003). This is viewed as a significant issue, since poaching vessels "can carry several tons of seafood to their homeland per trip" (TCI Government, 2013). Estimates of these foreign catches, using a flowchart of catch origins provided by Halls et al. (1999) suggest the equivalent of less than 1% of total conch catches is caught by foreign fishers. Since no specific information could be found regarding other foreign catches, this figure of "less than 1% of total conch" was used to create a proxy for foreign (illegal) conch, lobster and finfish catches. The equivalent of 0.5% of total reconstructed conch and 0.3% of total reconstructed lobster and finish (requiring more skill) catches were estimated to account for foreign poaching. The Dominican Republic was assumed responsible for 85% of these foreign catches and Haiti 15%, since Dominicans have a higher usage of motorized vessels.

RESULTS

Adjusted Reported Data Baseline

The FAO landings data, which were used as our time-series of officially reported catches, amounted to 219,173 t for the 1950–2012 period. Our reconstruction improved on the reported data using more trusted national data. From 1950–1964, these exported catch amounts were raised, and from 1965–1973 they were lowered which resulted in an adjusted reported baseline of 360,000 t for the 1950–1975 period (**Figure 3A**).

Reconstructed Total Catch

The reconstructed total catch resulting from the combination of exported fish and lobster with the newly estimated domestic and tourist consumption amounted to approximately 668,000 t for the 1950–2012 period (**Figure 3A**). The reconstructed total catch peaked in the early 1950s at around 20,000 $\text{t}\cdot\text{year}^{-1}$, after which it declined to a low of around 5300 t in 1970, gradually increasing thereafter to average about 11,500 $\text{t}\cdot\text{year}^{-1}$ in the 2000s (**Figure 3A**). Please see Appendix Table 1 in Supplementary Material for a detailed comparison of the reported data and the adjusted reported data, as well as each sector's catches for the duration of the time-series. The reconstructed total catch was 86% higher than the adjusted reported national baseline catch for 1950–2012, and 2.8 times higher than the data reported to the FAO for the TCI (**Figure 3A**).

The main fisheries catch in the TCI was from the artisanal sector, which contributed around 85% to the reconstructed total catch (**Figure 3A**). The artisanal catch consisted mainly of conch (89%) and lobster (6%), while various fish taxa (over 20 taxa) each made minor contributions. The subsistence sector contributed 15% to the reconstructed total catch (**Figure 3A**), and consisted of conch (85%) and lobster (11%), with various fish taxa making minor contributions. The recreational catches contributed only around 0.1%, or about 1,000 t in total, to the reconstructed catch.

Overall, the major taxonomic contributors to the total catch were conch (by weight, 87%) and lobster (7%), while bonefish, snapper, grunts, grouper, wrasses, sharks, and 18 other taxa contributed considerably smaller amounts to the total reconstructed catch (**Figure 3B**, Appendix Table 2 in Supplementary Material).

Domestic Consumption

Local subsistence consumption for conch averaged 200 $\text{t}\cdot\text{year}^{-1}$ in the early 1950's which gradually increased to about 350 $\text{t}\cdot\text{year}^{-1}$ from 2011 to 2012. For lobster, it averaged 143 $\text{t}\cdot\text{year}^{-1}$ in the early 1950s, which gradually increased until 1980 at 188 t. It then decreased to 95 t in 1984, before then gradually increasing again to average 305 $\text{t}\cdot\text{year}^{-1}$ from 2011–2012. Finfish consumption was at 124 t in 1965, but soon decreased to 89 t by 1971. It then gradually increased to average 167 $\text{t}\cdot\text{year}^{-1}$ for 2011

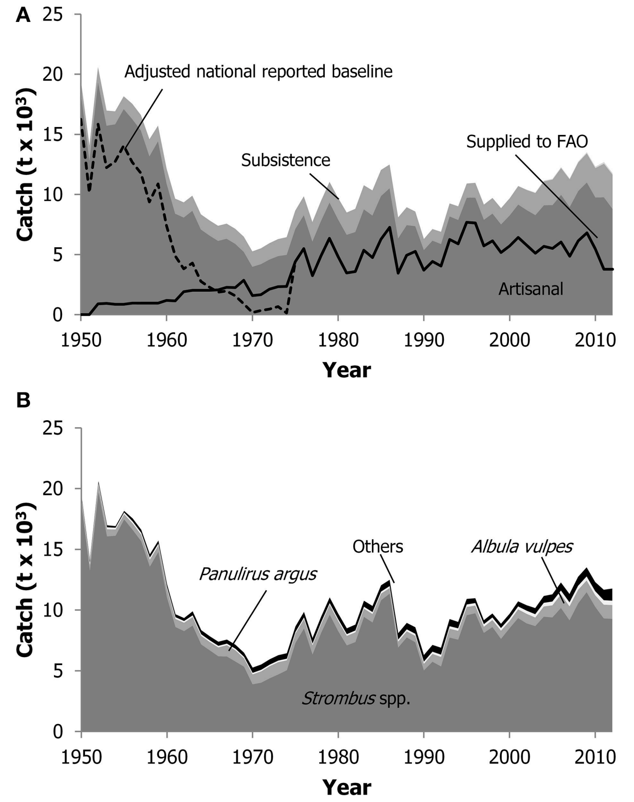

FIGURE 3 | (A,B) Time-series of reconstructed domestic marine catches for Turks and Caicos Islands by **(A)** fishing sector (recreational is too small to show), with data reported by FAO on behalf of the TCI, as well as the adjusted national reported data overlaid as dashed lines; and **(B)** by major taxa, with the "others" grouping consisting of 20 additional taxa.

and 2012. The catches were allocated to 17 taxa, with the most allocated to bonefish, snapper, grunts, and sharks.

Tourist Consumption

For the stopover tourists to the TCI, conch consumption was estimated to begin at 1.24 t in 1967, which gradually rose as tourism increased to average 533 t·year^{-1} for 2011 and 2012. Tourist lobster consumption was estimated to begin at 0.315 t in 1967 which gradually increased to average 134 t·year^{-1} for 2011 and 2012.

For the cruise ship tourists who spend less than a day ashore, conch consumption was estimated to begin in 2006 at 6.3 t which gradually increased to average 14.2 t·year^{-1} for 2011 and 2012. Lobster consumption of this group was estimated to begin at 0.16 t in 2006, increasing slightly to average 0.36 t·year^{-1} for 2011 and 2012.

Conch

Total conch catches from the TCI, including both exports and domestic consumption, amounted to nearly 573,000 t from 1950 to 2012, or 87% of the island's total catches by weight.

Lobster

Total lobster catches from the TCI, including both exports and domestic consumption, amounted to nearly 46,000 t from 1950–2012, or 7% of the islands' total catches by weight.

Finfish

Total finish catches from the TCI amounted to just over 39,000 t from 1950–2012, which consisted mainly of bonefish, and then to a much lesser extent, snappers, grunts and sharks (See Appendix Table 2 in Supplementary Material for annual details).

Recreational Catches

Recreational catches from sports fishing commenced in 1965 with 0.025 t of fish caught, which gradually increased to average 130 t·year^{-1} from 2011–2012.

Foreign (Illegal) Catches

The Dominican Republic was estimated to catch a total of approximately 2600 t, averaging about 44 t·year^{-1}, and Haiti just over 500 t in total at 9 t·year^{-1}. The catch composition for both countries was assumed to have consisted of conch (88%), finfish (7%), and lobster (4%).

DISCUSSION

The reconstructed baseline of the TCI fisheries is almost twice the pre-existing one, which has troubling implications. The incomplete totals have been used for decades to calculate supposedly sustainable catch limits for the islands' marine resources. We can now see that these limits have been far from sustainable and have facilitated overexploitation of national fish stocks. Considering marine resources contribute over 10% of the GDP as of 2015 (IndexMundi.com), and benefit residents by providing readily available and potentially long-term sources of local protein and employment, there is an urgent need to act on the results of this study. Policy-driven, future increases in the TCI's national population and its tourist numbers (TCI Government, 2012), with the increase in local seafood consumption that will result, will be devastating to the health of TCI fisheries without legislation to curb catches and/or consumption.

Queen conch were found to contribute 87% to the total reconstructed catches for the TCI, emphasizing that this is an extremely important species, however, their future looks bleak. The TCI's queen conch population is seen as one of the more abundant and thus, healthier populations in the greater Caribbean, and their continued "health" is important to the sustainability of the species as a whole. Although the TCI marine resource managers have tried to limit conch catch, the results of this study show that the unaccounted for local and tourist consumption essentially accounts for what managers see as a sustainable catch (the maximum sustainable catch calculated for the 2013–2014 season was assumed to be 372 t processed catch, with 145 t reserved as domestic quota, which nearly equates to the estimated local and tourist consumption). The whole export quota may resultantly be unsustainable catch. It should be no surprise that a snapshot assessment by means of a visual survey conducted toward the end of that season signaled a declining conch population, even with official landings inside the quota.

The TCI government, advised by DEMA, has looked to act on some of the new data used in this reconstruction. Referencing the 2013 seafood consumption survey, as well as the underwater visual survey, they subsequently announced that the sustainable catch quota will be reduced to just 277 t of processed conch for the following season. Knowing that over 90% of this quota would have been taken up by domestic consumption, DEMA then recommended an export cessation of up to five years. Reducing domestic consumption would be much more difficult as much of this fishery is unreported and therefore challenging to regulate. However, the TCI government has delayed in actually implementing the export cessation, which may further impair the conch stocks. The full reconstruction, as presented here, adds further weight to the their need to act as soon as possible to reduce conch landings. With the TCI only permitted to export conch to CITES signatories if it demonstrates a well-developed management plan, any lack of further action could see CITES effectively implement an export ban with the TCI.

The TCI is not the only country where marine policy-makers need to take notice of fishery catch reconstructions. The data presented here are part of the global study summarized by Pauly and Zeller (2016). Although the TCI is the only country where artisanal and subsistence catches decreased from the mid-1980s to the mid-1990s, the increase in artisanal and subsistence catches over time aligns with the results of other catch reconstructions. Overall catches in the TCI have noticeably declined, which fits the regional profile for the Western Central Atlantic of catches peaking around 1985 and declining thereafter. In the immediate neighboring region, the underreporting of fisheries catches has been a similar issue. Reconstructed catches for Haiti, the Dominican Republic and Jamaica were found to be over 3, 4 and 5 times (respectively) those reported (Ramdeen et al., 2012; Van der Meer et al., 2014). Findings in these studies also support calls for the more regular collection and estimation of local and tourist consumption, so that stock evaluations and catch quota estimation can be undertaken using the best available data.

In the TCI, only exports were being accurately assessed in the calculation of quotas. Local consumption, a necessary and substantial addition, was omitted or underestimated, as data were not always available or up-to-date. With this issue brought to light, it is hoped future catch quotas will be calculated based on total removals by all sectors. For a nation with limited resources, the recent seafood consumption surveys are a fairly simple and low-cost approach to collect the required domestic consumption data. With a high number of participants enrolled, the surveys are resistant to being skewed by atypical variations discovered in individual diets, and can be considered representative. It is recommended, if possible, they be continued at an interval of every 5 years.

The detailed technical catch reconstruction report that underpins the present contribution is freely available at http://www.seaaroundus.org/doc/publications/wp/2015/Ulman-et-al-Turks-and-Caicos.pdf, and can also be found at the Turks and Caicos EEZ data page at http://www.seaaroundus.org/data/#/eez/796?chart=catch-chart&dimension=taxon&measure=tonnage&limit=10.

ETHICS STATEMENT

The ethics committee that approved the seafood survey carried out as part of this study was the School for Field Studies (SFS) Office of Academic Affairs, IRB Administration. The IRB approval number is TCI-01-14a. The research was exempted from a full IRB process under Category 2 of the U.S. Code of Federal Regulation Title 45 Public Welfare Part 46 Protection of Human Subjects 46.101b. Qualification for this exemption was achieved as the survey procedures ensured (i) information was obtained and recorded in such a manner that human subjects could not be identified, directly or through identifiers linked to the subjects; and (ii) because any disclosure of the human subjects' responses outside the research could not reasonably place the subjects at risk of criminal or civil liability or be damaging to the subjects' financial standing, employability, or reputation.

AUTHOR CONTRIBUTIONS

The original methodology was decided upon by DZ. EH provided some of the background data. AU, RR, and DZ helped calculate the methodology. AU, LB, EH, and DZ contributed to both the writing and editing of the paper.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: http://journal.frontiersin.org/article/10.3389/fmars.2016.00071

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Spatio-Temporal Declines in Philippine Fisheries and its Implications to Coastal Municipal Fishers' Catch and Income

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The problem of overexploitation in global fisheries is well-recognized. However, published assessment of fisheries spatio-temporal trends at the national scale is lacking for many high biodiversity developing countries, which is problematic since fisheries management is often implemented at the local or national levels. Here, we present the long-term spatio-temporal trends of Philippine fisheries production based on the landed national fish catch data (1980–2012) and fishers' interviews. We found that the total Philippine fish catch volume (Metric Tons MT) of most capture fisheries throughout the country has either stagnated or declined over the last three decades. The decline is even more prominent when evaluating fisheries trends at the provincial level, suggesting spatial serial depletion of the country's fisheries. In contrast, the total Philippine fish catch value (US Dollars US$ or Philippine Pesos PHP) has continued to increase over time, despite the declining fish catch volume. However, local municipal fishers are experiencing both low fish catch and income, contributing to observable poverty in many coastal communities in the Philippines. The various stakeholders of Philippine fisheries need to recognize the depleted state of Philippine fisheries, and learn from various experiences of collapsed and recovered fisheries from around the world, in order to recover the Philippines' capture fisheries. Lessons from the literature on collapsed fisheries offer the following options for recovery: (1) regulate or reduce fisheries exploitation and other human activities impacting the fisheries to allow fisheries to rebuild or recover, (2) enforce effective networks of marine reserves, (3) engage fishers, consumers, and other stakeholders in fisheries management, (4) improve fisheries science, monitoring, and management capacities, and (5) provide alternative livelihood, skills, and improved education to fishers and their families.

Keywords: fish catch data, fishers' economics, fisheries management, fisheries production, overfishing

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INTRODUCTION

The state of global fisheries is continuously declining, with catch rates falling since the 1980's (Pauly et al., 2002). Despite this declining trend in fisheries production, global fishing effort has been continuously increasing (Anticamara et al., 2011). The world's fisheries have resorted to geographic, bathymetric, and taxonomic expansion to cover for declining catches in overexploited fishing grounds (Pauly, 2009). Catches for most trophic levels are still rising, potentially contributing to increasing fisheries collapse (Branch et al., 2010). To date, the global catch biomass of large predatory fish is estimated to be between 10% (Myers and Worm, 2003) and 60% (Juan-Jorda et al., 2011) of pre-industrial fishing levels, with most stocks fully-exploited, limiting further expansion of these important fisheries. Furthermore, FAO (2012) reported that in 2009, 57.4% of global fish stocks were fully-exploited, 29.9% were overexploited, and only 12.7% were non-fully exploited.

Monitoring and managing fisheries status throughout the globe is essential in maintaining their sustainability, or, in the case of depleted fisheries, facilitating their recovery (Pauly, 2009). Fisheries monitoring and management is typically carried-out at the national or regional level, most of which is being done in developed parts of the world such as North America, Oceania, and parts of Europe (Musick et al., 2000; Jelks et al., 2008). However, more attention must be given to developing nations that exhibit high marine biodiversity and increasing fish catch (i.e., suggesting increasing fishing activity), but often report patchy fisheries data and analysis to FAO or the scientific literature (i.e., data poor countries; Worm and Branch, 2012).

The Philippines, a nation considered to be a major hotspot of marine biodiversity (Roberts et al., 2002), currently lacks quantitative analysis on the long-term, spatio-temporal trends in its national fisheries production. Comprehensive national-scale studies on the trends of Philippine fisheries exist, but focused on particular fisheries sub-sectors (e.g., artisanal fisheries; Muallil et al., 2014a,b), policy and management (Briones, 2007), or total national production only (Sadovy, 2005). Currently, the Bureau of Fisheries and Aquatic Resources (BFAR) in the Philippines is the authority on monitoring the status and productivity of Philippine fisheries. However, the annual Fisheries Profile publications produced by BFAR (accessible at: http://www.bfar.da.gov.ph/, accessed 1 August 2015) typically review only short-term trends in fisheries production (i.e., changes in fisheries production from the past 2 or 3 years).

The lack of long-term analysis on Philippine fisheries is surprising, considering the socio-economic importance of fisheries and fishing activities to the country. The Philippines is among the top 15 nations in global marine fisheries capture production (FAO Fisheries Aquaculture Department, 2014), and many Filipinos depend on fish products for both food and livelihood—i.e., Filipinos derive an estimated 43% of their animal protein diet from fish and fish products (FAO, 2001), and over 1.6 million Filipinos were employed in fisheries-related occupations based on 2011 data (BFAR, 2011).The demand for fish products will only increase with time, as the Filipino population has been growing at an average rate of 1.9% from 2000 to 2010, with 2010 population estimates to be at over 92.3 million individuals (NSO, 2014). Thus, there is a great need to examine the Philippine's fisheries trends and its possible implications, in order to help drive science or data-based decision-making in the management of the nation's fisheries.

This study presents the most recent spatio-temporal analysis of Philippine fisheries production based on landed national fish catch and fishers' interview data. The objectives of the study are the following: (1) to quantify the spatio-temporal trends in Philippine fisheries production from 1980 to 2012; (2) to present the estimates of fishers' fish catch and income from five Philippine fishing provinces; and (3) to explore options and insights for improving the science and management of Philippine fisheries through a literature review focused on the most recent research on fisheries status assessments and recommendations for declining fisheries.

METHODS

Spatio-Temporal Trends in Philippine Fisheries Production

To analyze the long-term, spatio-temporal trends in Philippine fisheries, we obtained online fisheries data from BFAR, the Philippine government institution, which currently collects and maintains the most complete and up-to-date national database on Philippine fisheries production. However, the online data provided by BFAR is strictly fisheries-dependent (i.e., based on fish catch or landings). Relying solely on catch data to assess fisheries has been criticized as being misleading in estimating the actual status of fish stocks (Branch et al., 2011). Nevertheless, for developing countries such as the Philippines (which lacks the infrastructure and funding to consistently conduct expensive national-scale fisheries-independent surveys), monitoring fish catch data is often the only feasible method of assessment and most readily-available data source (Pauly et al., 2013). In addition, Froese et al. (2012) showed that fish catch data are consistent with trends in biomass data of fully-assessed stocks (i.e., those stocks assessed by fisheries-independent methods), refuting claims on the limited usefulness and misleading nature of fisheries-dependent data.

We also obtained Philippine national fisheries data from BFAR's annual Fisheries Profile publications, from 1980 to 2012 (accessible at: http://www.bfar.da.gov.ph/, accessed 1 August 2015). Each annual Fisheries Profile publication contains information on the country's total fisheries production and trade of aquatic resources and top fisheries products for that year. Philippine fisheries data for the years 2013 and 2014 are not yet available to date.

We plotted the temporal trends (from 1980 to 2012) of Philippine fisheries production volume (fish catch in Metric Tons or MT) and value (converted from Philippine Pesos PHP to US Dollars US$; conversion rate was 43.57 PHP = 1 US$ as of 5 Aug 2015), for total national production (i.e., all fisheries sectors combined), and production per sector (i.e., commercial fisheries sector, marine municipal fisheries sector, inland municipal fisheries sector, and aquaculture sector). We also examined the mean ($\pm$ standard error SE) fisheries production between successive decades—i.e., 1980–1989, 1990–1999, 2000–2009, and 2010–2012 (henceforth referred to as the 1980's, 1990's, 2000's, and 2010's, respectively)—using one-way ANOVA and Tukey's *post-hoc* analysis.

We then focused our subsequent analysis on the spatio-temporal trends in the marine municipal fisheries sector. We extracted data on marine municipal fisheries fish catch landings (in MT) from the CountrySTAT Philippines database (accessible at: http://countrystat.psa.gov.ph/, accessed 1 August 2015), which

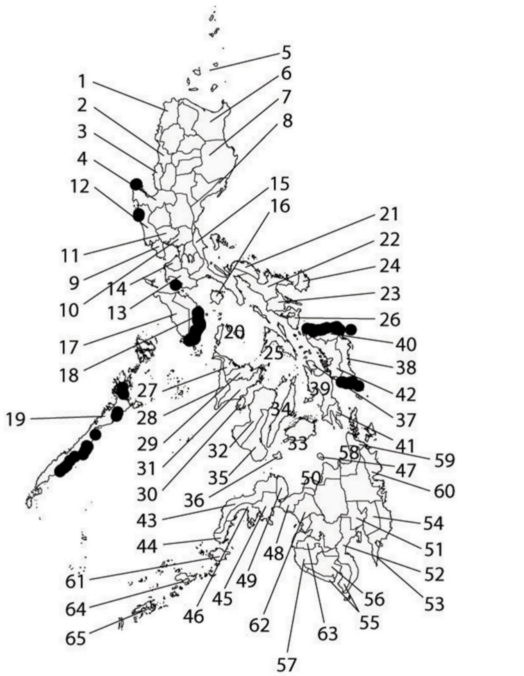

FIGURE 1 | Map showing sources of provincial municipal fish catch data (numbers), and fisher interview sites (dark circles). List of provinces with their corresponding number codes are listed in Table S1.

sources fish catch data from the Bureau of Agricultural Statistics. Fish catch data is presented as total sum per province. The goal of this analysis is to determine the contributions of each province to Philippine fisheries, and whether the marine municipal fisheries per province showed signs of increasing or decreasing production from 1980s to date. Provinces included in the analysis are shown in **Figure 1**. Province names corresponding to each province code are shown in Table S1.

Status of Municipal Fishers' Catch and Income

To present the status of Philippine fisheries at the level of the fishers themselves, we interviewed a total of 470 coastal municipal fishers from 84 coastal villages or *barangays* belonging to 17 municipalities throughout the Philippines (**Figure 1**). Here, we focused our analyses on the 470 fishers from the municipal marine fisheries sector, due to the following reasons: (1) majority (over 90%) of the fishers in the villages that we visited were coastal municipal fishers (i.e., municipal waters defined as 15 km away from the mainland as defined by the Philippine Republic Act 8550) and only few were commercial and off-municipal water fishers; and (2) coastal resource management and legislation in the Philippines is typically enforced at the municipal level (i.e., within the boundaries of municipal waters).

Fishers' interviews were conducted from July 2013 to July 2014. Interviews were conducted one-on-one, where fishers were asked questions regarding their estimated fish catch, fishing effort, and income from fishing. Interviewees were selected at random, or referred by previously-interviewed fishers.

Interview data was used to plot the mean ± SE fish catch volume (in kg), catch value (in US$), and fuel cost (in US$) per hour per fisher. We standardized catch data and fuel expenses to per hour because the amount of time spent fishing was highly variable between fishers. Most coastal fishers in the Philippines use multiple gears and switch gears during a single fishing trip, so we ignored gear types in current analysis and focused on the overall catches and incomes regardless of gears used, for as long as they fished within municipal waters. To compute for fuel cost per fishers, we multiplied each fisher's estimated fuel consumption with mean common gas price estimates for the year 2013 (i.e., estimates taken from the Philippine Department of Energy, accessible at: https://www.doe.gov.ph/oil-price-monitoring, accessed 1 August 2015).

Review of Relevant Fisheries Literature on Fisheries Status, Collapse, and Options for Recovery

We reviewed the published peer-reviewed fisheries status assessment literature to determine the following: (1) how many publications reported global or national assessment of fisheries trends; (2) what data types were used in published global or national fisheries assessments; (3) what were the trends in status or spatio-temporal dynamics in assessed fisheries; (4) what were the identified consequences of the observed fisheries trends; (5) what were the drivers of the observed fisheries trends; and (6) what actions were recommended or implemented to recover declining fisheries (assuming that those recommendations were based on the understanding of various authors on the best or effective ways to address fisheries decline).

To conduct the literature review, we used the Web of Science Core Collection online database and queried all literature from 2009 to 2014 (past 5 years) using the search parameters "[marine* AND fishery*]" (accessed March 2014). This initial search yielded nearly 2000 papers, but was filtered to only include studies that presented assessments of target fisheries status (i.e., studies that focused on the structure of management or socio-political factors driving fisheries without quantifying fisheries status were not included). Modeling papers where empirical data was used to present specific case studies were also included. We also included studies that did not explicitly measure the effectiveness of fisheries management strategies for as long as they presented fisheries status assessment, because the main purpose of the literature review was to explore the findings of recent fisheries assessments, rather than to quantify management effectiveness. We separately presented assessment studies on global fisheries (Table S2), and national fisheries (Table S3). Because of the large variation in data types, consequences, drivers, and recommendations provided by authors, we categorized each entry for presentation in the Supplementary Tables. For example, under the recommendations column, "Regulate fishing activity" may refer to any of the following: Total Allowable Catch TAC establishment; fishing quotas; gear restrictions; policing against IUU; fishing vessel limits; and fishing closure seasons. Further details on each category can be found in Table S4. Out of the initial 2000 publications we only included in our review a total of

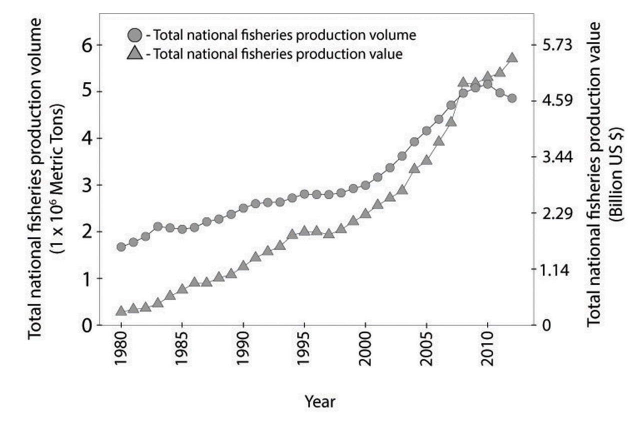

FIGURE 2 | Time-series data of total Philippine fisheries production volume and value from the years 1980–2012.

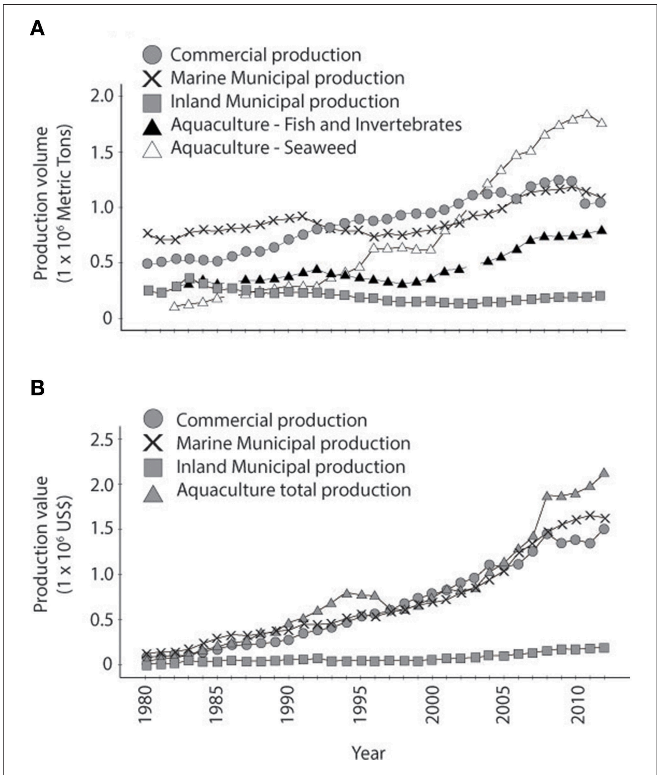

FIGURE 3 | Time-series data of Philippine production volume (A) and value (B) per sector from the years 1980–2012.

56 peer-reviewed publications that actually documented fisheries status at global or national scales. The rest of the publications mainly focused on various aspects of fisheries such as socio-political and economic issues, management issues, by-catch problems and estimates, etc.

RESULTS AND DISCUSSION

Spatio-Temporal Trends in Philippine Fisheries Production

The total landed Philippine fish catch volume showed a generally increasing trend from 1980 to 2010, followed by a decline in production from 2010 to 2012 (**Figure 2**). In contrast, total landed Philippine fish catch value showed a continuously increasing trend from 1980 to 2012 (**Figure 2**). The sector that contributed most to total Philippine fisheries production over the last three decades, in terms of both volume and value, was the aquaculture sector (although most of this was seaweed, which contributed on average about $56 \pm 2.8\%$ of total aquaculture production volume per year), followed by the marine municipal fisheries, commercial fisheries, and inland municipal fisheries sectors, respectively (**Figure 3**). One-way ANOVA and Tukey's *post-hoc* analysis showed that aquaculture production volume continued to increase significantly between successive decades from the 1980's up to recent times (Figure S2). In contrast, the capture fisheries sectors (e.g., municipal and commercial sectors) showed slight or non-significant increase in production volume since the 2000's, suggesting a stagnation in fish catch. However, the production values of all fisheries sectors continued to increase between successive decades from 1980's to recent times (Figure S3).

The top five provinces that contributed most to marine municipal fisheries production volume from 1980 to 2012, arranged in descending order, were Palawan, Zamboanga del Norte, Iloilo, Negros Occidental, and Surigao del Norte—while the rest of the other provinces contributed much smaller fisheries production volume (**Figure 4**). A large portion of marine municipal fish catch over the past decade was due to Palawan, which showed a steep increase in production volume from the year 2000 until 2006, after which its production volume began to drop continuously until 2012. Similarly, Zamboanga del Norte and Negros, two more provinces belonging to the top five marine municipal fisheries producers, experienced noticeable drops in production volume in the late 1980's and early 1990's, respectively, with production failing to return to previous levels ever since. When we examined decadal trends in production volume, we found that 75% of the 65 provinces showed no significant increase in fish catch since the 2000's, suggesting that municipal fish catch has stagnated in those provinces over the last decade (**Figure 4**, Figure S1, Table S1).

Our examination of long-term, spatio-temporal data of Philippine fisheries reveals that capture fisheries have either stagnated or declined in terms of production volume. The bulk of total production volume of Philippine fisheries since the 2000's has been mainly supplied by aquaculture (albeit mainly seaweeds), rather than wild fish catch, and the country's municipal fish catch is sustained by only a few provinces. Stagnating capture fisheries in the Philippines is a matter of economic and ecological concern, since low wild fish catch could be an indication of depleted fish stocks. Fish catch may not always be an accurate reflection of fish stock status, particularly under conditions of effective management, wherein declines in fish catch records are due to the effectiveness of policies that limit fishing (e.g., enforcement of Total Allowable Catch quotas (TACs) and Marine Reserves (MRs)). However, given the lack

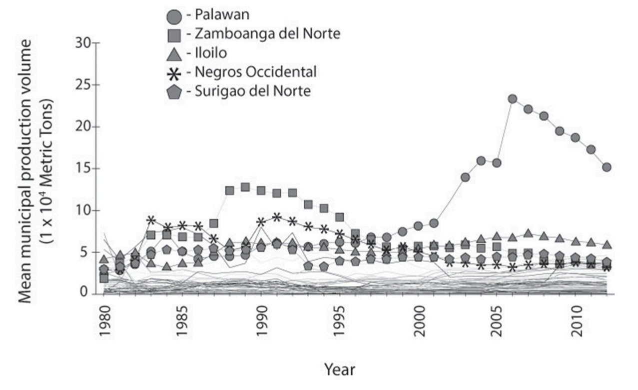

FIGURE 4 | Time-series data of Philippine marine municipal fish catch highlighting the top five fish-producing provinces (indicated by symbols and legends) from 1980 to 2012. Other provinces are represented as lines without symbols, and generally showed much lower fisheries production than the top five provinces.

of enforced fisheries management and the high exploitation rate in many Philippine reefs and coastal areas (Alcala and Russ, 2002; Muallil et al., 2014b), we doubt that the decrease in fish catch recorded in Philippine waters is due to effective fish catch restrictions and management (with the exception of a few well-enforced MRs in the country). Instead, we highly suspect that the decrease in fish catch perhaps reflects the depleted and overexploited status of many Philippine fish species, particularly commercially-important, large-bodied reef fish species (Go et al., 2015).

Previous studies have lamented the un-sustainability of most Philippine fisheries (Sadovy, 2005; Stobutzki et al., 2006; Muallil et al., 2014b). Once exploitation rate exceeds a certain threshold, the number of collapsed species increase, and declines in total fish catch, fish stock biomass, and mean fish body size follow (Worm et al., 2009). Our analysis suggests that Philippine fisheries may indeed be overexploited; fish catch has not increased overtime (and in fact, has decreased for several provinces), despite continuously increasing fishing effort in the country (Briones, 2007), and the increasing number of registered municipal and commercial fishers in the Philippines (according to BFAR's annual Fisheries Profile publications 1980–2012). Evidence in other studies also point to Philippine fisheries' un-sustainability, with most authors citing overfishing as a major factor in the declines of Catch Per Unit Effort (CPUE), catch biomass, diversity, and shifts in fish community structure observed in Philippine waters (Silvestre et al., 2003; Stobutzki et al., 2006; Muallil et al., 2014a; San Diego and Fisher, 2014).

Despite recent declines in fish catch, the value of Philippine fisheries has continued to increase significantly over the last three decades. This could suggest that the market price of fish throughout the country is generally increasing—an effect of the high demand for fish brought about by the growing Filipino population and the declining fish catch in Philippine waters. Increases in the price of fish products could also be due to the increasing cost of fishing itself. For example, fishers may be exerting greater fishing effort (e.g., by spending more time and fuel fishing or investing in more expensive fishing technology) to compensate for the declining abundance of fish in most coastal areas. Increased costs of fishing, combined with declining fisheries production, will undoubtedly have negative effects on the resource's primary users, the fishers.

Fishers' Fish Catch and Income

The declining fish catch of Philippine capture fisheries is reflected in the low income of most municipal fishers. Based on our interview data, mean fish catch of the average Filipino municipal fisher was 1.87 $\pm$ 0.14 kg/h (**Figure 5A**). Mean catch value of interviewed fishers was 1.7 $\pm$ 0.1 US$/h (**Figure 5B**), but their mean fuel cost was 0.4 $\pm$ 0.0 US$ per h (**Figure 5C**). After conversion to daily estimates, we found that the average Filipino fisher earns only about 12.4 US$ from fishing per day (with a mean of 7.3 $\pm$ 0.2 fishing hours per day, based on interviews). By factoring-in their daily fuel cost of about 2.9 US$ after 7.3 h of fishing, it becomes apparent that most fishers are left with less than 10.0 US$/day, a value comparable to that found by Muallil et al. (2014b). This amount is hardly enough to pay for a fisher's daily expenses, especially considering that interviewed fishers had an average of 3.3 $\pm$ 1.5 dependents to support, in addition to their own personal expenses ($n = 160$ respondents with dependents). Furthermore, fishers generally do not fish every day, or throughout the year (mean of 19.8 $\pm$ 0.4 fishing days per month, and 9.7 $\pm$ 0.3 fishing months per year based on interviews), and 61% of the interviewed fishers ($n = 303$ respondents) did not have any alternative livelihoods other than fishing.

The low fish catch and income of most fishers, in addition to their over-reliance on fishing as a livelihood, has contributed to the extreme poverty in many Philippine coastal communities. The extreme poverty and continued overexploitation observed in many coastal fishing communities throughout the Philippines is indicative of Malthusian overfishing, wherein per capita fish catch (and subsequently, income) declines over time, as fishers continue to overexploit a rapidly-degrading resource (Pauly, 1990). To alleviate resource degradation, the responsibilities and costs of coastal resource management in the Philippines typically fall to multiple stakeholders. These stakeholders include the following: (1) the municipal Local Government Units (LGUs), who have the political power to establish and enforce coastal management policies based on Philippine Republic Act 8550 (e.g., enforcement of MRs, bans on destructive fishing methods, or implementation of fishing area zoning), (2) national government agencies such as the Bureau of Fisheries and Department of Environment (3) the fisher communities themselves, who have the responsibility to follow and participate in fisheries policy implementation, (4) the donor agencies and non-government organizations, and (5) the consuming public and the fisheries business sectors. However, enforced and sustainable coastal resource management is lacking in many Philippine coastal communities. In addition, fishers have little incentive to support coastal resource management efforts, partly because of the lack of alternative and because equitable distribution of management benefits (e.g., increased fish catch and income) is rare (Christie et al., 2005; but see further

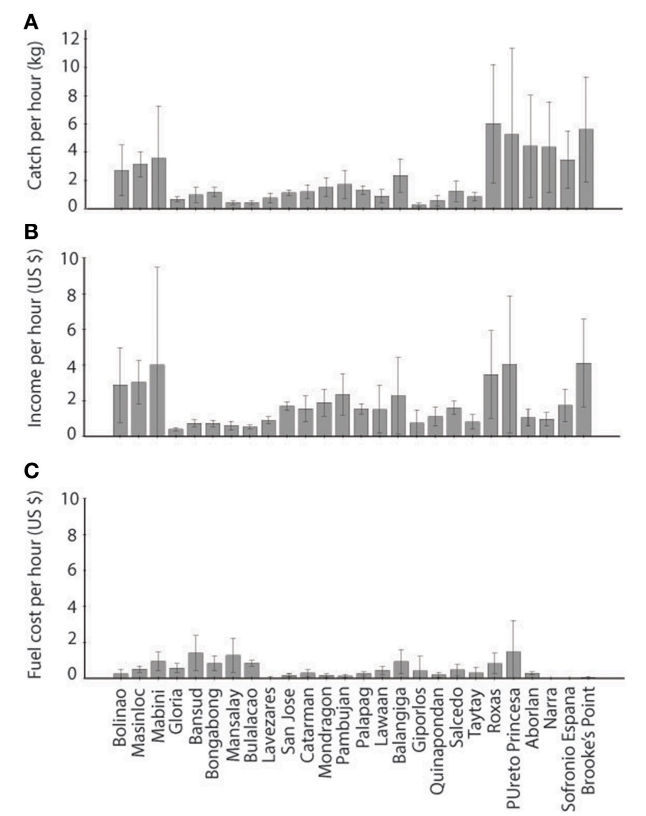

FIGURE 5 | Bar plots showing mean and SE fish catch per hour (A), mean income per hour (B), and mean fuel cost per hour (C) per fisher for each surveyed fishing municipality. Municipalities are arranged by their geographic locations, from north to south of the Philippines.

discussions below). However, the various Philippine fisheries stakeholders need to (1) recognize the depleted state of Philippine fisheries, and (2) learn from experiences of collapsed and recovered fisheries from around the world, in order to help improve the current state of Philippine fisheries. Otherwise, maintaining the current status quo will depress the fisheries further and will put all stakeholders at a disadvantage—i.e. the fishers (in terms of lost livelihood and income), the government (in terms of lost fisheries rent), and the consuming public (in terms of lost availability of fish food). There is a great need to further explore the sharing of management costs and benefits to improve current conditions of declining Philippine fisheries by the various concerned stakeholders.

Review of Relevant Literature on Fisheries Trends and Options for Fisheries Recovery

Many of the publications we reviewed documented declining or potentially-declining fisheries across the globe (73% of 56 studies; Tables S2, S3). Only 20% of studies reported stable or recovering fisheries, while 7% gave mixed interpretations on the status of the studied fisheries.

Of the 41 studies that reported declining or potentially-declining fisheries, the most documented consequences were declining fish catch biomass (73% of 41 studies), poor status of evaluated fish stocks (51%), and low or declining fish catch diversity (39%). Overfishing was the most cited driver of declining fisheries (80% of 41 studies), which includes IUU, increases in fisher population, and implementation of subsidies that increase fishing pressure (e.g., by providing more boats or fishing gear to fishers). Anthropogenic disturbance was the next most cited driver (20%), followed by natural causes (14%). In contrast, many of the studies that documented stable or recovering fisheries reported high or increasing fish catch biomass (64% of 11 studies), good fish stock status (45%), good fish diversity (27%), and economic gains associated with fishing (27%). The most cited driver of these stable fisheries was implementing strategies that regulated fishing activity (91%), mainly through the establishment of fishing quotas, fishing closures, MRs, and policies against illegal fishing. Such strategies are mainly applied in the context of developed countries, but to date have been challenging for developing countries (including the Philippines) to apply because of the associated costs of research and expertise, assessment, management implementation and enforcement, and the costs of providing alternative livelihoods for fishers displaced by management implementation.

Most studies, whether reporting declining or stable fisheries, recommended some form of management for fisheries recovery and sustainability (87% of 56 studies). Among the 49 studies that provided management recommendations, the most frequent suggestion was the direct regulation of fishing activity (71% of 49 papers). Direct regulation of fishing activity could be done through a variety of methods, including the implementation Total Allowable Catch (TACs), fishing quotas, gear restrictions, policing against IUU, fishing vessel limits, fishing closure seasons, fishing permits or licenses, and carefully-implemented fisheries subsidies (i.e., subsidies that do not lead to increased fishing pressure). Among these options, establishment of MRs, gear restrictions, and policing against IUU may be realistically applied to Philippine fisheries management today (though enforcing these policies may be challenging, considering the high costs of management implementation and the spatial variability of multi-gear and multi-species fishing activity in most Philippine coastal areas, Muallil et al., 2014a). Other methods, such as TACs and quotas, are set by data-intensive stock assessments and monitoring that require consistent funding and institutional support—which coastal resource management bodies (e.g., municipal LGUs) in the Philippines generally lack. However, conducting such data-driven assessments is imperative to improve the management of Philippine fisheries, and hopefully, the Philippine government will allocate sufficient funding to cover the costs of fisheries assessment and management in order to rebuild Philippine fisheries and recover the lost fisheries benefits from current overfished and depleted fisheries status. Indeed, the next most frequently-suggested option in the literature was enhancing scientific-based management (40%), which includes conducting research, stock assessments, and monitoring the status of fisheries and other marine resources, to help make data-driven decisions in coastal resource management. Scientifically, assessed stocks are typically in better condition than unassessed stocks throughout the world, as rigorous assessments usually coincide with increased management attention (Hilborn and Ovando, 2014).

Improving collaboration between stakeholders was also suggested (28%), which means increased transparency and communication between the different levels of management, encouraging co-management, and integrating local knowledge in fisheries assessments and decision-making.

Establishment and enforcement of MRs was also recommended (25%). MRs have a long history as a management tool in the Philippines, and studies have shown that MRs can increase density and biomass of exploited fisheries species inside MR boundaries through protection of adults (Russ and Alcala, 2004; Samoilys et al., 2007) and self-recruitment (Almany et al., 2007). However, proper enforcement is vital to MR effectiveness (Samoilys et al., 2007), and even long-established MRs can become degraded and depleted when support is lost (Russ and Alcala, 1999, 2003). In addition, few studies have empirically demonstrated the benefits of MRs on surrounding fisheries beyond MR boundaries (Maypa et al., 2002; Russ et al., 2004; Abesamis et al., 2006; Harrison et al., 2012).

Finally, alternative livelihood for fishers (17%), and increasing stakeholder education and awareness (16%) were also recommended, particularly by studies conducted in the Philippines. These two recommended management options help improve the economic status of fishers, while simultaneously alleviating fishing pressure. Livelihood diversification decreases the over-reliance of fishers on a single (and highly fluctuating) resource (Allison and Ellis, 2001), while improved education increases fishers' skills and opportunities to enter occupations other than fishing. Thus, alternative livelihoods and improved education are expected to decrease fishing pressure, though the effectiveness of these projects are determined by the type of alternative livelihood provided and the social and demographic background of fishers (Pollnac and Pomeroy, 2005; Muallil et al., 2013). However, many alternative livelihood projects in the Philippines are discontinued after the project's duration expires, because fishers perceived minimal incentive to continue such projects due to a lack of equitably-distributed benefits (Christie et al., 2005; Pollnac and Pomeroy, 2005). In contrast, projects that successfully sustain implementation are those where (1) fishers are actively involved in project planning and implementation, and (2) benefits of alternative livelihoods and other forms of coastal resource management are equitably distributed among stakeholders (Pollnac and Pomeroy, 2005; Pomeroy et al., 2005). While local communities have the responsibility to comply with these management measures, governing bodies have the responsibility to provide adequate incentives toward effective management (Beddington et al., 2007), so regression back to unsustainable practices is prevented. In the Philippines, capacity-building and alternative livelihood programs are implemented by various government and non-government institutions, which include stock provision for farming and livestock, technical skills development to increase employment opportunities in other fields, and micro-financing from small business as implemented by the local government and various line agencies (Muallil et al., 2014b). Thus, platforms for encouraging reductions in fishing effort through alternative livelihood programs are taking shape in the country, but need further assessment and improvement, considering the great spatial scale and increasing number of marginalized fishers that rely upon the dwindling fish stocks in most Philippine coastal waters.

Caveats and Future Research

One of the caveats of the current study is that the data used to analyze Philippine fisheries was limited to fish catch data. Although, fish catch has been criticized as being mis-representative when analyzing fisheries status (Branch et al., 2011), catch data is currently the most complete, publicly-available data type on Philippine fisheries to date. Fish catch data is far from useless, and should be used to infer the status of fisheries wherever it is available, at least tentatively (Pauly et al., 2013). However, stakeholders in Philippine fisheries management should still strive to collect data through fisheries-independent research surveys, monitoring, and stock assessments, which can be used in conjunction with catch data to provide more comprehensive assessments of the nation's fisheries, in the future.

Another caveat is the questionable quality of the Philippine fisheries data. For instance, the existing BFAR database does not take into account Illegal, Unreported, and Unregulated (IUU) fishing. In the Western Central Pacific, which includes the Philippines, it was estimated that IUU comprised 34–38% of total fish catch from 1980 to 2003 (Agnew et al., 2009). This is a large proportion of catch, and implies that levels of overexploitation in Philippine fisheries may be under-reported. In addition, overlaps between catches of municipal and commercial fishers are largely un-accounted for. Moreover, mobility of fishers and their landings (e.g., movement between provinces) are not clearly accounted for in the database, thus preventing analysis of spatial serial fisheries depletion or geographical expansions. Further, improvement in the quality of Philippine fisheries statistics is essential for better fisheries management applications.

A final caveat of the current study is the inconsistency of Philippine fishing effort records to date. Fishing effort was reported inconsistently in BFAR's annual Fisheries Profile publications from 1980 to 2012, i.e., some BFAR publications reported only the number of registered municipal fishing boats or *bancas*, while other BFAR publications reported only the number of fishing operators, or registered commercial fishing vessels. In addition, fishing effort data was patchy and not regularly updated. For example, the BFAR Fisheries Profile for the year 2007 presented registered fishing vessel records from the year 1999. Clearly, there is a great need to improve the consistency of tracking fishing effort in the Philippines, in order to monitor the state of the nation's fisheries more accurately.

Future, research on Philippine fisheries should focus on more in-depth analysis of fish catch rates, exploitation levels, and fish stock status recorded in the country. For example, elucidating fish stock status using Underwater Visual Census (UVC) surveys of coastal areas could provide alternative and non-destructive fisheries-independent data collection to complement fish catch records, considering many important municipal fisheries species (e.g., belonging to families Acanthuridae, Caesionidae, Lutjanidae, Lethrinidae, Labridae (particularly

Scarinae), Nemipteridae, Serranidae, Siganidae, and Kyphosidae) are demersal or reef-associated (Maypa et al., 2002; Abesamis et al., 2006; Muallil et al., 2012, 2014a), and are typically detected by UVC methods. Also, future studies could tap other sources of data not usually accessible online and therefore will be costly to collate. These would include municipal reports, surveys conducted by Non-Government Organizations (NGOs), and the studies of university students and researchers.

In addition, the effects of fisheries management efforts—which include both costs and benefits incurred by all stakeholders involved (Toribio et al., 2013)—should be further explored and analyzed to understand Philippine context of fisheries management. For example, regarding MR establishment, the costs of displacing fishers should be accounted for in addition to the monetary costs of enforcing MR protection (e.g., costs of guardhouse construction, purchase and operations of patrol boats, and costs of manpower to police MRs). Regarding alternative livelihood projects, ensuring the equitable distribution of benefits would give local communities greater incentive to maintain enforced fisheries management, but this also needs to be quantified (Pollnac and Pomeroy, 2005). Such management measures may serve as responses to pressures often faced in developing coastal communities (e.g., overexploited resources, poverty and low income, undernourishment, vulnerability to sudden climactic disturbances), though there are still significant gaps regarding the appropriate responses to particular pressures (Cabral et al., 2013). Thus, there is a great need to study the complexities of fisheries as social-ecological systems (Lebel et al., 2006; Cinner et al., 2012), and to provide specific management recommendations appropriate to the social-ecological dynamics of a particular locality or context (Johnson et al., 2013).

Finally, our examination of long-term, spatio-temporal data of Philippine fisheries highlights the need to examine and monitor Philippine fisheries production at finer spatial scales. For example, the high municipal fish catch in only a few provinces (e.g., Palawan) may have masked the overall stagnation or decline of fish catch in most other provinces (**Figure 4**). Examining fisheries production at finer scales will allow stake-holders and decision makers to apply appropriate management measures based on the spatial variations in Philippine fisheries between different regions, provinces, and municipalities.

CONCLUSION

Our analysis of Philippine fisheries production suggests that Philippine fisheries production is declining, with the high production volume of the aquaculture sector (i.e., mostly seaweeds) masking the stagnating or declining fish catch of most capture fisheries in recent times. The decline in catch volume of most provincial and municipal fisheries throughout the country is reflected in the low incomes of many Filipino fishers (despite the fact that the total value of capture fisheries continues to increase). Managing fisheries and coastal resources does not end with the implementation of policies that directly influence fishing pressure (e.g., MR enforcement, fishing bans, and catch quotas). Policies related to community management that indirectly influence fishing pressure, such as increasing education levels and providing alternative livelihood to fishers and their families, should be further explored to help reduce the levels of over-exploitation experienced by Philippine fisheries. The Philippine media, government, scientific communities, and conservation organizations need to clarify the declining state of Philippine fisheries and explore options to recover or rebuild the overexploited fisheries to meet the needs of rapidly increasing Filipino population.

AUTHOR CONTRIBUTIONS

JA conceptualized this paper, actively participated in the data gathering, data analysis, and write-up, and set the overall directions for the paper. He also secured the funding for this work. KG gathered the data actively participated in the data gathering, processing, analysis, and write-up. Both authors equally contributed to the development of this paper.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: http://journal.frontiersin.org/article/10.3389/fmars.2016.00021

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